SEDIMENTARY MODELS AND GEOMORPHOLOGICAL CLASSIFICATION OF RIVER-MOUTHS ON A SUBTROPICAL, WAVE-DOMINATED COAST, NATAL, SOUTH AFRICA.

BY

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Preface

The research described in this thesis was carried out in the Department of Geology and Applied Geology, University of Natal, Durban and at the offices of the CSIR in Durban from January 1987 to December 1991, under the supervision of Professor T.R. Mason.

These studies represent original work by the author and have not been submitted in any form to another university. Where use was made of the work of others it has been duly acknowledged in the text.

To my friend John whose own thesis will remain forever unfinished.

The clock of life is wound but once,
And no man has the power to tell
Just when the hands will stop
At late or early hour

Now is the only time you own,
Live, love, toil with a will,
Place no faith in tomorrow,
For the clock may then be still
Anon.

ACKNOWLEDGEMENTS

Having studied various aspects of coastal and estuarine sedimentology, Quaternary geology and geomorphology on the Natal coast for the past seven years, arriving at the final subject matter of this thesis was not a straightforward procedure. From initial effort in the Mgeni Estuary through subsequent investigations in several small Natal river-mouths to Kosi Bay in northern Zululand, the thesis subject matter ultimately evolved to a study of river-mouths between the Mlalazi and Mtamvuna Rivers. During the formulation and execution of several research projects and the vagaries associated with settling on a final thesis subject, I have been assisted, encouraged, supported, stimulated, calmed and restrained by a number of people.

Chief among these is my supervisor, Professor Tom Mason, who throughout the meandering path of my post-graduate career has been a constant supporter and promoter. Without his help much less would have been accomplished. I thank him sincerely.

Many friends and colleagues at the University of Natal, the Geological Survey and the CSIR have played a vital role in my excursions into the realms of sedimentology. From among these people I especially wish to thank Peter Ramsay and Ian Wright, fellow members of that rare club who have dived to 35 m in zero visibility in Lake Nhlange. They provided invaluable help and lively discussion and together we learned a great deal from the depths of Zululand to the murky depths of the Mtamvuna Estuary. Without Peter's surveying skills many of my efforts would have come to nought.

Arjoon Singh and Trevor Harrison, of the CSIR, with whom I share the dubious honour of having scaled the steep face of the Kosi mouth gabbions (in a downward direction), having indulged in copious amounts of both gin and brandy, have accompanied and assisted me in my wanderings to many field locations. Without their help and friendly impudence, fieldwork would have been mere drudgery. I thank (or blame) Trevor for my rudimentary knowledge of estuarine fish and the art of ichthyoimbibology and Arjoon for introducing me to the delights of Indian cuisine. I express my special thanks to Arjoon for the long hours spent expending his artistic talents to prepare the figures for this and my other literary efforts.

Dr Alan Ramm had the boldness to employ me and, working together with him and Trevor Harrison, I have each learned a great deal about multidisciplinary approaches to estuarine and coastal research. I thank Alan for supporting my research efforts at every turn and helping me in many aspects of research from statistical methods, computing, water chemistry to introducing me to the biogeochemistry of sulphur and the thrill of diving in H_2S-laden water !!!

Peter Bova, of the Geological Survey in Bellville, Cape Town, became my friend during several visits to Zululand since 1988. He expended a great deal of his own time and effort to build a giant raft for vibracoring at Kosi Bay, assisted me during seismic profiling, and encouraged me no end with his enthusiasm for my research. He also introduced me to Czech folk music at Tembe Elephant Reserve, an experience never to be repeated!!!

The Chief Director, Dr Nok Frick and deputy director Mnr André du Plessis of the Geological Survey gave permission for their staff to assist me in my research at Kosi Bay. I am extremely grateful.

To my Divisional Director, Dr Ben van Vliet, I wish to record my sincere thanks for the time and financial support granted me during the past 18 months which allowed me to devote most of my time to compilation of this thesis. Without such support this thesis may never have materialised. I also thank the Division of Water Technology of the CSIR for supporting my attendance at conferences in Washington D.C., Nottingham, U.K. and La Plata and Tierra del Fuego, Argentina. Through my experiences there and discussions with other workers I learned a great deal.

I also extend a belated thank-you to my parents who encouraged and supported my initial interest in geology and expressed genuine interest in my early projects.

Many other people have assisted me during the many stages of this research with discussion or physical assistance and I wish to record my thanks to them also: Nico Grobbler, Scott Callow, Wade Kidwell, Malan van Niekerk, Piet Huizinga. Frank Junor kindly loaned me his oblique aerial photograph collection. I also thank John Bufton who came to my rescue at the last minute when our trusty laser printer said "enough!".

In that space traditionally reserved for spouses at the end of thesis acknowledgements I wish to say simply, 'thanks Mandy, for your love, encouragement, help, patience, support and belief in my abilities, during this and my other endeavours during the past seven years or more'.

ABSTRACT

This thesis documents sedimentation of the fluvio-marine transition on a 300 km sector of the Natal coast of South Africa between the Mlalazi and Mtamvuna river-mouths. Sixty-four rivers form independent outlets to the sea along this near-linear coastline. Sandy coastal deposits occupy river-mouths and shallow coastal embayments.

The coastal hinterland rises steeply to 2000 m within 200 km of the coast. The climate is subtropical and mean annual precipitation amounts to 1000 mm. Seasonal precipitation and episodic rainfall events cause severe flooding. Individual river drainage basins range from 4 km^2 to 29 000 km^2 in area.

The coast is microtidal and coastal hydrodynamics are dominated by wave action, particularly long-period swells from the southeast and south-southeast. Median wave height is 1.49 m. The continental shelf is narrow (7 to 40 km) and dominated by the south-flowing Agulhas Current.

Sediment yield is high from the steep, deeply weathered coastal hinterland, although the best current estimates appear to be over-estimates. These characteristics affect river-mouth environments along the coast.

The study area is tectonically stable and Holocene sea-levels rose from about -130 m 17000 years BP to reach present level about 7000 BP. Available data suggests that four higher sea-level peaks have existed since 7000 BP. Three of these correlate well with temperature records for the past 5000 years.

Geomorphological and sedimentological variation among river-mouths is assessed by reference to four case studies, the Mtamvuna, Mgeni, Mhlanga and Mvoti, which were selected because of clear geomorphological differences.

The 1570 km^2-catchment Mtamvuna River discharges into the Indian Ocean via a 5 km-long, narrow, cliff-bound river-mouth, protected from direct marine influences by a sandy barrier. The river-mouth is 13 m deep and is still in a youthful stage of development. The channel is divided into three main units: (a) shallow, sandy lower reaches adjacent to the barrier; (d) deep, muddy middle reaches, and (c) shallow upper reaches, characterised by gravelly sand. The lower reaches receive marine sediment through flood-tidal and overwash deposition. The middle reaches are dominated by

suspension settling and the upper reaches are a lag deposit derived from rockfalls from adjacent cliffs, from which the fine fraction is winnowed.

Little fluvial bedload material is supplied to the adjacent rocky coast. Floods erode barrier-associated sediments and deposit a submerged delta offshore. After floods this is reworked landward, reforming the barrier and migrating upstream through barrier rollover and flood-tidal deposition, until equilibrium is reached with the ambient wave field.

The Mgeni River drains an area of 4863 km^2. The river-mouth occupies a narrow alluvial valley and the channel is contained within cohesive muddy banks. The river-mouth extends northward at the coast behind an elongate barrier. The river-mouth is dominated by fluvial sand. A small flood-tidal delta occurs under stable conditions. After a major flood in 1987, extensive vertical scour in the channel eroded 1.6×10^6 m^3 of sediment from the lower 2.5 km of the river course.

Post-flood channel recovery took place through a distinctive series of stages. Initial suspension settling shallowed the channel to a uniform water depth throughout. Subsequently, rapid downstream migration of fine-grained sand filled the remaining channel areas, causing much of the river-mouth to be exposed intertidally. Then mud deposition began in the intertidal areas followed by vegetal colonisation.

Photographic records since a major flood in 1917 show that long-term adjustment involves stabilisation of banks and intertidal areas and the formation of a cohesive central island. Flow is then confined and effects downward scour to facilitate discharge. Consequently the channels deepen. When sampled before the 1987 flood the channels were characterised by lag gravels, indicating the amount of scour achieved under mature conditions.

The barrier and adjacent coastline prograde temporarily after major floods as the eroded barrier is reformed by wave action. Wave refraction around ephemeral flood-generated deltas controls the shape of the newly emergent barrier.. Excess sediment is ultimately eroded as waves adjust the barrier to an equilibrium planform.

The 118 km^2-catchment Mhlanga River flows into an elongate, coast-parallel river-mouth area behind a 900 m-long barrier. No outlet is present for about 90% of the year and stream discharge is accommodated by seepage and evaporation. Sediments in the river-mouth are of fluvial origin, but near the barrier, overwash-derived sediment predominates.

Sedimentation is dominated by suspension settling when the barrier is closed. Breaching causes rapid outflow and draining. Associated erosion is limited to fine-grained sand and mud which accumulated during closed phases. Breaching produces bedforms typically associated with intertidal flats, but distinctive biogenic structures offer a potential means of distinguishing such environments.

Barrier breaches are sealed by elongation of the outlet channel in the direction of longshore drift. Outflowing water loses competency and the breach is sealed by wave action. Breaches seldom remain open for more than 10 days. Sedimentation is dominated by a cyclic pattern of breaching and closure which maintains equilibrium in the river-mouth.

The Mvoti River has a catchment of 2773 km^2. Its river-mouth flows across a broad floodplain of sandy alluvium and enters the sea across an elevated rocky outlet channel which prevents tidal exchange. The back-barrier area contains exclusively fluvial sediment and marine sediment is restricted to the barrier.

Major floods erode a flood breach through the northern end of the barrier and cause widespread overland flow. Flood discharge is accommodated by lateral channel erosion and downward scour is limited. Widespread overbank deposition occurs. Flood-generated deltas are deposited in the nearshore environment opposite flood breaches. Wave-reworking of these deltas reconstitutes the barrier in post-flood periods and flow reverts to the elevated outlet channel. Barrier reconstruction is controlled by wave refraction around the flood delta.

Post-flood channel adjustment occurs by lateral accretion through vegetation encroachment and mud deposition in abandoned channels. Mud deposition and vegetation growth stabilise the channel margins and promote formation of a single, relatively deep channel in interflood periods.

Differences in morphology and sedimentation between the four river-mouths discussed can be broadly linked to four parameters: catchment size; catchment geology; nearshore topography; and surrounding geology.

Using the four identified genetic parameters a new classification was developed for all 64 river-mouths in the study area. This involved the assignment of a numerical value to each parameter, which in itself involved the combination of several measured parameters.

The following seven factors were used to classify Natal river-mouths:

1) percentage of year mouth closed;
2) average floodplain width;
3) percentage of the catchment underlain by granitoid rocks;
4) percentage of the catchment underlain by Dwyka Tillite and Natal Group Sandstone;
5) percentage of the catchment underlain by shales;
6) barrier length;
7) catchment size.

These variables were grouped using a cluster analysis which divided them into 8 main associations which displayed distinctive morphologies. The classification may be used to identify evolutionary trends and human impacts on river-mouth morphology. It also offers a predictive capability to assess the impact of future changes.

Four basic river-mouth types are identified: drowned river-valley estuary; delta-top estuary; coastal lagoon and and non-tidal river-mouth. Outliers of this classification include a beachridge plain delta and an estuarine plunge pool.

The sedimentary process models presented, of drowned river-valley estuaries, delta-top estuaries, coastal lagoons, non-tidal river-mouths and beachridge plain deltas on steep hinterland, subtropical, wave-dominated coastlines augment current knowledge of transitional coastal environments. Pre-Holocene deposits were eroded from the restricted valleys during low Pleistocene sea-levels and most valley fills are Holocene in age. Holocene evolution of these features can be related to the relative importance of fluvial sediment supply and the rate of basin increase during sea-level rise. Late Holocene sea-level lowering caused channel incision into earlier alluvial deposits in river-mouths and accelerated evolutionary trends.

All river-mouths in the study area except the Mtamvuna are at a mature stage of evolution. Channel changes are a response to discharge variation, particularly during major floods. Excess sediment yield from river catchments passes into the sea after only a temporary residence period in river-mouths.

* * *

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CHAPTER 1.

INTRODUCTION

1.1. AIMS AND OBJECTIVES

This thesis is concerned with the geomorphology and sedimentology of the lower reaches of rivers in the Province of Natal, a subtropical area with a strongly wave-dominated coastline. The steep gradients of the rivers, their abundance, and high sediment yield from their catchments combine to exert a major influence on river-mouths and the contiguous coastal system. The lower reaches of these rivers (here collectively termed river-mouths) have been little studied from a sedimentological viewpoint, although current dogma maintains that they are undergoing rapid siltation as a result of anthropogenic influences in the river catchments (Heydorn, 1973a,b, 1979; Begg, 1984a; Perry, 1985a).

Against this background the objectives of this thesis may be stated as follows:

a) to investigate sediment distribution and facies in four selected Natal river-mouths;
b) to investigate sedimentological processes in various types of river-mouth;
c) to assess the role of river-mouths in the sediment budget
d) to determine the basic physical factors which control variation in river-mouth morphology in the study area;
e) to develop a geomorphological classification scheme for Natal's river-mouths;
f) to synthesise sedimentary models for rivermouths in this type of environmental setting and relate them to other transitional fluvio-marine environments.

This thesis is an overview of geomorphological and sedimentary variation in rivermouths and the adjacent coast on the Natal coast in terms of their physical framework, on a local and world scale. Although reference is made to several case studies, it is not intended as a precise hydrodynamic assessment of river-mouth processes and form. Much work remains to be done in this field and future research needs are identified in the concluding chapter.

In this thesis the environmental setting of the study area is outlined. Sediment distribution and sedimentary facies are documented and long- and short-term sedimentation processes are compared in the four river-mouths selected as case studies. The case studies are compared in relation to each other and other river mouths in the study area. Geomorphological reasons for the differences are discussed. A classification scheme is proposed for Natal estuaries, based on the controlling geomorphological variables identified. An attempt is made to justify the scheme using numerous examples. Finally, sedimentary models for rivermouth sedimentation on steep-hinterland, subtropical, wave-dominated coastlines are presented and compared with other areas. The river mouths are compared with world examples and the classification of transitional fluvio-marine environments is discussed.

1.2. SEDIMENTATION AT THE FLUVIO-MARINE TRANSITION

When terrestrial drainage paths enter the sea any of a wide variety of transitional fluvio-marine sedimentary environments are formed. These environments vary widely in morphology and size and include coastal embayments, coastal lagoons, estuaries, fjords and deltas and barrier islands to name but a few. In many cases the terminology for the sedimentary environments is unclear due to the wide variety of definitions adopted for each environment. Strict divisions and classifications may not even be appropriate as there appears to be a finite set of transitional end members between which various intermediate forms occur. The controls on these morphologies have not been investigated thoroughly in terms of the environmental setting of the coast and hinterland and distinctions are still made in very general terms. Suites of sedimentary models have been established for some of these environments, particularly those associated with economic deposits (for example deltas and barrier islands). In most cases diagnostic structures and facies associations enable their recognition in the geological record. Estuaries, however, remain the most enigmatic environment, followed by coastal lagoons, and some authors argue that no undisputed estuarine sequence has yet been described from the geological record. Part of that problem stems from the wide range of concepts and definitions of what constitutes an estuary or lagoon, while a second and more important problem arises from the limited range of "estuarine" environments which have been described and the even more limited range of applicable sedimentary models.

Estuaries are abundant on the modern world coastline, mainly as a result of drowning of river valleys during the Holocene Transgression. However, they vary in formative processes, tidal range, climate, river catchment size, coastal geology, sediment supply and a host of other factors. It is widely accepted that estuaries are ephemeral features on a geological time scale and that they may be dramatically altered by changes in relative sea level. Under conditions of relatively constant sea level they act as depocentres for sediment from a variety of sources including rivers, adjacent coastal erosion, ocean floors, bank erosion and organic production and therefore generally tend to be infilled. The infilling process from the landward side is accelerated where climatic conditions favour deep weathering and high sediment yields and river flow is sufficient to transport this material into the estuary. Such conditions are generally met in the humid tropics and subtropics, thus implying a climatic control on fluvially dominated environments. Infilling from this source may be further accelerated by human influences including poor farming practices and destruction of soil-stabilising vegetation. Even when filled, estuaries may still act as conduits for water, sediment and nutrients to the coast.

In the study area transitional fluvio-marine environments are located directly at the mouths of rivers and are generally confined to the river valley: high wave energy and a steep nearshore gradient do not permit the formation of deltas or offshore barriers and consequently longshore extension of river courses into extensive lagoons is generally restricted. Furthermore, the lack of a coastal plain and rocky coastal framework, mean that the lower reaches of rivers are laterally confined.

The range of river-mouth environments observed in Natal are produced by a unique set of variables; climatic, oceanographic, and topographical, and provide a set of observations additional to those currently available for transitional fluvio-marine environments. These will assist in formulation of a comprehensive suite of sedimentary models in the future. Along the limited coastal area, several variables remain constant and the number of factors controlling the range of morphologies is reduced compared to a global study. This provides the opportunity to assess the controls on morphology within a limited area.

Sedimentary models for environments such as those seen in Natal are poorly documented and our state of knowledge of transitional sedimentary environments is severely restricted. This stems from a lack of integrating studies on transitional environments.

1.3. THE STUDY AREA

1.3.1. Locality

The study area is the 300 km section of the east coast of South Africa between the Mlalazi River-mouth (28°56'S; 31°48'E) in the north and the Mtamvuna River-mouth (31°04'S; 30°11'E) in the south (Fig.1.1.). The entire area lies within the Province of Natal and includes about half of its coastline. The coastline is near-linear and runs in a SSW-NNE direction. It comprises a mixed sandy rocky shore which lacks a coastal plain. Sixty-three rivers enter the sea in this coastal area. The study area is a geomorphologically distinct unit because, it is bounded to the north by the Zululand coastline which is backed by a broad coastal plain and contains large coastal lagoons (Orme, 1973), while to the south, the Transkei coast is predominantly rocky and has a more temperate climate.

The study area is located on the eastern side of the Great Escarpment of southern Africa and lies outside any of the major drainage systems of Africa. The Orange River drains the area to the west, the Limpopo and Zambesi rivers, areas to the north (Fig.1.2). In the study area, sixty-three rivers enter the sea through a variety of small transitional environments (Fig.1.3a) which collectively drain a coastal hinterland area of 57 000 km^2. Of this, 29 000 km^2 (51%) is drained by the Tugela River, which is the largest single point source of terrestrial sediment to the east coast of South Africa (Flemming & Hay, 1983). Five other large rivers dominate the drainage region south of the Tugela (Fig.1.3b).

The abundance of river-mouths in Natal renders them an important element of the coastal environment. The term "river-mouth" is used with as few implications as possible in this thesis for reasons of terminology and classification outlined subsequently (Chapter 8). To avoid confusion, no particular attributes are ascribed to the term "river-mouth" in terms of discharge, morphology, water chemistry, fauna or flora. A river-mouth, in this context, is simply defined as the sedimentary environment that exists at the interface between a river and the sea. It includes not only the open water area but also the surrounding floodplain or other areas periodically inundated during high river flows.

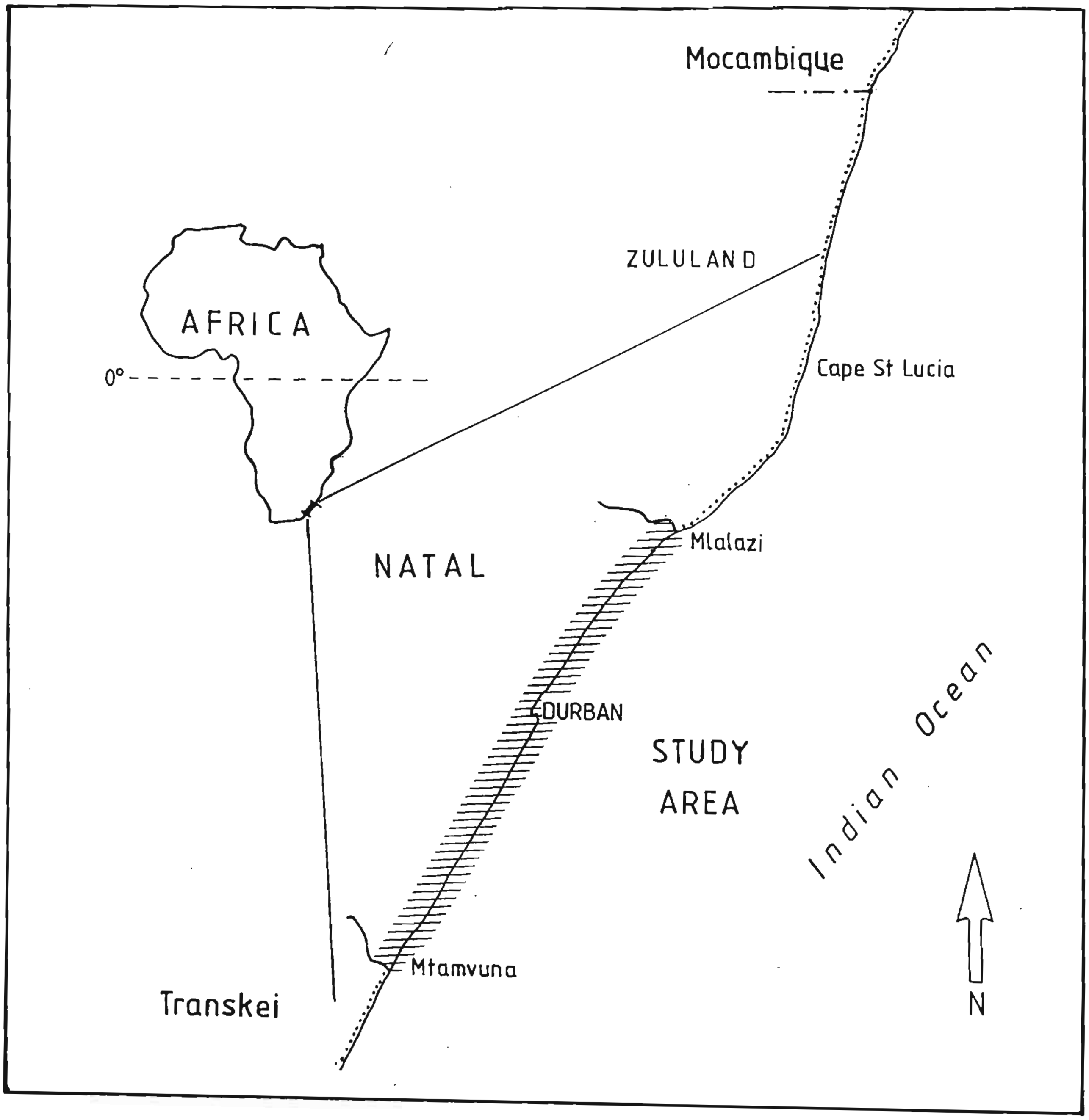


Fig.1.1. Location of the study area in relation to Africa. The northern and southern-most rivers are shown.

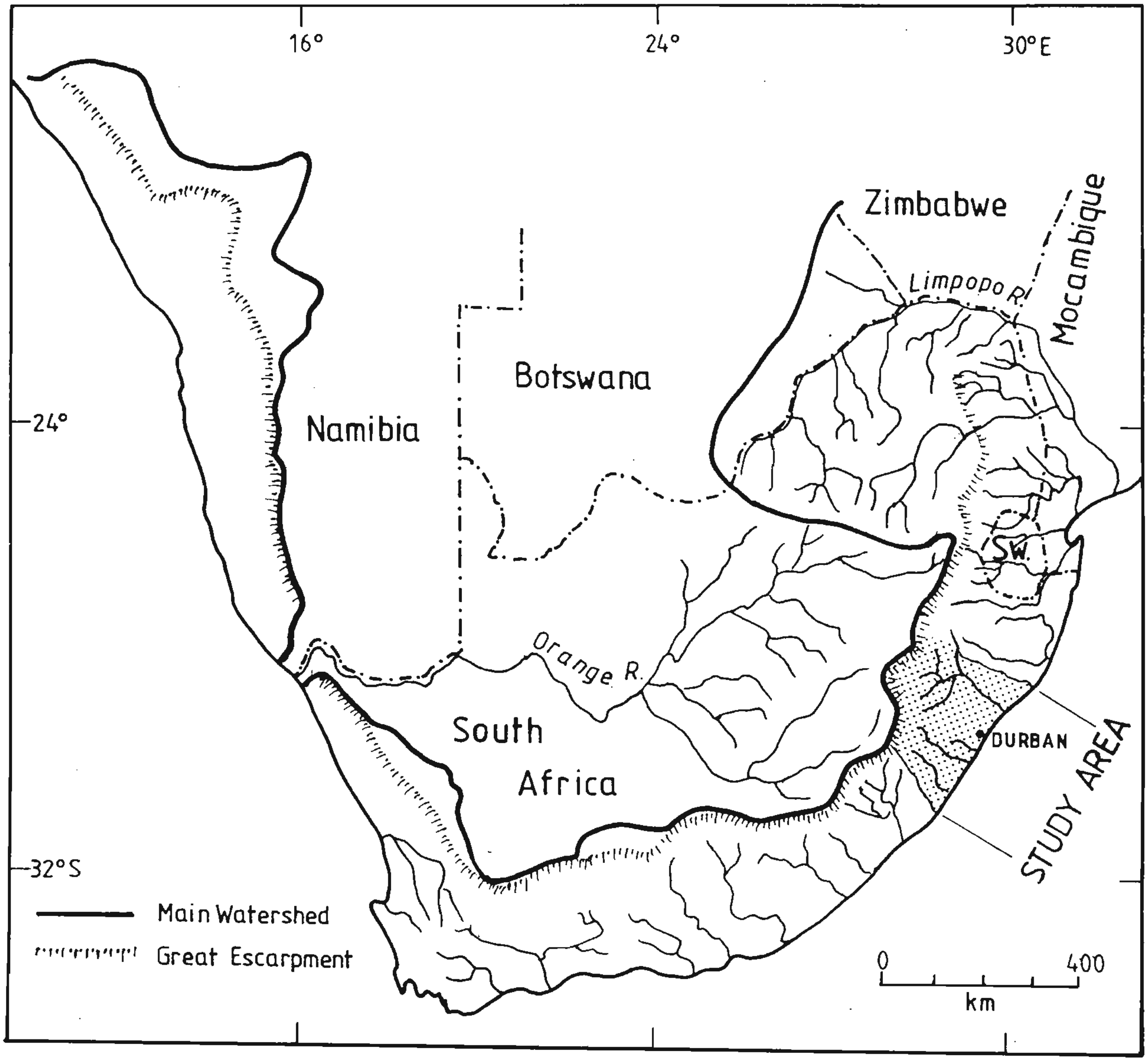


Fig.1.2. The study area in relation to major southern Africa drainage patterns and its relationship to the Great Escarpment of southern Africa.

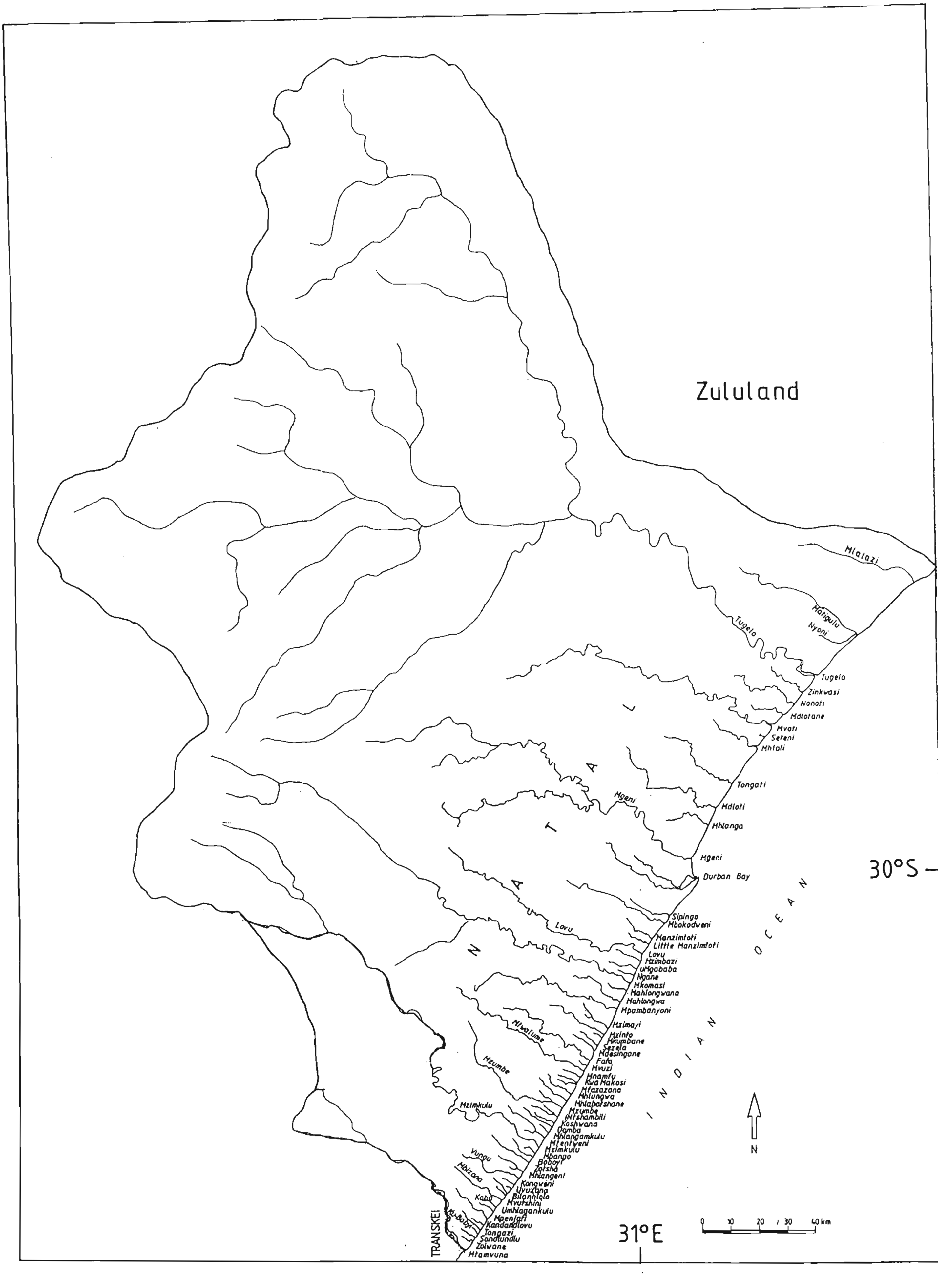


Fig.1.3. The study area, showing: (A) the abundance of transitional fluvio-marine areas produced where the rivers enter the sea; (B, overleaf) the domination of the hinterland by six large-catchment rivers, between which numerous small rivers are located.

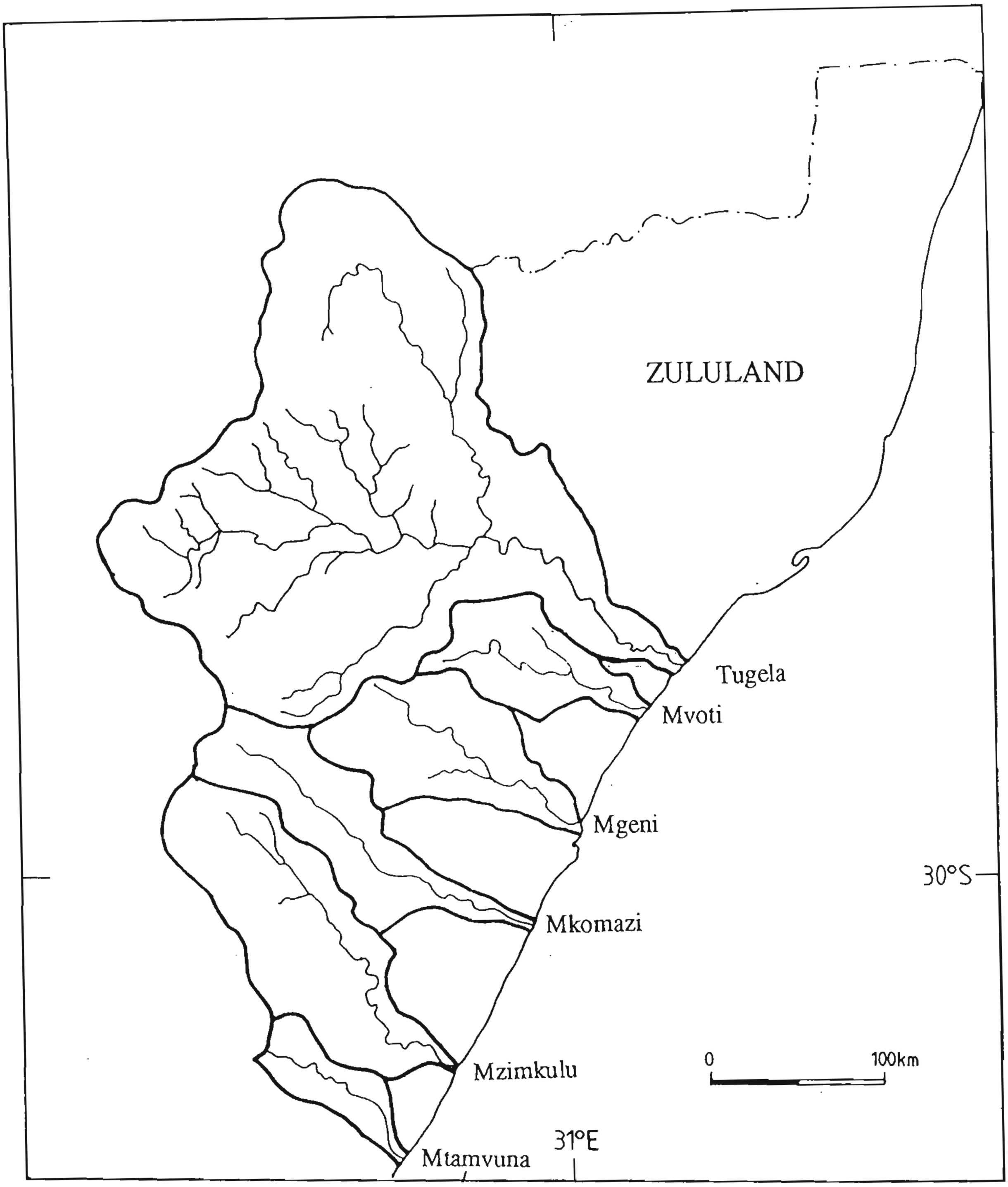


Fig.1.3B. The hinterland of the study area is dominated by six main drainage systems, the Tugela, Mvoti, Mgeni, Mkomazi, Mzimkulu and Mtamvuna.

1.3.2. Climate

The climate of the Natal hinterland is dominated by the subtropical high pressure belt (Schulze, 1965; van Zinderen Bakker, 1976, Tyson, 1987). Mean annual rainfall is between 900 and 1000 mm (Orme, 1974; Tyson, 1987) and is largely restricted to the summer months when 80% of the rain falls (Tyson, 1987). The hinterland is classified as subhumid to extreme humid (Tinley, 1985). In summer, a central high pressure system is typically located in the southeast and moist air flows into the interior from the Indian Ocean (Fig.1.4A). The rapid altitudinal rise from the coast to the Great Escarpment produces orographic forcing of rainfall (Tinley, 1985; Terblanche, 1988). Winter rainfall in the study area is typically associated with coastal low pressure systems moving northwards from the Cape (Fig.1.4B). This type of rainfall produces only a minor proportion of the total annual precipitation. Summer thunderstorms which are moved coastward from the interior, by upper air westerly winds can also affect large areas of the hinterland and coast (Tinley, 1985). Associated variable stream discharges impact on sediment transport in rivers.

A feature of Natal rainfall is its variability, not only seasonally but also on a decades-long scale. Tyson (1987) described a cyclic pattern of wet and dry periods marked by weak peaks and depressions in rainfall spectra in South Africa. He linked these to pressure variations associated with the Southern Oscillation (El Niño). The weak quasi-periodic oscillations in rainfall overprint a large measure of random variability. The most prominent peak has a period of about 18 years but others occur at 2.3, 3.5, 4-5, 6-7 and 10-12 year intervals. Along the Natal coast, extended periods of above-average rainfall are typified by greater frequency of (a) anticyclonic ridging to the rear of westerly waves; and (b) lows and cold fronts which control the distribution of rain-bearing winds (Tyson, 1987, p.151). Such long term variations in precipitation also affect stream runoff and sediment supply to the coast.

Temperature in Natal is at a maximum in February and a minimum in August (Schulze, 1965). Absolute maximum and minimum temperatures for Durban and Cape St Lucia respectively are 42.0 and 4.1°C and 39.0 and 5.7°C (Tinley, 1985). Climographs for Durban, Cape St Lucia and Maputo are shown in Figure 1.5.

1.3.3. Hinterland topography

Natal is located on the eastern side of the Great Escarpment of southern Africa. The peak of the escarpment is over 3000 m above sea-level and is only 200 kilometres from the coast. This produces a steep coastal hinterland (Fig.1.6). The western side of the continent, in contrast, falls to sea level over a much greater distance and topographical gradients there are consequently less steep. This has marked consequences for drainage patterns. The Orange River which, together with its major tributaries, the Vaal and Fish Rivers, drains most of the interior of the subcontinent, flows to the west coast. Drainage systems along the eastern seaboard, however, are comparatively short and steep. A consequence of the steep gradient is that rivers are short, and water flows at high velocity. In addition, rivers have little opportunity to coalesce and consequently most drain small, laterally restricted catchments, separated from each other by marked divides in the deeply dissected hinterland. River courses are narrow and have poorly developed floodplains which offer little storage capacity for riverine sediment (Le Roux,

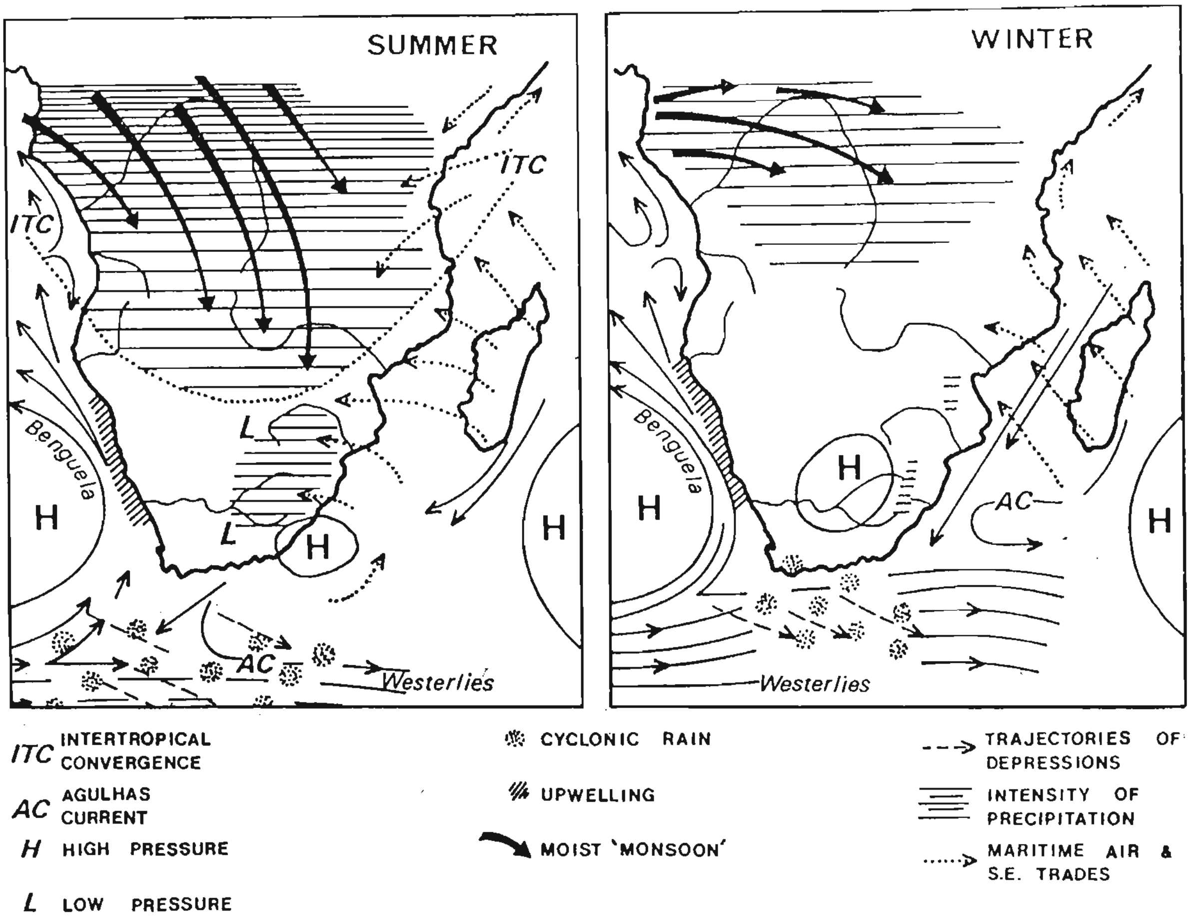
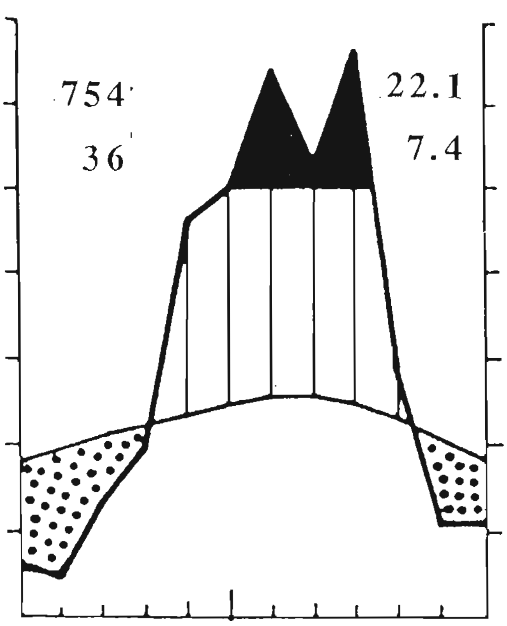
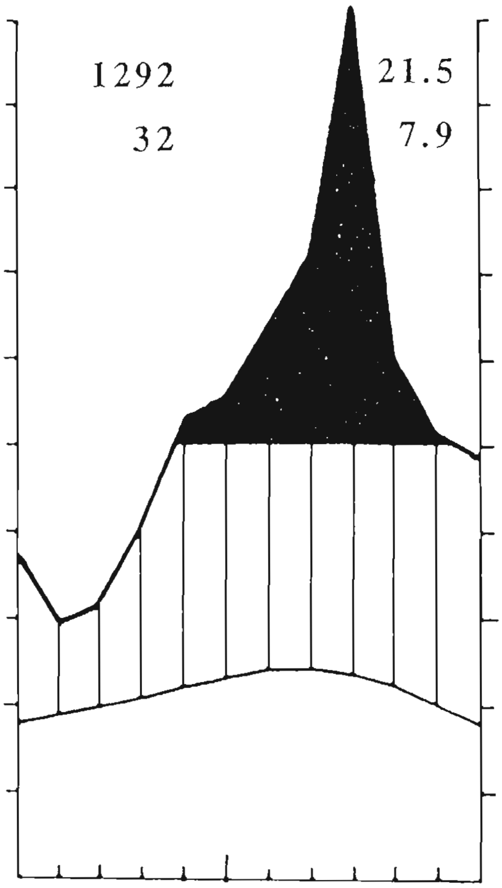


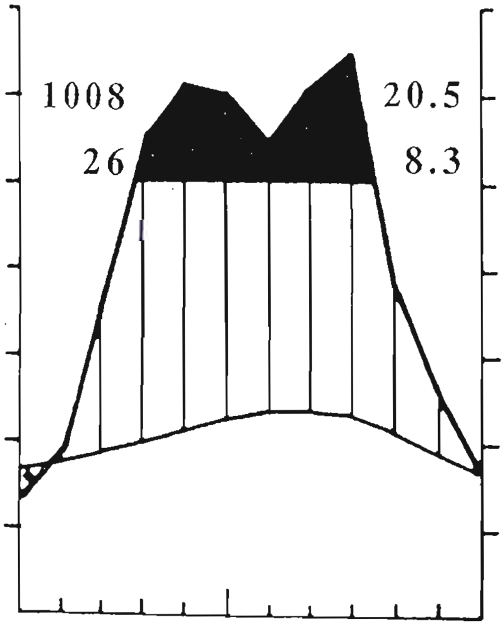
Fig.1.4. Atmospheric circulation over southern Africa during summer and winter. This variation in dominant circulation controls rainfall distribution which is strongly, though not exclusively, seasonal in the study area. (after van Zinderen-Bakker, 1976).



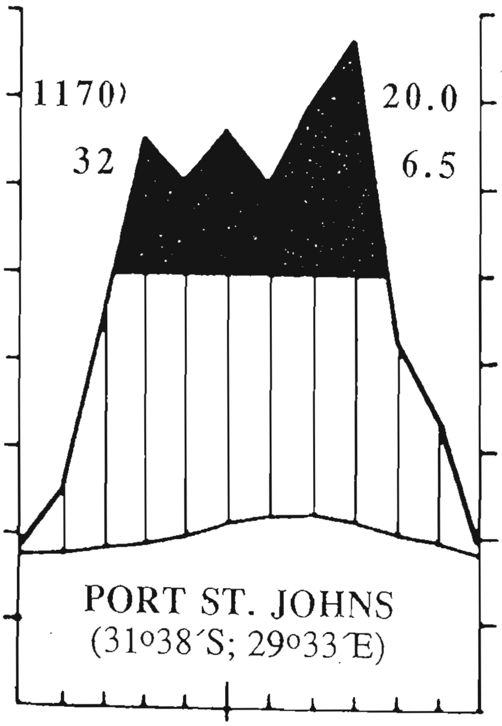
MAPUTO
(25°58´S; 32°36´E)



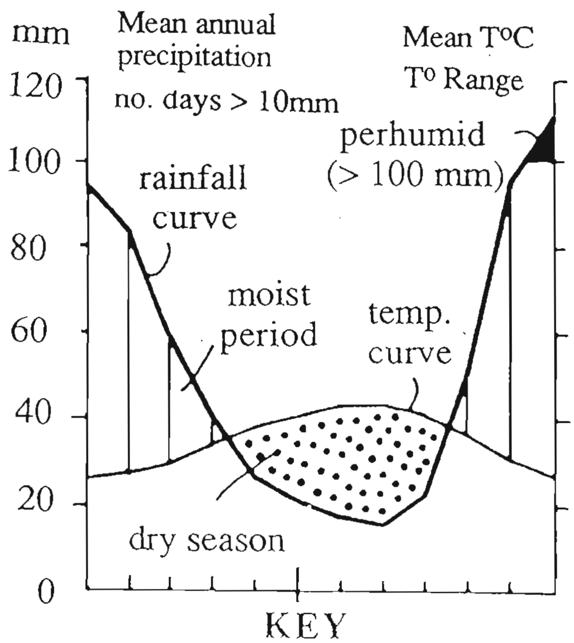
CAPE ST. LUCIA
(28°30´S; 32°24´E)



DURBAN
(29°50´S; 31°02´E)



PORT ST. JOHNS
(31°38´S; 29°33´E)



KEY

FIG. 1.5. Climographs for Port St Johns, Durban, Cape St Lucia and Maputo on the south east African seaboard (after Tinley, 1985). The climograph for Durban is broadly representative of conditions in the study area. Note the seasonal rainfall patterns and high mean temperatures.

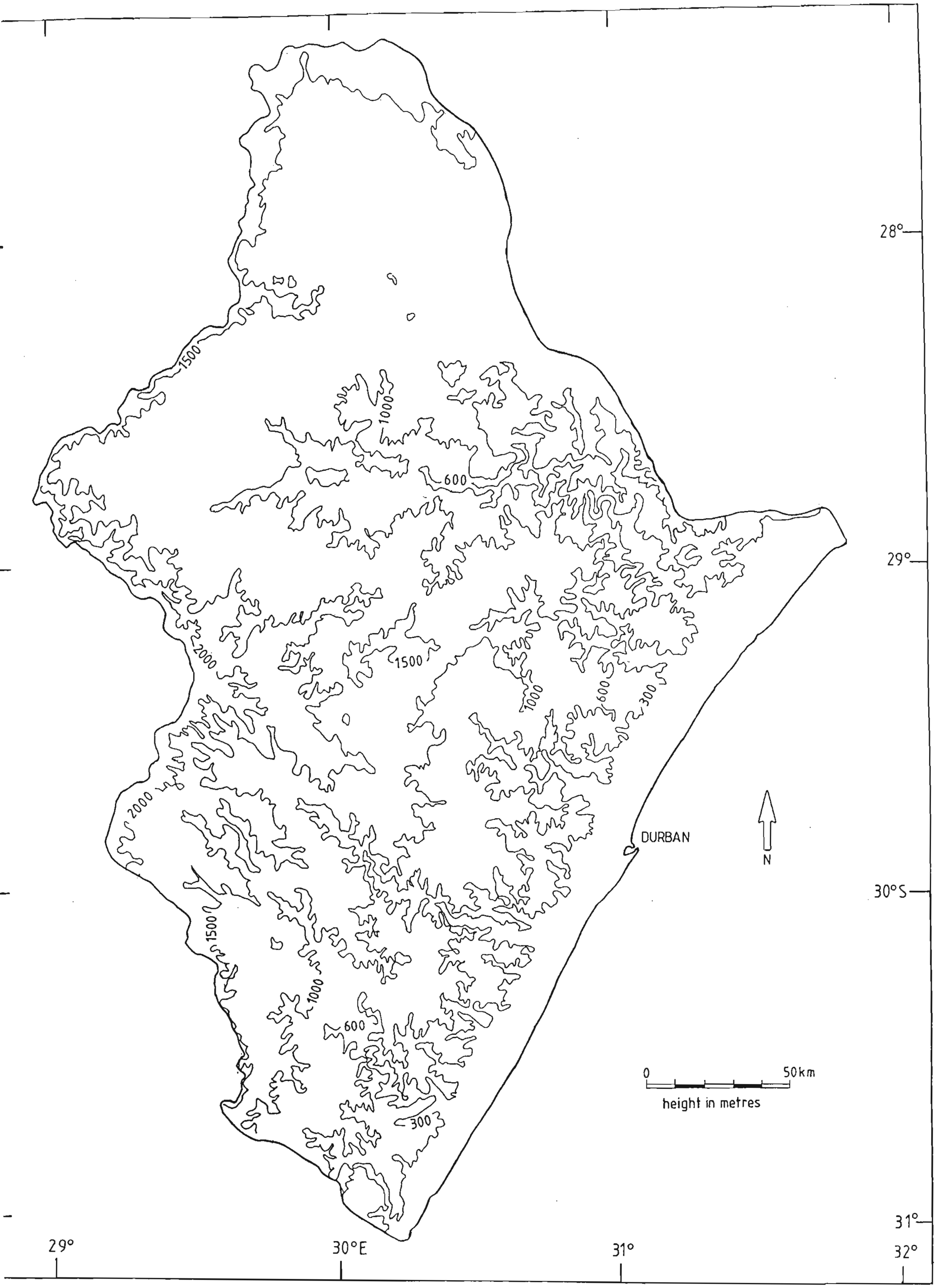


Fig.1.6. The hinterland of the study area. The topography rises steeply to over 2000 m. Although most rivers have much lower source elevations closer to the coast, they still maintain steep gradients.

1990). The steep hinterland, and lack of a coastal plain, means that the abundant small rivers form independent outlets at the coast. (Fig.1.3). North of the study area the Limpopo River exerts a strong control on regional drainage and this, coupled with the extensive Zululand/Moçambique coastal plain means that rivers there are longer and less steep than those in the study area and many drain into large coastal lagoons rather than directly into the sea.

A scan of global coastlines in the Times Atlas (1958) reveals only a few comparable areas of similar coastal and nearshore topography. In Figure 1.7 Natal is compared at the same scale with three similar areas; the central Chilean coast; New South Wales, and southwestern Sumatra. In each case topography rises rapidly from sea-level to over 1000 m (and beyond) within 100 km. River courses are comparatively short compared to those on more gently sloping continental margins. Continental shelves are narrow and offshore topography typically drops to -1000 m within 70 km of the coast.

Central Chile and Sumatra are volcanically and tectonically active margins while Natal and southeast Australia are not. The Chilean area and New South Wales receive similar total rainfall to Natal, but in Chile, snow melt in the high interior probably influences river discharge and sediment yield. Western Sumatra receives considerably more rainfall than Natal (over 3000 mm). In all four cases orographic forcing contributes to high rainfall (Times Atlas 1958). Sumatra is an equatorial region, and the other areas are located between 30° and 35°S in subtropical or warm temperate areas.

1.3.4. Hinterland geology

Of particular importance to any study of coastal morphology is the nature of the hinterland geology and the soils developed on it, for they control the nature and volume of sediment available for transport by rivers to the coast.

A synopsis of the geological succession in Natal is given in Table 1.1 and a simplified geological map is shown in Figure 1.8. Several major units may be identified which, in general, outcrop in bands sub-parallel with the coast. The symmetrical arrangement about a band of Proterozoic rocks was interpreted as a monoclinal fold (King, 1940, 1972), known as the Natal Monocline. This is no longer universally accepted and an alternative suggestion (Maud, 1961) is that the structure resulted from extensive tensional faulting.

The Proterozoic basement complex is exposed in a narrow strip which trends roughly north-south and runs obliquely across Natal from a coastal position in the south to some 30 km inland in the north. This complex comprises coarse-grained granites of varying composition, granodiorites, and gneisses. It is typically deeply weathered and is best exposed in the valleys of the larger rivers which traverse it, the Mzimkulu, Mkomazi, Mgeni, Mvoti, Tugela and Matigulu and on the coast in the southern part of the study area.

Overlying the basement is the Ordovician Natal Group Sandstone. This sequence of cross-bedded quartz arenites, arkoses and conglomerates represents deposition in fluvial and high-energy nearshore

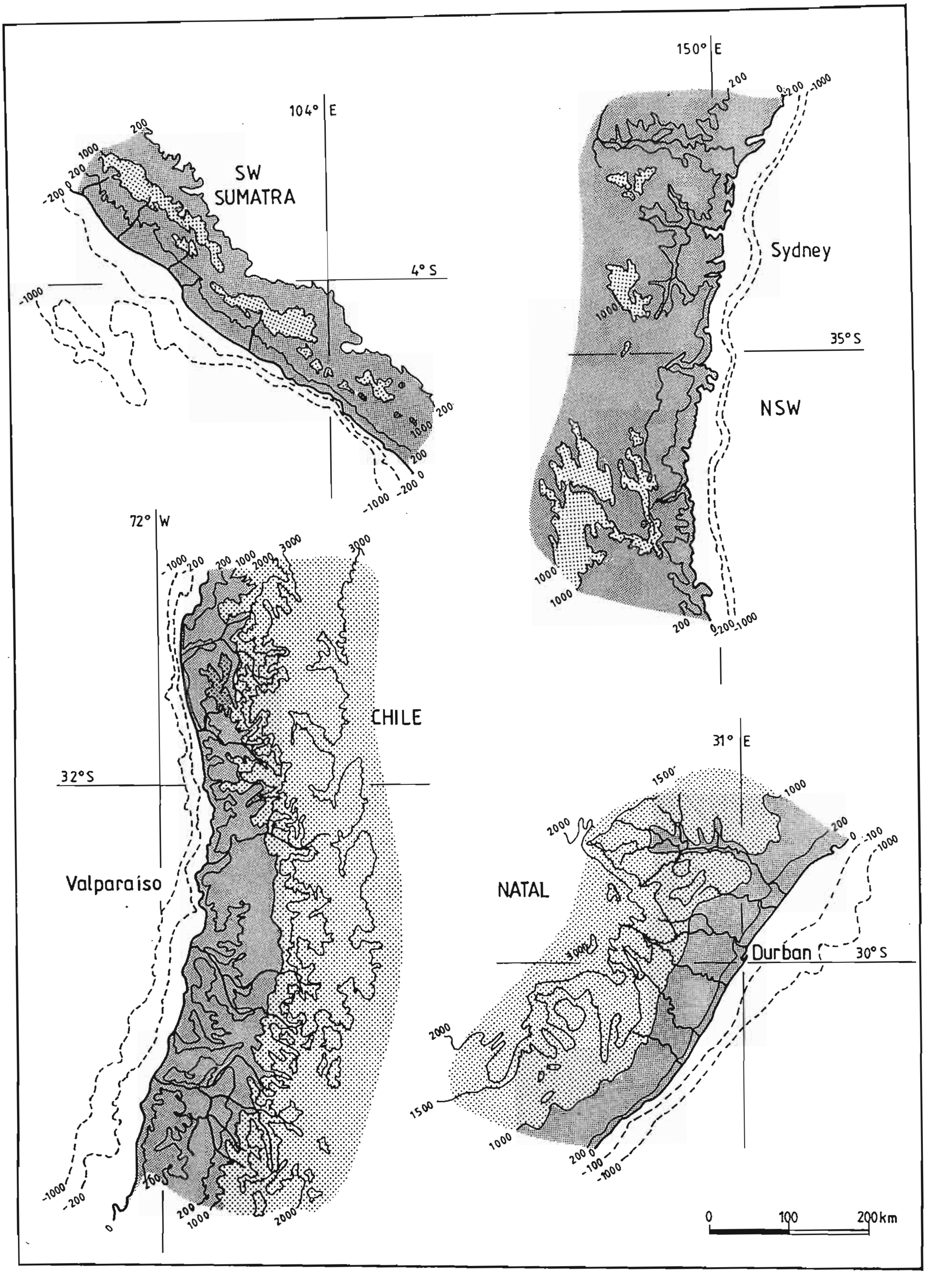


Fig.1.7. The Natal coastal hinterland compared at the same scale to similarly steep coastal areas. All of the areas rise to over 1000 m within a similar distance of the coast, but only the tectonically active Chilean coast rises to elevations comparable with and exceeding those of Natal.

Late Tertiary-Pleistocene	Berea-Type Red Sand	
	Carbonate-cemented coastal arenites	
	unconformity	
Cretaceous	Mzamba Formation	
	unconformity	
Karoo Sequence (Late Carb. - Triassic)	Drakensberg Volcanics	
	Former Stormberg Group	
	Beaufort Group	
	Ecca Group	Volksrust Formation
		Vryheid Formation
		Pietermaritzburg Formation
	Dwyka Group	
	unconformity	
Cape Supergroup (Ordovician)	Natal Group	
	unconformity	
Natal Structural and Metamorphic Province (Proterozoic)		

Table 1.1. Table of main stratigraphic units in the coastal hinterland of Natal

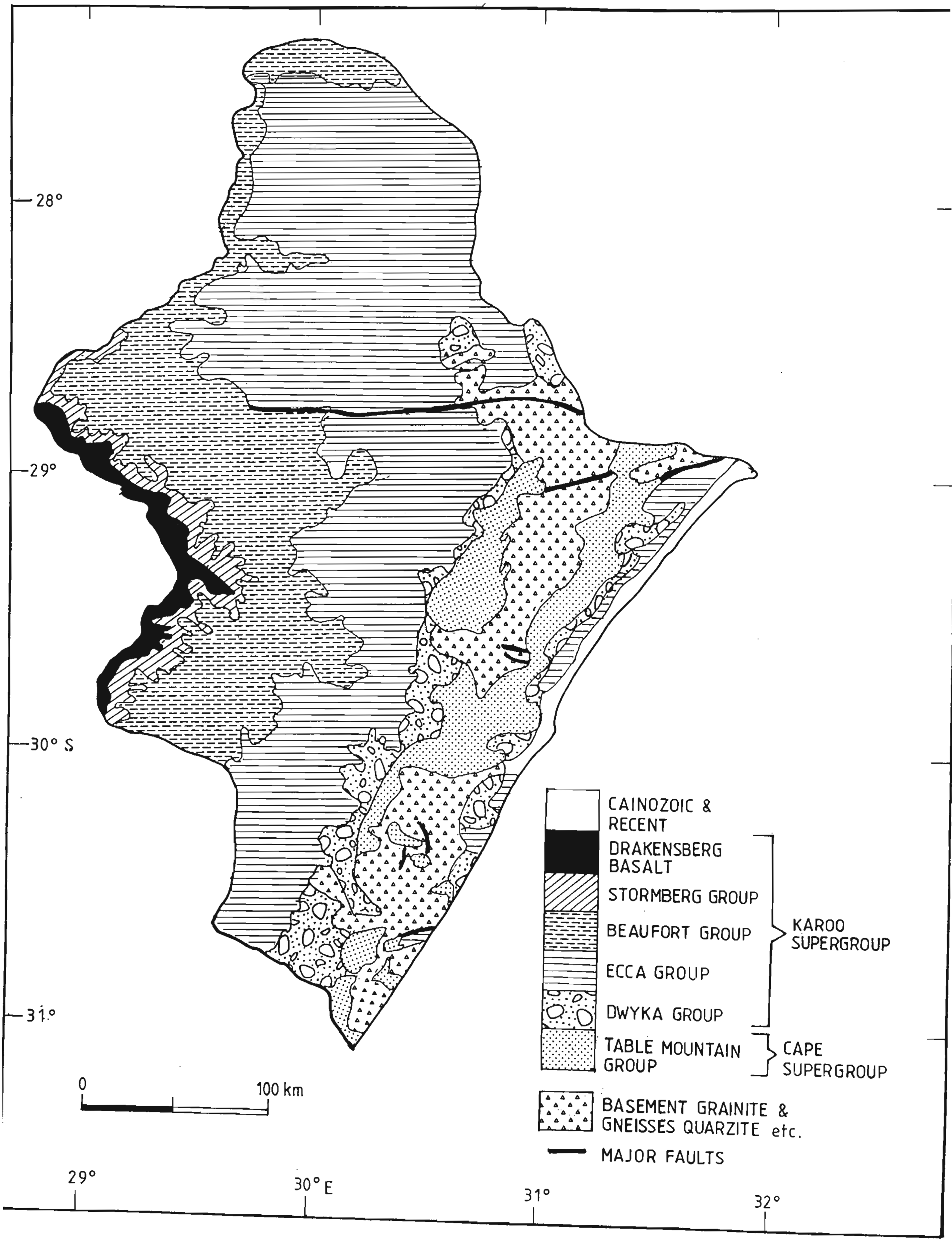


Fig.1.8. Simplified geological map of the hinterland, showing the distribution of the major lithologies. Note the symmetrical arrangement of facies around a central core of Proterozoic basement rocks. These granitic basement rocks intersect the coast in the southern part of the study area.

marine environments (Kingsley, 1975). These erosion-resistant lithologies form steep cliffs in many areas and outcrop extends parallel to the basement complex on either side of it. In places it is deeply weathered to over 40 m, a fact attributed to prolonged tropical and subtropical weathering since the Miocene (Partridge & Maud, 1987).

Unconformably overlying the Natal Group Sandstone is the 1000m-thick Karoo Sequence. The lowermost unit in this sequence is the Dwyka Group which comprises mainly a structureless glacial diamict with isolated varved glacial lake deposits. Clasts within the diamict are up to 0.5 m in diameter (Thomas, 1988). This Formation outcrops locally at the coast and in discontinuous bands parallel to the Proterozoic basement.

The Ecca Group conformably overlies the Dwyka Formation and is divided into three units. The lowermost Pietermaritzburg Formation consists of up to 400 m of dark grey fissile shales. Bedding is on a millimetre scale and fine-scale jointing causes the rocks to break up into small pieces (Thomas, 1988). The Pietermaritzburg Formation is extensively intruded by sills of Karoo Dolerite. The middle Ecca Vryheid Formation consists of alternating cycles of coarse-grained sandstones and shales, interpreted as prograding fluvial delta lobes (Hobday, 1973). The Volksrust Formation is a sequence of dark grey massive to finely laminated shales with thin fine-grained sandstones, interpreted as marginal marine lagoonal or lacustrine deposits (Tavener-Smith *et al.*, 1988). Only the Peitermaritzburg and Vryheid Formations outcrop at the coast but all three formations underlie much of the upland sections of the river catchments.

On top of the Ecca Group are typically fine-grained sedimentary rocks of the Beaufort Group which represent lacustrine, fluvial and floodplain deposits (van Dyk *et al.*, 1978). They overlie the Ecca group conformably and the transitional contact is frequently difficult to define. These and the overlying lithologies are represented at the upper limit of the catchments of the largest rivers and occupy only a small portion of the hinterland.

Intrusive bodies of Karoo Dolerite are common within the Ecca Group, particularly the Pietermaritzburg Formation (Thomas, 1988). Most of the intrusions are sills which are up to 130 m thick (Thomas, 1988). Dykes occur in fractures in the more competent lithologies below the Ecca Group. In the uppermost reaches of the largest rivers small areas of Drakensberg Basalt overlie the sedimentary sequences described.

Post-Karoo geological units in the hinterland are mainly limited to coastal areas. Small areas south of the Mpenjati River are underlain by Cretaceous siltstones assigned to the Mzamba Formation (SACS, 1980). These typically outcrop in the intertidal zone as wave-cut terraces (Thomas, 1988).

Berea-Type Red sand (McCarthy, 1988) which consists of reddened coastal dunes deposited at higher sea-levels during the Late Tertiary and Pleistocene is exposed semi-continuously along the Natal coast and forms a prominent ridge. McCarthy (1988) urged against the application of a formational name as proposed by SACS (1980) as the dunes represent several distinct depositional events whose relationships have not yet been resolved. These sands have been subjected to a tropical weathering phase (McCarthy, 1967; Maud 1968) and have a characteristic deep red colour produced by the breakdown of feldspars to clay minerals. This generally extends to about 5 m depth and is a surficial weathering feature (Thomas, 1988).

Carbonate-cemented Pleistocene shoreline deposits which occur intermittently along the coast are traditionally referred to the Bluff Formation (SACS, 1980). This formational term also is probably inappropriate as it refers to littoral sediments at various elevations and of different, as yet unresolved, ages. Deposits from the Durban area have been linked to at least two Late Pleistocene high sea-levels about 5 and 6 m above present (Cooper & Flores, 1991). Similar facies deposited at higher elevations are probably of Late Tertiary age (McCarthy, 1967).

1.4. HINTERLAND SOIL CHARACTERISTICS

1.4.1. Introduction

Orme (1974) stated that the depth of weathering in Archaean basement rocks and sandstones of the Natal Group and Karoo Supergroup reaches 200 m. Recent evidence indicates a somewhat lower (but still considerable) figure of 20 m for the depth of weathering in Natal Group sandstone of 20m (Partridge & Maud, 1987, Fig. 9). These authors attributed the thick weathered profile to an extended period of tropical weathering extending from Miocene to Recent times. The soils developed in the hinterland control the nature and availability of sediment carried by rivers. Stocking (1984) estimated that African weathering rates produce new soil at rates up to 100 tonnes per km per year.

Most soils in the coastal area of Natal are comparatively youthful and only in the interior are ferricretes of a mid-Tertiary land surface developed (Beater, 1970). The soils have been divided into several soil series but for the purposes of this thesis only the major grainsize characteristics of soils developed on the various lithological groupings are discussed. The difficulty of associating soil series with particular bedrock lithologies was stressed by Beater (1970) but in a general review of this nature where the weathering products of the lithologies are of prime concern, such associations are justified.

1.4.2. Proterozoic igneous and metamorphic rocks

These lithologies weather to soils with a clay content up to 30% (Beater, 1970). Figures given in Van der Eyk *et al.*, (1969) show that the amphibolites weather to a sandy loam with about 60% sand, up to half of it in the medium to coarse range. Migmatite-derived soils from Umkomaas contained 76% sand, two thirds of which was medium to coarse-grained. Schists produced soils with about 70% sand, over half of which was in the medium and coarse grades. Beater (1970) noted that a large area between the Mtwalume and Mzumbe Rivers is underlain by the basement complex on which soils comprised a gritty loam, characterised by about 20% clay with up to 45% of coarse and medium sands.

1.4.3. Natal Group Sandstone

Soils developed on the Natal Group Sandstone are characteristically thin, permeable, sandy and cohesionless (Maud, 1988) and are commonly underlain by a clay-rich horizon, produced by kaolinisation above the unweathered rock (Partridge & Maud, 1987). Groundwater moves downslope within the sandy horizon until it meets the underlying clay-rich horizon. The soil becomes saturated during heavy or prolonged rainfall, loses strength and moves downslope as earthflows (Maud, 1988).

Five soil series are associated with this lithology (Beater, 1970). They are typically loamy sands with about 5-15% clay are about 1.8 m thick. The major component of the sand fraction is medium-grained sand which is overwhelmingly quartzose, the feldspars having broken down to kaolinite (Beater 1970). In the Tugela catchment, Van der Eyk *et al.* (1969) described several soils developed on Natal Group Sandstone in which the sand fraction in the A horizon varied between 42% and 77%. Of these respective figures, 32% and 57% were in the fine sand class.

1.4.4. Dwyka Tillite

This lithology typically gives rise to one of two soil series (Beater, 1970) both of which are fine sandy loams containing about 25% coarse and medium sands and 50% fine sand. Silt and clay together comprise about 25%. Van der Eyk *et al.*, (1969) cite figures of 64% sand of which 40 is fine sand for soils developed on Dwyka Tillite.

1.4.5. Ecca Group

Soils developed on the rocks of the Ecca Group were not always divided in the field into the three formational units but the characteristics reported by Beater for the shale lithologies are that clay is the dominant constituent and comprises 70 to 80% of the soil if rubble is excluded. The results presented by Van der Eyk *et al.*, (1969) are in agreement with this figure.

1.4.6. Karoo Dolerite

This lithology appears to develop a number of different soil series: four were identifed by Beater (1970). They are all clayey loams in which clay comprises up to 85% but averages between 50 and 60%. Fine sand and silt are in the range of 20% and coarse sand is present in minimal amounts. Several analyses of dolerite soils Van der Eyk *et al.* (1969) show sand (mostly fine-grained) between 20 and 40% while silt and clay account for 60 to 80%.

1.4.7. Beaufort Group shales

These lithologies are restricted largely to the upper reaches of the river catchments. In the Tugela catchment Van der Eyk *et al.*, (1969) decribe several soils developed on Beaufort rocks. They are characterically fine sandy loams with silt and clay up to 71%, similar to the Ecca Group which is unsurprising as the two are difficult to distinguish in outcrop. The sand fraction is dominated by fine sand.

1.5. FLUVIAL SEDIMENT YIELD

The nature of terrestrial sediment supply to the coast is controlled largely by the type of soils developed on the underlying rock. However, sediment yield from a river catchment is also influenced by a number of factors including climate, catchment geology, sediment erodibility, hinterland topography and transport capacity of the river.

Natal, with its subtropical climate, favours the production of a deep weathering zone in rocks (Maud, 1968; Partridge & Maud, 1989). This weathering, coupled with accelerated stream flow and sheet flood, particularly during thunderstorms, favours widespread and vigorous erosion (Orme, 1974). Estimates of denudational rates in the hinterland, based on sedimentation rates in dams and other environmental factors, have been consolidated to produce a map of potential sediment yield over the whole of South Africa (Rooseboom, 1975). Areal variation in potential sediment yield for the study area hinterland based on this map is shown in Figure 1.9.

Flemming & Hay (1983, 1984) updated earlier data on Natal and southern Moçambique coast fluvial sediment yields (Flemming, 1981), based on sediment production rates (Rooseboom, 1978) summed for the various river catchments (Midgley & Pitman, 1969). Rooseboom's (1978) estimates are based on numerous environmentally sensitive factors such as geology, soil cover, slope, nature and state of vegetation cover, seasonal rainfall patterns and locally-measured suspended solids discharge of the larger rivers (Flemming & Hay, 1988). They are considered by Flemming & Hay (1988) to be the most reliable source on sediment yields in South Africa and superior to earlier over-estimates based on indirect measures (Schwartz & Pullen, 1966; Midgley & Pitman, 1969). As will be discussed in subsequent chapters, however, the calculated sediment yields for small Natal rivers, based on Rooseboom's (1978) data, also appear to be over-estimates when compared to measured suspended sediment concentrations from Natal rivers. A similar assessment was made of the predicted sediment yield in the Knysna Estuary in the southern Cape based on Rooseboom's (1978) data (Reddering & Esterhuysen, 1987a).

Flemming & Hay (1983) calculated an annual sediment yield of 133.1 x 10^6 m^3 to the east coast of South Africa (Cape St Lucia to Port Elizabeth). Flemming & Hay (1988) subsequently estimated the total fluvial sediment supply to the Natal coast (including Zululand) as 20 x 10^6 m^3 (30 x 10^6 tonnes) per year.

Recent estimates of the annual sediment yield from the Tugela River range from 5.1 to 6.3 x 10^6 m^3 (Nicholson, 1983) to 5.6 x 10^6 m^3 (Flemming & Hay, 1984). Goodlad (1986) estimated the annual sediment yield from the 29 000 km^2 Tugela River catchment at approximately 5.9 x 10^6 m^3 and calculated that the combined yield of the four major rivers south of the Tugela (Mvoti, Mgeni, Mkomazi and Mzimkulu) was 4.8 x 10^6 m^3.

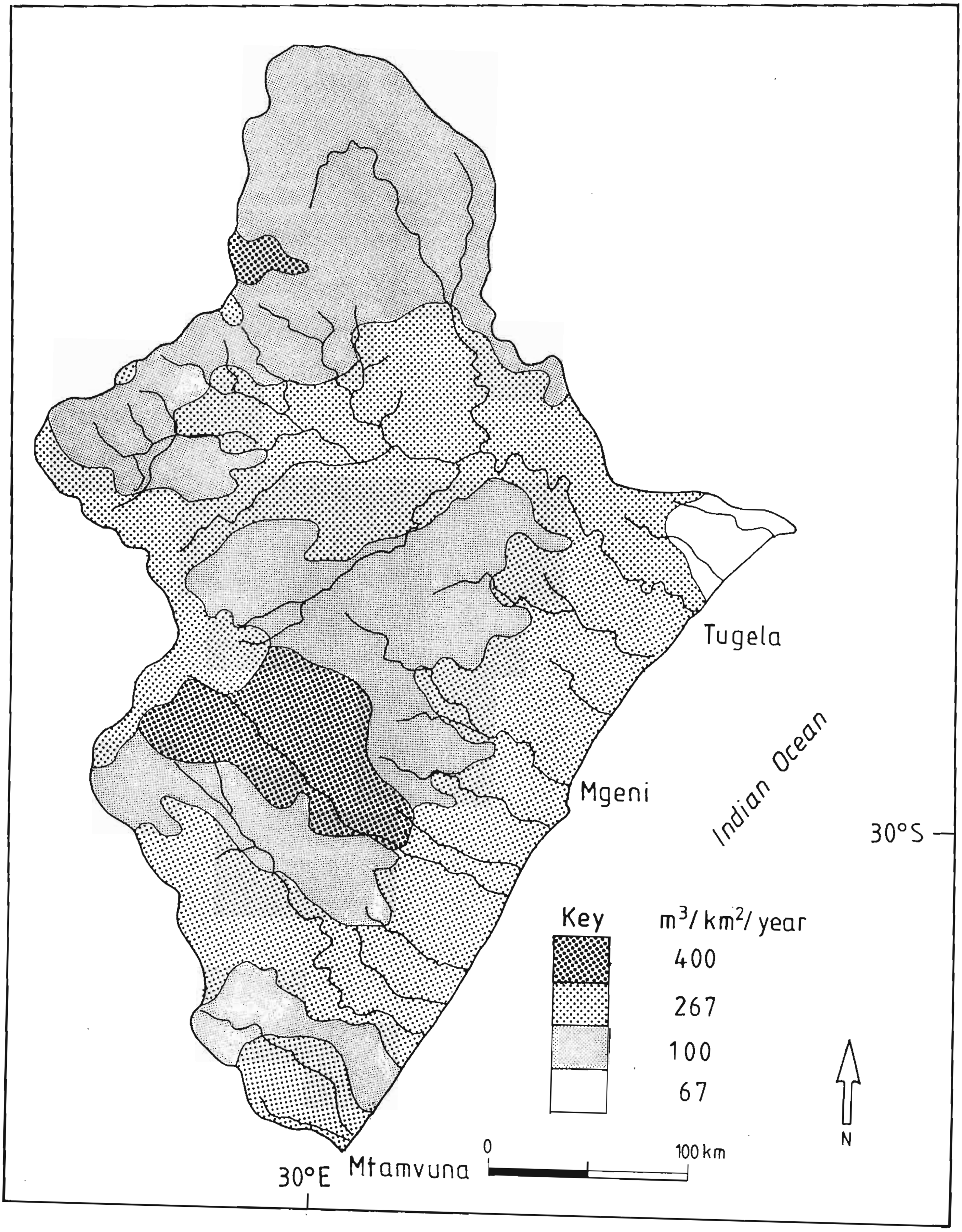


Fig. 1.9. Map showing areas of equal potential sediment yield in the Natal hinterland. (Modified after Rooseboom, 1978)

The data calculated by NRIO (1986) using Rooseboom's (1978) sediment yield map, yields a total figure of 18 x 10^6 tonnes or 12.2 x 10^6 m^3 (using the conversion factor proposed by Flemming & Hay, 1984) for all the rivers which enter the sea in the study area.

These total sediment volumes are small compared with the estimated annual yield of 65.1 x 10^6 m^3 (Goodlad, 1986) or 33 x 10^6 tonnes (Milliman & Meade, 1983) for the 410 000 km^2 Limpopo River catchment but indicate much higher sediment yields per km^2.

The average sediment loss from the whole Natal Hinterland is 323 tonnes/km^2/year (Martin & Flemming, 1986), which is significantly higher than the figure of 80 tonnes/km^2/year considered by Milliman and Meade (1983) as representative of east African rivers. This supports the suggestion of Milliman & Meade (1983) that total sediment yields to the oceans have been underestimated by not adequately considering the sediment yield of small-catchment rivers. The average sediment yield per km^2 for Natal is only exceeded in China, south-east Asia, north-west South America, central America and glacial areas of Alaska (Milliman & Meade 1983). Murgatroyd (1979) and Martin (1987) calculated that modern sediment yields in Natal exceed long-term rates by a factor of 12 to 22. Martin (1987), however, cautioned that field erosion rates may be 10 to 20 times higher than actual fluvial sediment yields (Stocking, 1984; Walling, 1984; Holeman, 1980).

Numerous problems exist in the estimation of sediment yield and sediment discharge. Milliman & Meade (1983) cite observations from the Yellow River in China which show a dramatic downstream decrease in sediment discharge, indicating that much of the sediment yield from the catchment never reaches the ocean. This factor is probably minimised in Natal due to the narrow incised river channels (Le Roux, 1990).

Assessment of the relative contributions of bedload and sediment load poses a further problem. Although bedload is generally assumed in Natal to be about 12% of the total load (Swart, 1987; Nicholson, 1983), there are instances elsewhere, for example in the Zaire River (Peters, 1978), where bedload exceeds the suspended load. Further problems in estimating sediment discharge arise from the role of episodic major floods. Milliman & Meade (1983) cite the case of the 4100 km^2-catchment Santa Clara River in California which carried an amount equal to its mean annual sediment load during a single flood event. Bremner *et al.* (1990) calculated that during the Orange River flood of 1988, an amount equivalent to the mean annual sediment load was carried in a three month period. An amount equal to about 5% of the total load was deposited as bedload offshore from the river mouth and suggests that during such events in the Orange River, bedload comprises only about 5% of the total load. Episodic floods in Natal might be expected to produce similar results.

The importance of bedload in the sediment budget of the study area is enhanced because of the wave-dominated coast and current-dominated shelf which limit deposition of fine-grained sediment landward of the shelf break. The widely different catchment areas of coastal rivers must produce variation in the proportion of the total load accounted for by bedload by limiting potential peak discharge in smaller streams.

Estimated total sediment yields per catchment were calculated from Rooseboom's (1978) data by NRIO (1986) for each river catchment reaching the coast in Natal. Sediment yields for the rivers under discussion are given in Table 1.2. They are the best estimates presently available and will undoubtedly be improved as more information becomes available.

1.6. RIVER-MOUTHS

In the study area sixty three independent water bodies fed by rivers (Fig.1.3) are present at the coast. In all cases they are located behind a sandy river-mouth barrier, whose crest is elevated above sea-level but they display a wide range of morphologies. Exchange of sediment, nutrients, fauna, flora and water with the sea depends largely on the ability of tidal and river currents to maintain an outlet though the river-mouth barrier. In most cases the back-barrier aquatic environments contain brackish and occasionally fresh water (Begg, 1984b). They exhibit a wide range of salinity characteristics which vary temporally and spatially. Overwash is an important mechanism for maintaining salinity in the absence of stream outlets (Begg, 1978, 1984b).

Morphological variation in the sixty-three river-mouths arises from differences in channel pattern, water depth, water area, floodplain size, presence of islands, nature of bottom sediments and so on. Faunal variation was assessed by Begg (1984a) and Ramm *et al.*, (1986) both of whom recognised distinct groups of faunal assemblages. Vegetation also varies (Begg, 1984b) from mangroves in more tidal river-mouths to fresh and brackish-water plants in other types of river-mouth, but this has not been investigated systematically.

The inflowing rivers which formed these water bodies vary greatly in size and discharge. Their characteristics, based on the authors own measurements with additional data from NRIO (1986) are summarised in Table 1.2. Location of each river-mouth is shown in Figure 1.3.

1.7. COASTAL MORPHOLOGY

The coast under consideration has a narrow continental shelf and steep nearshore zone, which originated through tectonism associated with the breakup of Gondwanaland in the Jurassic and early Cretaceous Periods. The continental margin evolved as the Indian Ocean expanded during the dispersal of the Gondwana fragments and its morphology was controlled by the type of rifting, drainage patterns, terrestrial and marine sediment supply, sediment loading and subsidence and currents and sea-level of the adjacent ocean (Martin & Flemming, 1988). The present narrow coastal plain and continental shelf represent emergent and submerged portions of the same near-linear feature, and the position of the junction between them (the coastline) depends on relative sea-level at any time.

Estuary	Catchment (sq km)	River length (km)	Source Elevation (m)	M.A.R. (million cubic m)	Av. Sediment Yield (tonnes/year)
MTAMVUNA	1570.00	162.0	1920	303.78	434290
ZOLWANE	7.00	6.5	259	1.73	4200
SANDLUNDLU	16.00	7.5	282	6.40	9600
KU-BOBOYI	4.00	4.0	107	1.20	1800
TONGAZI	17.00	8.5	385	6.80	10200
KANDANDLOVU	9.00	8.0	290	3.60	5400
MPENJATI	79.00	18.0	480	25.52	60000
KABA	11.00	6.5	180	2.00	3600
MHLANGANKULU	9.00	9.0	220	2.44	4400
MBIZANA	141.00	26.0	480	29.56	72500
MVUTSHINI	7.00	6.5	180	1.82	2800
BILANHLOLO	21.00	12.0	240	5.46	8400
UVUZANA	8.00	2.5	130	2.08	3200
KONGWENI	20.00	6.0	180	5.20	8000
VUNGU	118.00	24.0	610	26.44	85200
MHLANGENI	38.00	12.5	340	9.60	15200
ZOTSHA	59.00	20.0	415	14.40	22800
BOBOYI	25.00	14.0	370	8.53	12800
MBANGO	17.00	8.0	139	3.47	5200
MZIMKULU	6562.00	329.0	2440	1478.21	2170020
MTENTWENI	50.00	20.0	340	14.62	20000
MHLANGAMKULU	11.00	7.0	185	3.22	4400
DAMBA	25.00	11.0	300	7.31	10000
KOSHWANA	11.00	6.3	200	3.22	4400
INSHAMBILI	33.00	12.5	210	9.65	13200
MZUMBE	549.00	84.0	933	71.03	214400
MZIMAYI	47.00	16.0	240	8.14	18800
MHLUNGWA	32.00	18.0	222	5.55	12800
MFAZAZANA	16.00	10.5	278	2.77	6400
KWA MAKOSI	16.00	7.0	183	2.77	6400
MNAMFU	16.00	9.0	233	2.77	6400
MTWALUME	553.00	85.0	985	60.02	226000
MVUZI	12.00	6.5	178	0.84	3200
FAFA	254.00	66.0	918	24.17	88150
MDESIGANE	6.00	5.2	76	0.90	2400
SEZELA	20.00	12.0	180	2.99	8000
MKUMBANE	28.00	14.0	300	4.18	11200
MZINTO	149.00	37.0	520	22.29	59600
MZIMAYI	31.00	20.0	178	4.64	12400
MPAMBANYONI	546.00	100.0	962	52.02	184550
MAHLONGWA	92.00	23.0	430	12.04	36800
MAHLONGWANA	15.00	6.0	218	1.96	6000
MKOMAZI	4183.00	298.0	2650	1036.17	1616360
NGANE	16.00	8.0	219	2.90	6400
MGABABA	37.00	14.5	244	6.71	14800
MSIMBAZI	35.00	16.0	244	6.35	14000
LOVU	785.00	135.0	1280	111.78	398900
LITTLE TOTI	18.00	15.0	165	3.78	7200
MANZIMTOTI	39.00	11.6	274	8.20	15600
MBOKODWENI	220.60	59.0	732	35.58	113200
SIPINGO	49.00	27.0	328	6.41	20400
MGENI	4863.00	232.0	1829	682.88	1657670
MHLANGA	105.00	28.0	324	26.00	47200
MDLOTI	474.00	81.0	854	116.99	210800
TONGATI	422.00	50.0	747	74.99	174400
MHLALI	226.00	46.5	580	49.40	121600
SETENI	12.00	5.0	61	2.60	6400
MVOTI	2773.00	197.0	1479	468.19	813850
MDLOTANE	78.00	13.0	122	9.10	17200
NONOTI	180.00	37.5	488	44.47	84000
ZINKWASI	89.00	22.0	229	15.46	29200
TUGELA	29000.00	405.0	3109	4594.94	8798000
MATIGULU	814.00	96.0	762	201.07	224440
MLALAZI	492.00	54.0	549	117.01	49200

Total yield (tonnes)	18335930
Total yield (cubic m)	12230065.31

Table 1.2. Tabulated data on river catchments in the study area. M.A.R. = Mean annual runoff. (after NRIO, 1986).

Present coastal morphology in Natal has been divided into several types (Cooper, 1991a,b), of which the most important to the present study are headland-embayment, linear clastic and prograding beachridge coasts. No part of the study area exhibits long-term coastal erosion and appears to be in equilibrium with the contemporary wave field.

The presence at all river-mouths of sandy barriers reflects conditions suitable for sand deposition and retention. This is frequently attributable to the presence of an embayment located in the river valley on an otherwise near-linear rocky coastline. These barriers fulfill an important function in dissipating the energy of marine waves. The back-barrier river-mouth environments thus form a series of relatively calm, low-energy environments on an otherwise high-energy, wave-dominated coastline.

Of particular importance to barrier structure on the Natal coast, is the formation of beachrock which may form the core of barriers across the mouths of several rivers. At Kelso (35°22' S) an intertidal outcrop of carbonate cemented boulders (Thomas, 1988) appears to mark the southern limit of Holocene beachrock formation in Natal. Beachrock forms the core of several rivermouth barriers north of this but appears to be restricted to those small rivermouths which have an elongate, coast-parallel extension behind the barrier. In such circumstances there is sufficient frequency between flood breaches at any particular location to enable beachrock cementation.

1.8. COASTAL HYDRODYNAMICS

Tides on the Natal coast are semi-diurnal. Predicted tidal elevations for Durban are given in Table 1.3. (SAN, 1988). De Cuevas (1986), has shown that significant deviation from the predicted level (up to 35 cm) may occur due to low pressure systems moving along the coast. At Durban mean spring tidal range is 1.72m and mean neap tidal 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 difference between the highest and lowest astronomical tides is 2.32 m. Highest and lowest astronomical tides are respectively the highest and lowest levels which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions.

	LAT	MLWS	MLWN	ML	MHWN	MHWS	HAT
Durban	-0.02	0.24	0.85	1.10	1.35	1.96	2.30
Richard's Bay	-0.11	0.19	0.83	1.09	1.35	1.99	2.37

Table 1.3. Predicted Tidal elevations for Durban and Richard's Bay (from South African Navy Tide Tables, 1988) with respect to chart datum (-0.900 m relative to land levelling datum). LAT = lowest astronomical tide, MLWS = mean low water springs, MLWN = mean low water neaps, ML = Mean level, MHWN = mean high water neaps, MHWS = mean high water springs, HAT = highest astronomical tide.

The coastal sedimentary regime is wave-dominated. Several methods were applied at different locations to determine the wave characteristics of the Natal coast (HRU, 1968). Records from wave clinometers on the Durban Bluff over a two year period included 1323 observations and were concluded to be most accurate and reliable measure. They were used to compile the wave height and period roses reproduced in Figure 1.10 (HRU, 1968). The Durban Bluff records were not affected significantly by wave refraction and can be used to assess the direction of approach of deep sea waves toward the near-linear Natal coast. The measured wave heights were converted to deep sea-heights and wave directions were corrected for refraction before the diagrams were compiled. This renders them more widely applicable to the entire study area.

These diagrams show that the dominant direction of wave approach at Durban is ESE to SE. All swell recorded came from directions between NNE and SW. Seventy-one percent of all records were more southerly than 90° and only 8% of the observations were more southerly than 157°.

The greatest significant wave heights were recorded from SSE to SW directions and the lowest from E to ESE directions. The wave heights cover a broad range from 0.3 to 7.6 m (HRU, 1968) and the median wave height is 1.49 m.

Maximum wave periods over 17 seconds occurred from SE to SSE while the shortest wave periods (5- 7 seconds) came from E to NE. The median wave period is 10.7 seconds. HRU (1968) noted an increase in significant wave height with wave period from 11 seconds at 0.6 m to 14 seconds at 4.6 m for waves from SE to SW. For ESE directions wave periods are about 0.6 seconds lower for equivalent wave heights but follow a similar trend. Waves from N and NE showed no increase in period related to height.

HRU (1968) calculated significant wave heights, defined as the average height of the highest one third of the waves occurring in a specified recording period (normally 15 minutes), for the Natal coast. The maximum wave height was calculated to be 1.6 x the significant wave height. Significant wave heights expected to be exceeded at least once per year for each direction are listed below in Table 1.4.

Direction	**Significant Wave Height (m)**	**Significant Wave period (seconds)**
NE	4.45	14.1
E	4.11	18.1
SE	5.3	20.6
S	7.25	15.1

Table 1.4. Significant wave heights and periods for the Durban area expected to be exceeded once per year.

As a result of dominant southerly wave approach the dominant littoral drift is to the north and calculated mean northward flux in the Durban Bluff region is approximately 0.65 x 10^6 m^3 per year (Swart, 1987), at Richards Bay it is 0.8 x 10^6 m^3 per year (Swart, 1980) and at the Tugela River-mouth is 1x 10^6 m^3/year (Nicholson, 1983). These rates must be regarded as potential rates only as they are

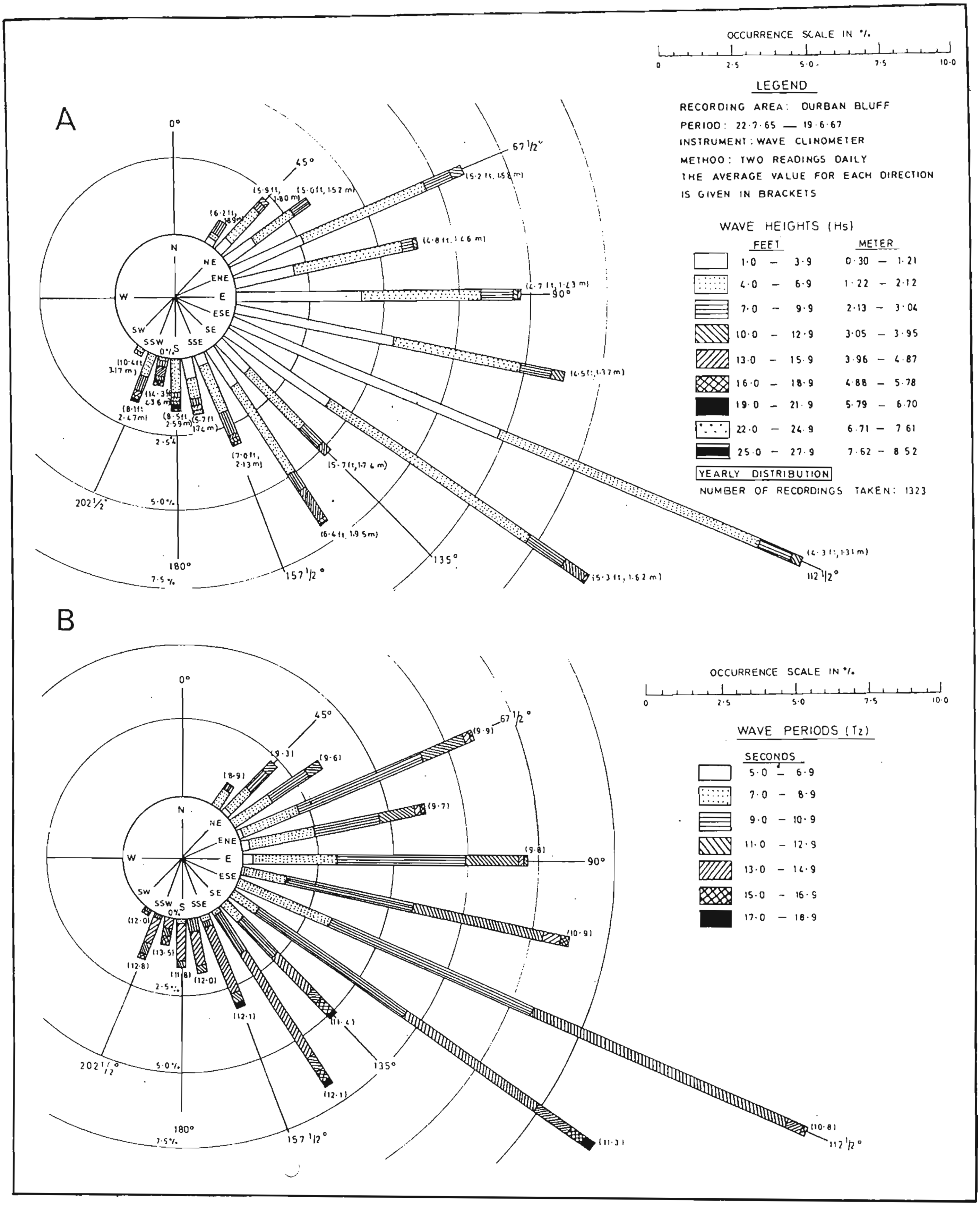


Fig.1.10. Wave Height (a) and Period(b) roses for each approach angle encountered on the Natal coast. (After HRU, 1968).

calculated from refraction diagrams and take no account of sediment availability or grainsize. The actual longshore transport rates are probably very much lower as discussed subsequently.

Coastal winds in Natal are related to alternate dominance of cyclonic frontal systems and the south-west Indian Ocean anticyclonic high pressure (Martin & Flemming, 1986). HRU reported wind data from Durban, Cape St Lucia and offshore Natal (Fig 1.11). Durban wind records are dominated by NNE to NE and SW to SSW directions (HRU, 1968). The dominant winds are parallel to the shoreline. Winds from NW and N are more common in winter but the wind speed is normally less than 7.2 ms^{-1}. Autumn and winter are the calmest seasons, each having about 34 % calms. Wind speeds over $17ms^{-1}$ were recorded from SW and SSW only during summer and spring. Spring is the windiest season in Natal, having the highest average wind speeds at all three stations studied.

The importance of coastal sediment transport by winds in the study area is often reflected in the presence of precipitation dunes (Tinley, 1985) associated with river-mouth barriers. In the Durban region, potential sand transport by wind was calculated by Swart (1987) to be approximately equally divided between northeast and southwest (ie coast-parallel) directions. Potential northeast flux amounted to $45m^3$/m/yr and southeast flux to $35m^3$/m/yr. The fact that inland winds slightly exceeded offshore winds implied a potential net loss of $3m^3$/m/year from the beach at Durban. This is a maximum estimate as it takes no account of sand moisture, vegetation, beach width, humidity, or surface armouring. Actual transport rates are probably very much smaller.

At St Lucia Estuary mouth, Wright (1990) calculated a resultant drift potential of 13 x 10^3 m^3/km/year ($13m^3$/m/year) in a northward direction. Van Heerden & Swart (1986), using a different equation, estimated 20 x 10^3 m^3/km/year for the same area. The discrepancies encountered indicate the variation between alternative calculations and underscore the need for physical measurements of wind tranport on the Natal coast.

1.9. MORPHOLOGY AND HYDRODYNAMICS OF THE CONTINENTAL SHELF

The continental shelf of Natal extends to a depth of approximately 100 m, beyond which a steep continental slope drops to over 1000m (Fig 1.12). The shelf is less than 12 km wide in the southern part of the study area, but north of Durban it widens to a maximum of 40 km off the Tugela River. This increase in width was ascribed to a change in the tectonic origin of the margin from a sheared to a short rifted section (Martin, 1984; Martin & Flemming, 1986, 1988). North of St Lucia the shelf narrows to 3 km. Submarine canyons occur on the narrow parts of the continental shelf (Flemming, 1981). Several lines of aeolianites, representing Pleistocene shorelines, are preserved on the shelf. Bases of these aeolianites indicate sea-level stillstands at depths of 40, 50-55, 65-70 and 85-90 m (Martin & Flemming, 1986).

The continental shelf off the study area is dominated by the south-flowing Agulhas Current, one of the world's major geostrophic currents (Gründlingh, 1980). The current generally flows along the

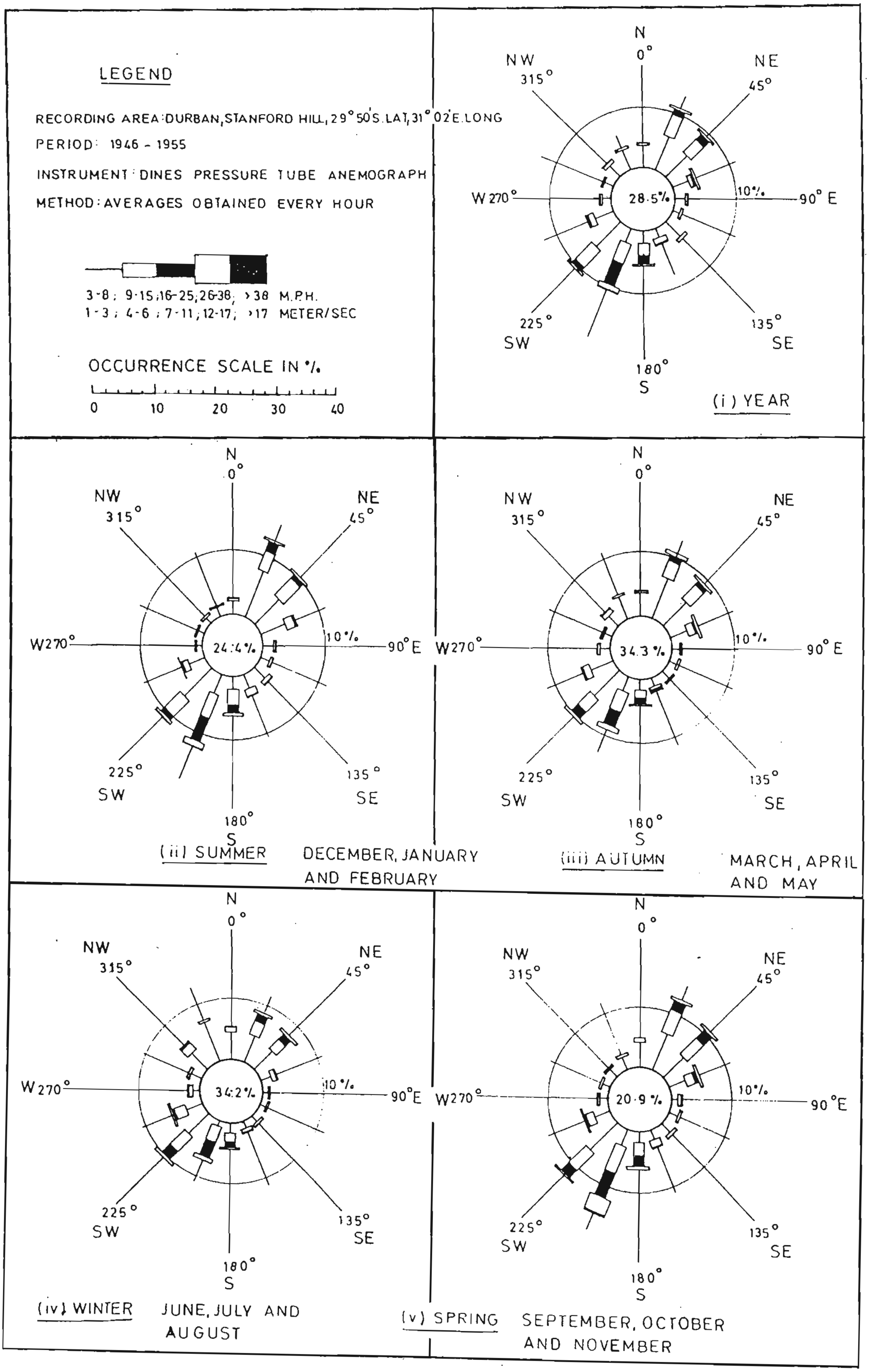


Fig.1.11. Wind roses from the Durban area for the whole year and seasonally (after HRU, 1968)

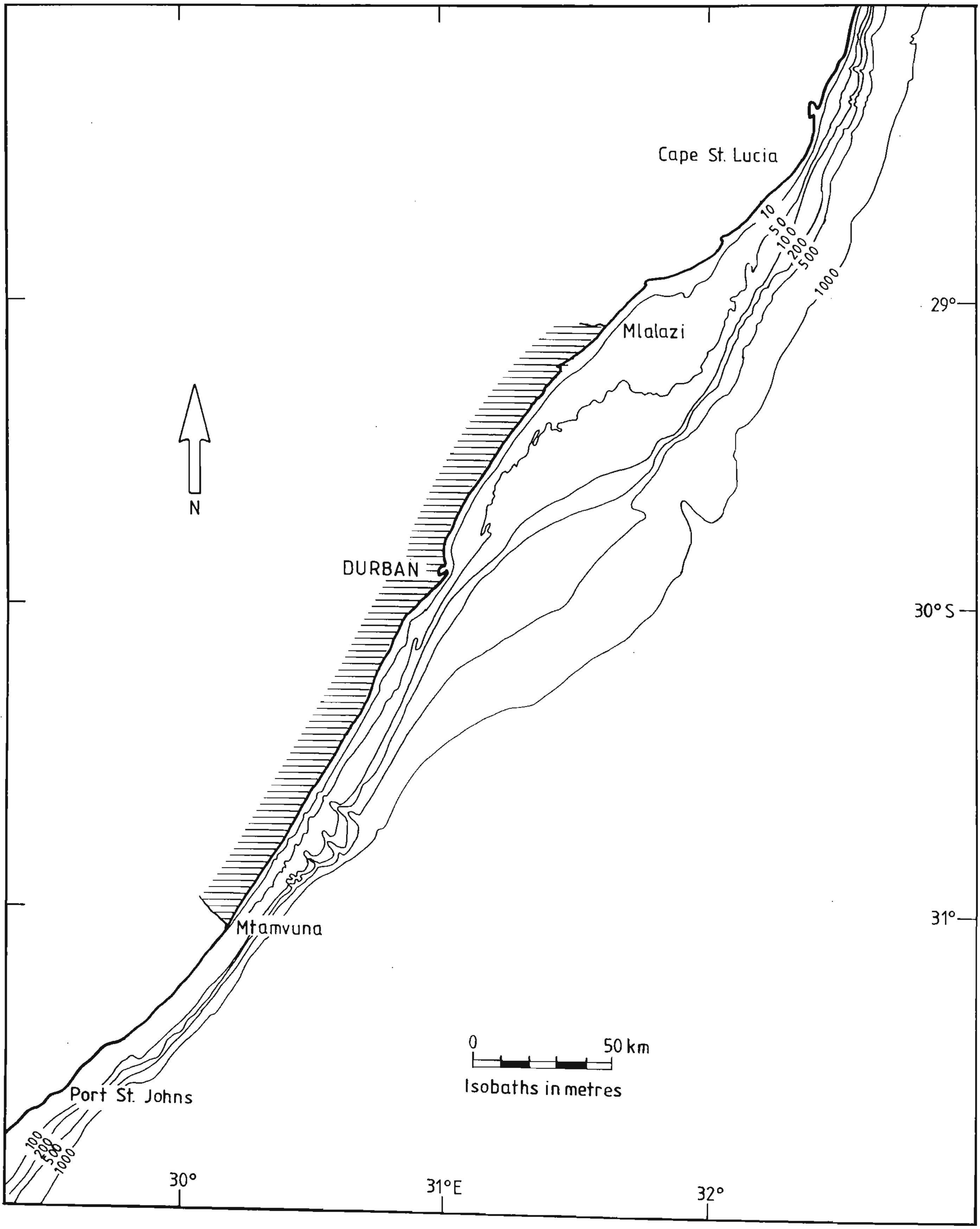


Fig. 1.12. Bathymetry of the continental shelf off Natal. The shelf break is at about 100 m. Note the narrow shelf throughout the study area. The increase in shelf width off Durban is due to a change in tectonic style from a sheared to a rifted section of the continental margin (Martin, 1984).

continental slope between 35 and 50 km offshore (Gründlingh, 1983). Surface water velocities can exceed 2 ms^{-1} and 0.34 ms^{-1} have been recorded 4 m from the seabed at 49 m depth (Martin & Flemming, 1986). Multiple cyclonic eddies occur between Durban and Cape St Lucia where the coast is offset to the west (Martin & Flemming, 1986) and these induce north-flowing inshore counter-currents landward of the mainstream of the Agulhas Current (Schumann, 1982).

Sediment transport on the shelf is current-driven and occurs at rates normally only associated with tidal currents (Flemming, 1980). This shelf sediment is supplied by hinterland rivers. Holocene sediment is "dammed" landward of aeolianite ridges and is up to 34 m thick in the area between the Lovu and Mpambanyoni river-mouths. Bedload sediment transport of fine- and medium-grained sand occurs in large-scale bedforms up to 4 m high and 170 m in wavelength (Flemming, 1980). Because of dominant north-directed nearshore currents, these bedforms prograde northward and have been termed submerged spit bars (Martin & Flemming, 1986). On straight sections of the coast periodically affected directly by the Agulhas Current, Flemming (1980) reported submerged large dune migration rates up to 3.5 m/day.

The Natal shelf represents a sink for fluvially-derived sand and gravel sized-sediment (Flemming & Hay, 1988). Because of high energy conditions on the shelf, mud is typically deposited seaward of the shelf break (Goodlad, 1986), except in exceptional circumstances where a semi-permanent eddy occurs in the Agulhas Current. Such circumstances are only encountered at Port St Johns (Hay, 1984) and off the Tugela River (Felhaber, 1984). Upward accretion of the Holocene shelf sediment body is limited by wave action and losses occur through submarine canyons (Martin & Flemming, 1986).

1.10. LATE PLEISTOCENE AND HOLOCENE SEA-LEVEL HISTORY OF THE NATAL COAST

In order to fully understand the significance of the estuarine environment it is necessary to place estuaries in their evolutionary context. During the Pleistocene the world entered a period of cycles of glaciations and intervening interglacial periods at roughly 100 000 year intervals (Imbrie & Imbrie, 1979). The present interglacial period is characterised by relatively warm conditions and a relatively high sea level. Current predictions are that a contemporary global sea-level rise will impact on coastal environments (Pirazzoli, 1989). In South Africa historical records of mean sea-level from tide guages at Simons Town and Luderitz show a statistically significant rise of 1.2 mm per year (Hughes, 1990).

During interglacial periods incised valleys cut during low sea levels of glacial periods are drowned and become sites of sedimentation. Thus, present conditions are, geologically speaking, atypical. River-mouths on the Natal coast were drowned during the past few thousand years when sea level rose (during the Holocene Transgression) from a maximum low of 130 m below present some 17 000 years ago. Since they formed they have acted as sites of sediment accumulation as the inflowing rivers adjusted to a new profile equilibrium. Once they are filled with sediment they act simply as part of a continuous or episodic transport mechanism, carrying sediment eroded from the hinterland, into the sea. Sediment

C-14 Age	.+/-	Depth	Number	Locality	Reference
910	120	0		Vilanculos	Seisser, 1974
920	140	0		Vilanculos	Seisser, 1974
1580	50	1.5	Pta-417	Luderitz	Vogel & Visser, 1981
1610	70	1.5	Pta-4972	Kosi Bay	Cooper, unpublished
1905	60	1.5	Y-467	Groenvlei	Martin, 1968
2040	50	1.5	Pta-1601	Saldanha Bay	Flemming, 1977
2070	60	1.5	Pta-461	Saldanha Bay	Flemming, 1977
3500	60	1.5		Saldanha Bay	Flemming, 1977
3780	60	0	Pta-5052	Sodwana Bay	Ramsay, 1990
3820	50	2.8	Pta-4041	Elands Bay	Yates et al., 1986
3880	60	0	Pta-4462	Keurbooms	Reddering, 1987
4660	50	2	Pta-4998	Kosi Bay	Cooper, unpublished
4940	60	3.6	Pta-419	Luderitz	Vogel & Visser, 1981
5180	70	1.5	Pta-4317	Keurbooms	Reddering, 1987
5750	60	0	Pta-1351	Orange River	Vogel & Visser, 1981
6870	161	1.5	Y-466	Groenvlei	Martin, 1968
7130		-20.4	Pta-1099	Orange River	Vogel & Visser, 1981
7580	70	-51	Pta-183	Cape St Francis	Vogel & Marais, 1971
8070	80	-18	Pta-3575	Mkomazi	Grobbler et al., 1987
8100		-12		Cape Flats	Schalke, 1973
8140	70	-18	Pta-3573	Mkomazi	Grobbler et al., 1987
8280	80	-18	Pta-3622	Mkomazi	Grobbler et al., 1987
8420	140	-29	GaK-1389	Mgeni Estuary	Maud, 1968
8840	90	-28	Pta-4346	Mfolozi	Grobbler et al., 1987
8950	30	-28	Pta-3570	Mkomazi	Grobbler et al., 1987
9350	90	-44	Pta-4343	Mfolozi	Grobbler et al., 1987
9440	90	-36	Pta-4344	Mfolozi	Grobbler et al., 1987
9990	30	-48	Pta-3597	Mkomazi	Grobbler et al., 1987
12990	100	-120	Pta-185	Cape St Francis	Vogel & Marais, 1971
13300		-75.5	Pta-955	Orange River	Vogel & Visser, 1981
13670	120	-115	Pta-264	Cape St Francis	Vogel & Marais, 1971
14510	120	-112	Pta-265	Cape St Francis	Vogel & Marais, 1971
15700	160	-87.2	Pta-1105	Orange River	Vogel & Visser, 1981
16990	100	-130	Pta-182	Cape St Francis	Vogel & Marais, 1971
24950	950	-22	GaK-1390	Durban Bay	King, 1972
27400	440	-78.4	Pta-1104	Orange River	Vogel & Visser, 1981
39100	1530	-52	Pta-4142	Richard's Bay	Maud, unpublished
45200		-46	Pta-4140	Richard's Bay	Maud, unpublished
48000		-35		Mlaas Canal	Maud, unpublished

Table 1.5. Tabulated data on dated sea-level indicators from around the southern African coast from various authors. For localities refer to Figure 1.14

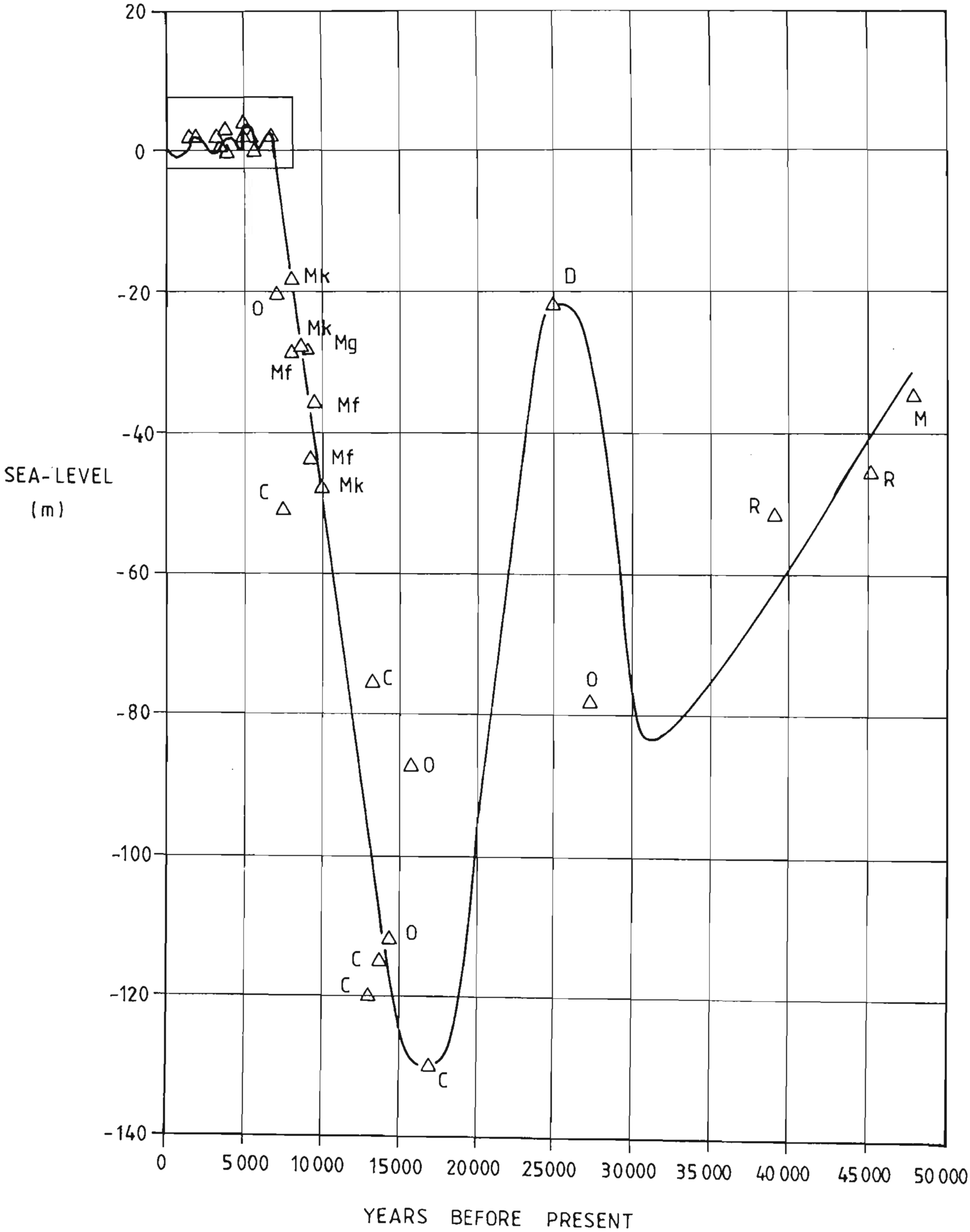


Fig.1.13. Sea-level curve for southern Africa since 50 000 BP. Based on data from various sources listed in Table 1.5. Letters refer to localities as follows: M-Mlaas canal; R-Richard's Bay; O-Orange River; D-Durban; C-Cape St Francis; Mk-Mkomazi Estuary; Mf-Mfolozi Estuary; Mg-Mgeni Estuary. Local evidence for an interstadial sea-level lower than present at about 25 000 years, although consistent with Chappel & Shackleton's (1986) proposed eustatic curve, is scant and requires further verification. For localities see Figure 1.14

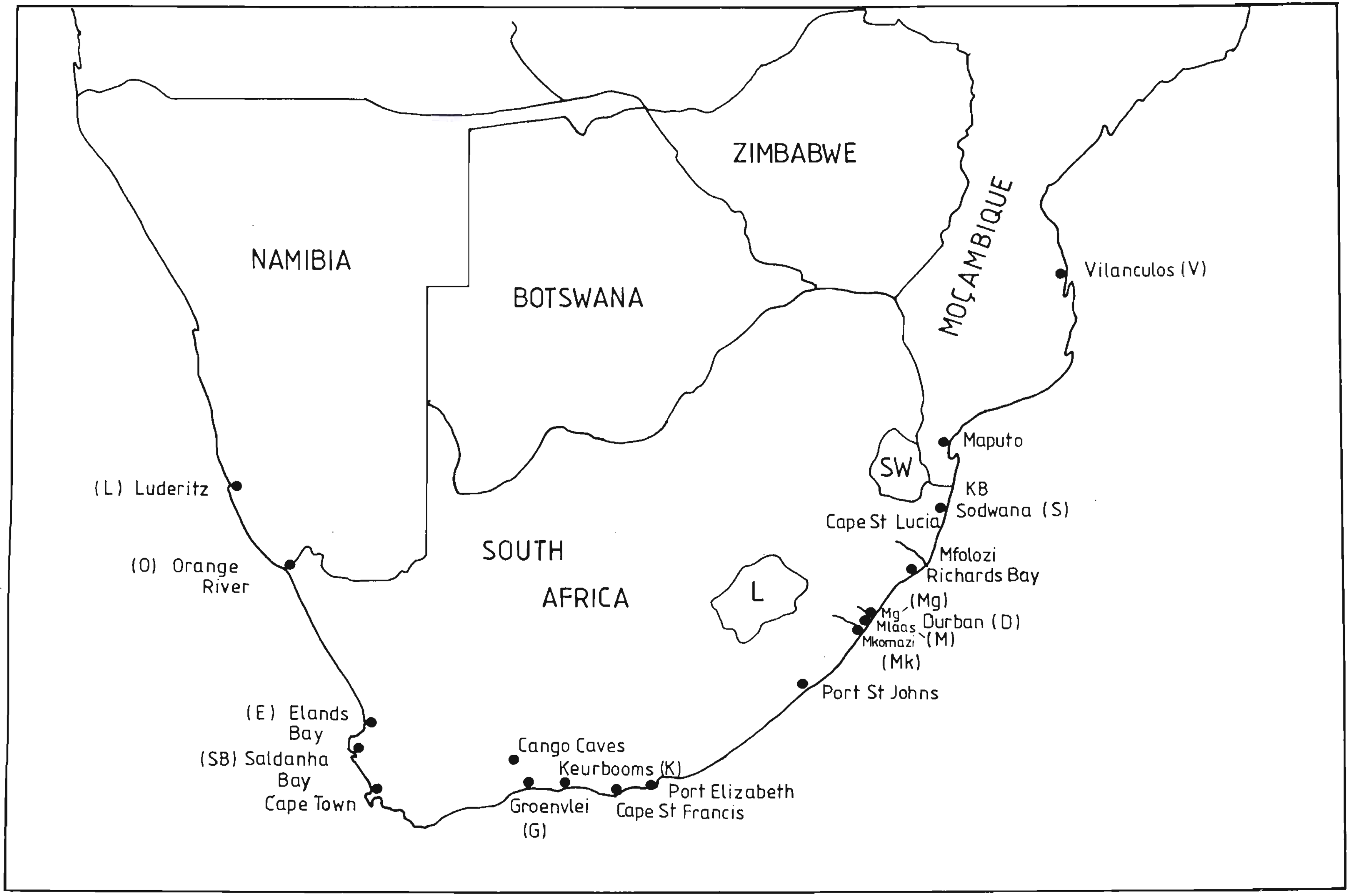


Fig.1.14. Locality map for sea-level data used in compilation of Figure 1.13 and listed in Table 1.5.

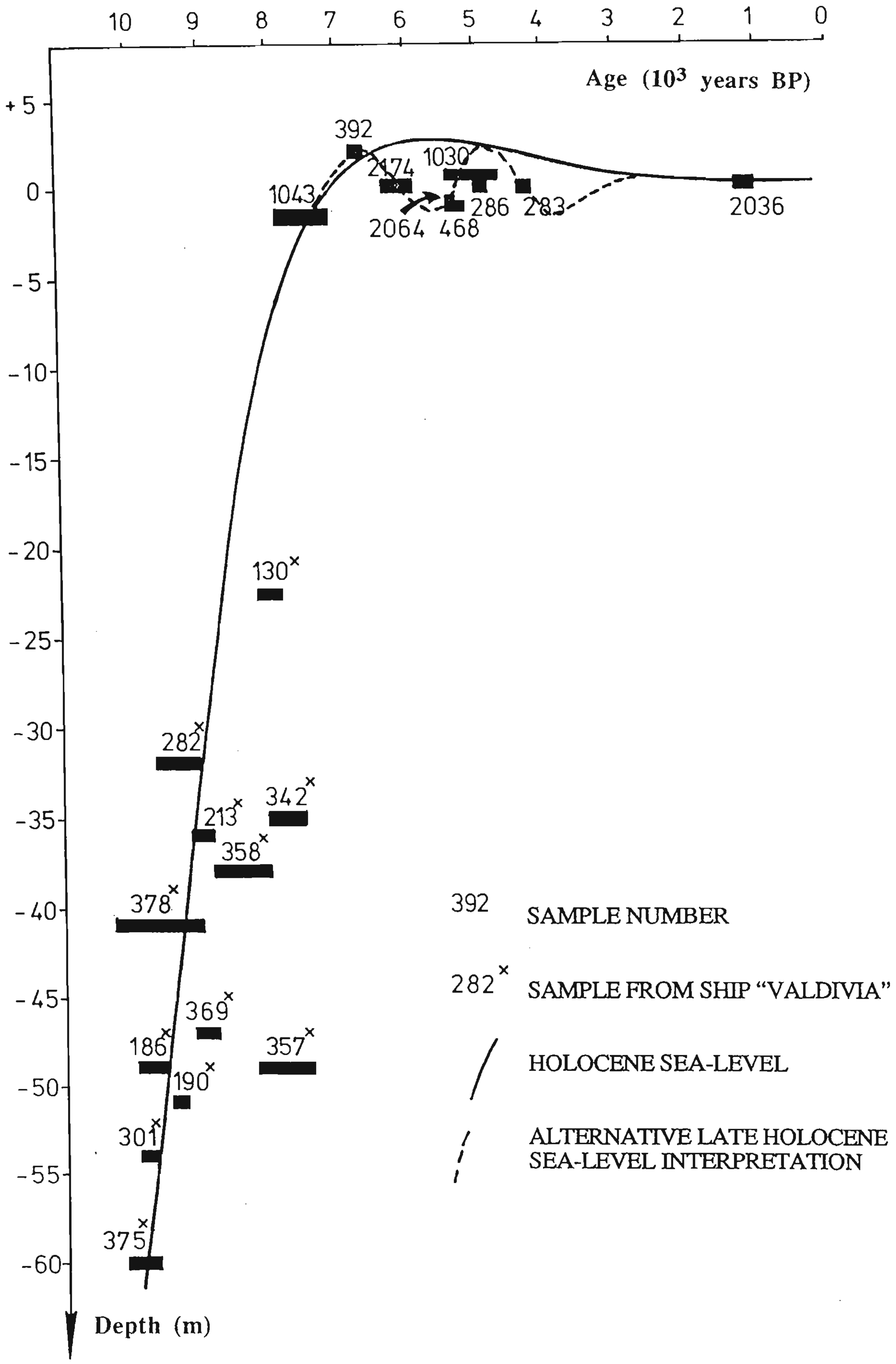


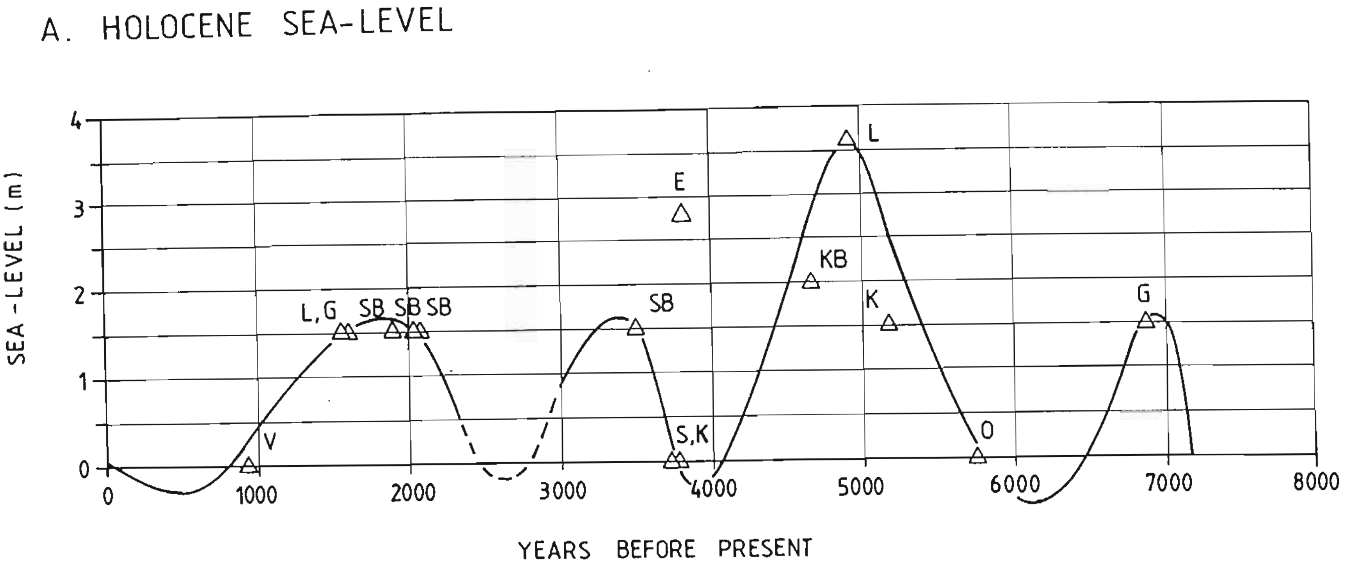
Fig.1.15. Holocene sea-level curve from Moçambique (After Jaritz et al., 1977.) Although their curve does not recognise possible peaks of higher than present sea-level, such an interpretation (shown by the dotted line) is not inconsistent with the data presented. An alternative interpretation of late Holocene sea-levels is shown as a dotted line.

may be temporarily stored in an estuary during prolonged low flow conditions (drought) but it is removed with renewed runoff from the catchment during wetter periods. Recurring occupation of the same narrow river course during successive transgressions and regressions erodes sediment from previous accumulative periods. Thus in most cases all of the sediment present in Natal's river-mouths is Holocene in age. Important in the development of South African river-mouths is the fact that comparatively recently, sea level was approximately 1.5 - 2 m higher than at present, during a postglacial sea level maximum. The fact that most river courses are incised into deposits pre-dating this period, means that even at that stage bedrock valleys had filled.

In compiling a Late-Pleistocene and Holocene sea-level curve, records from the southern African coast from Luderitz (Namibia) to Vilanculos (Mocambique) were used (Table 1.5). In many cases the precise relationship of the dated sample to sea-level is unclear, but the curve does give an indication of sea-level changes. Precision is enhanced for samples collected above present sea-level and in some cases samples of mollusc shells in life position, can be placed within centimetres of the contemporary sea-level (Reddering, 1988c). The stable cratonic basis of the African continent, particularly in the south, has rendered the coastline stable tectonically thus facilitating comparison of dated sea-levels from around the coast.

The curve generated by plotting these data is shown in Figure 1.13. It shows a general Late Pleistocene fall in sea-level to a maximum of 130 m below present. There is a possibility of an Interstadial at about 25 000 BP, which corresponds closely to proposed eustatic sea-level curves (Fairbridge,1961; Williams *et al.*, 1981). It is, however, based on a single date and requires further verification. Dated littoral deposits on the continental shelf off Cape St Francis (Fig 1.14; Vogel & Marais, 1971) provide dates of 16990 BP for the lowest sea-levels of the Last Glacial Maximum (Fig. 1.13). During the Holocene Transgression (Fig 1.13) sea-level rose rapidly from -130 to its present level between approximately 17000 and 7000 BP at an average rate of 13 mm/year. Little variation in the rate of sea-level rise is evident on the curve, although this may be due to insufficient data. This Holocene sea-level curve agrees closely with that for Moçambique (Fig 1.15; after Jaritz *et al.*, 1977). In both cases sea-level rose from -60 m to its present level between 10 000 and 7000 BP.

During the late Holocene sea-level was above its present level for a considerable period. No thorough investigation has been made into the late Holocene sea-level but fragmented evidence from around the subcontinent (Table 1.5) can be used to compile a preliminary curve of Late Holocene sea-level fluctuation (Fig.1.16A). Martin (1968) cited evidence for a sea-level approximately 1.5 m higher then present about 6870 BP. A single date from the Orange River suggests sea-level was about its present level about 5750. This is succeeded by a period between 5180 and 3800 during which dated sea-level elevations range from 3.6 to 2 m above present. Dates from the Keurbooms Estuary (Reddering, 1988c) indicates a rapid drop to present level about 3800 BP. This is backed up by a date of 3780 BP from present sea-level deposits from Zululand (Ramsay, 1990). The period of high Holocene sea-level broadly coincides with the period of maximum Holocene temperatures (7000-4000 BP) recorded in the



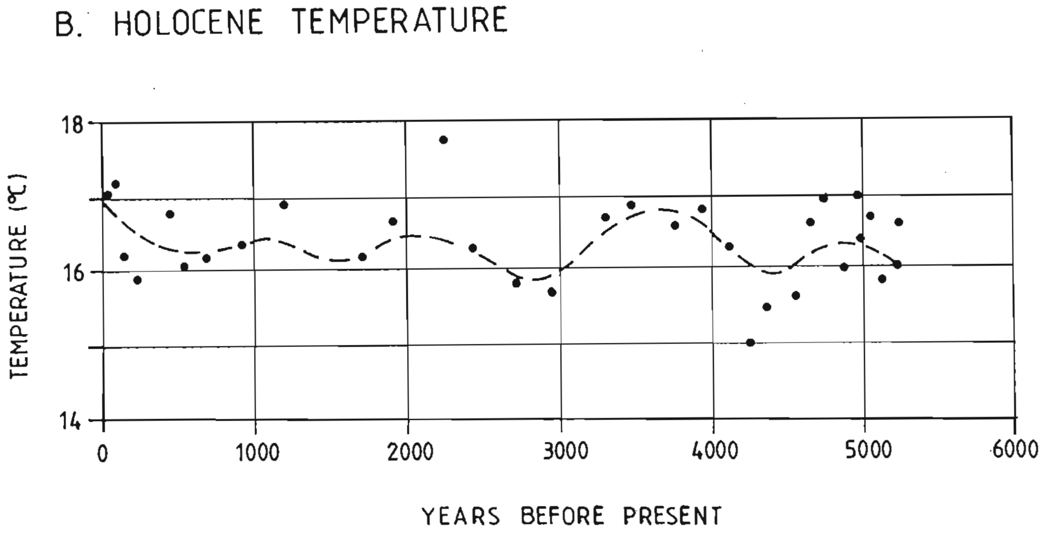


Fig.1.16. Sea-level and calculated air temperature at Cango Caves during the late Holocene both appear to show at least three distinct peaks. (A). Late Holocene sea-levels from southern Africa, deduced from published and unpublished radiocarbon dates from a variety of sources (Table 1.3). The curve drawn suggests three peaks with intervening low sea-levels after 6000 BP. Localities marked are: KB-Kosi Bay; V-Vilanculos; S-Sodwana; L-Luderitz; G-Groenvlei; SB Saldanha Bay; E-Elands Bay; O-Orange River and K-Keurbooms Estuary.

(B). Late Holocene temperatures deduced from a cave speleothem from the Little Karoo in the eastern Cape interior (After Vogel & Talma personal communication in Deacon & Lancaster 1988). The inferred dotted curve of the authors averages out differences in temperature, but nonetheless three distinct peaks can be discerned, which coincide closely with the sea-level curve proposed above.

summer rainfall area of southern Africa (Beaumont, 1986). Charcoal analyses from archaeological sites indicate 6400 BP to have been the warmest time during the Holocene (Scholtz, 1986).

A sea-level of +1.5 m inferred from Saldanha Bay at 3500 BP (Flemming, 1977) was followed by a period up to 2070 BP which lacks any evidence of sea-level position. Sea-level was about +1.5 m between 2070 and at least 1580 BP. The period between about 3500 and 2000 for which evidence is lacking, may have been a period of low sea-level. Avery (1982) inferred a rapid rise in temperatures between 2500 and 2000 BP from micromammalian data. This rapid temperature increase could coincide with a transgression to +1.5 m at 2000 BP and supports a low intervening sea-level. This may explain the lack of dated samples for this period.

Radiocarbon dates from beachrock in the modern intertidal zone in southern Moçambique (Seisser, 1974), indicate that the high sea-level which persisted from 2070 to at least 1580 dropped to its present level before 920 BP.

If this proposed mid- to late-Holocene sea-level curve is compared to isotopic temperatures for the past 5500 years deduced from a speleothem from the Cango Caves in the Little Karoo (Vogel & Talma, personal communication in Deacon & Lancaster, 1988) a close correlation is apparent between sea-level and temperature (Fig 1.16B). A marked decrease in temperatures between 5000 and 4000 BP agrees closely with a drop in sea-level. A rise in temperature from 4000 to 3500 BP correlates well with the proposed transgression to about 1.5 m. A drop in temperature about 3000 BP provides back-up evidence for the inferred lowering of sea-level at that time and the subsequent increase and consistency of temperatures between 2000 and 1000 BP coincides with a 1.5 m high sea-level. Temperatures dropped from 900 to about 300 BP since when they have risen. This suggests a fall in sea-level, followed by the observed modern rise.

The single date for a high sea-level at 6870 BP (Martin, 1968) urges caution in its acceptance without further evidence, particularly as other dates suggest sea-level to have been at -20.4 m only 130 years earlier (Vogel & Visser, 1981). Flemming (1977) suggested from physiographic evidence and a dated fossil reef with an imprecise relationship to sea-level at Saldanha Bay, that sea-level must have stood 3-4 m higher than present some time between 6000 and 5000 years BP. This lends support to the date from Groenvlei (Martin 1968). The consistency of subsequent dated material and inferred sea-levels from around the subcontinent suggests that, in the period after 5000 BP, three periods of higher than present sea-level occurred.

This complex Late Holocene sea-level variation is only a preliminary assessment of the situation in Southern Africa but it is not without precedent on tectonically stable coastlines. Fairbridge's (1961) eustatic sea-level curve depicted four Late Holocene sea-level stands: 6000-4600 BP; 4000-3400 BP; 2600-2100 BP and 1600-1000 BP. In Brazil, Dominguez *et al.* (1987) identified three emergent phases during the late Holocene: 7000-4000 BP; 4100-2900 BP and a generally falling sea-level from 2700 to present. In Mauritania Einsele *et al.*, (1974) documented three Holocene high sea-levels in the period between 6500 BP and present during the following approximate intervals: 6500-4600BP; 3700-2600BP; after 2300 BP. These coincide remarkably closely with the curve proposed above for Southern Africa. The Holocene sea-level curve for Moçambique (Jartitz *et al.*, 1977) does not differentiate these peaks in the mid- to late-Holocene but the data presented could be alternatively interpreted as at least two peaks with an intervening trough (Fig 1.16A).

Tjia (1975) and Isla (1989) noted the widespread occurrence of high Holocene sea-levels throughout the southern hemisphere and in the tropical northern hemisphere (Mauritania and Senegal). Tjia (1975) ascribed the lack of high Holocene sea-levels in the high latitudes of the northern hemisphere to isostatic uplift from glacial unloading and suggested that high Holocene sea-levels represented the true eustatic situation. The absence of sufficient Late Holocene dates has apparently resulted in oversimplification of sea-level history in South Africa and Moçambique, where a single extended period of elevated Holocene sea-levels has often been suggested.

Discrepancies in dates of particular sea-levels from around the southern hemisphere led Isla (1989) to suggest that maximum Holocene sea-levels were attained earlier in the south and progressed toward the Equator and the low northern latitudes. In view of the lack of comprehensive data on the earliest Holocene high sea-levels from many coastal areas this hypothesis requires more rigorous testing. If true, this phenomenon may account for the similarity in overall sea-level history in stable areas of the southern hemisphere and the northern tropics. Differences in timing point to a time-transgressive series of eustatic sea-level curves rather than a single eustatic Holocene sea-level curve.

What is of most importance to river-mouth evolution on the South African coast is that sea-level *fell* by a few metres to its present level during the mid to late-Holocene. This had the effect of incising river channels into surrounding alluvial plains or submerged deposits and effectively accelerated the process of river-mouth evolution. Holocene river incision of up to 2m was also noted in alluvial plains in the Zambesi delta region by Jaritz *et al.* (1977) and in the eastern Cape (Reddering, 1988c).

1.11. NATAL RIVER-MOUTHS - PREVIOUS STUDIES

Until recently the geology and sedimentology of Natal river-mouths were poorly known and little research had been carried out, with the exception of that of Orme (1973, 1974, 1975). Orme's work was largely a descriptive overview of river-mouth geomorphology and particularly the sedimentary record preserved in boreholes, on the Natal coast with little detail on any particular system. Attention was focussed on sedimentological aspects of Natal river-mouths when Begg (1978, 1984a,b) suggested that their apparent biological degradation was caused in many cases by increased siltation due to soil erosion from agricultural malpractice. Since that time a number of geologically-orientated studies of individual Natal river-mouths have been carried out (Cooper, 1987, 1988a; Cooper & Mason, 1987; Grobbler *et al.* 1987, 1988). These have revealed significant differences in sedimentology and geomorphology between the various systems. These differences result from complex inter-relationships between catchment size, coastal geomorphology, nearshore processes, hinterland geology, sediment yield, and a number of other factors. Much of the work reported in this thesis has been published by the author in the course of data collection and compilation of the thesis. Many of these papers dealt with specific aspects of river-mouth and coastal sedimentation on the Natal coast and are an integral part of the studies involved in this research. The aim in this thesis is to present new data and to draw together many aspects to compile an overall picture of the sedimentology of Natal river-mouths. The role of "episodic" (high magnitude, low frequency) hydraulic conditions in river-mouth sedimentation in relation to "normal" conditions (regular seasonal, daily and monthly fluctuations) alluded to in previous studies (Cooper, 1989; Cooper *et al.*, 1990) is also assessed, both in specific and general cases.

* * *

CHAPTER 2.
METHODS

2.1. INTRODUCTION

In this chapter the methods of sampling and analysis are outlined. Tabulated grainsize, organic and carbonate data for each estuary are contained on computer data files in the Department of Geology and Applied Geology at the University of Natal in Durban and at the offices of the CSIR in Durban from which data may be obtained.

2.2. SEDIMENT SAMPLING

At each selected river-mouth sediment samples were collected from the channel on a pre-determined grid system. Because of the elongate, narrow channels, the grid comprised a series of channel transects. Each sediment sample weighed about 0.5 kg and, to ensure reproducibility, they were collected directly from the bed using skin and Scuba diving. Only the top 5 cm of the channel sediment was collected. Samples were sealed in plastic vials and returned to the laboratory for analysis.

2.3. SEDIMENT ANALYSIS

The sediment analysis procedure is illustrated diagramatically in Figure 2.1. Each sample was thoroughly mixed in the laboratory and subsamples were removed and dried at 100°C. These were then ground to powder using an agate pestle and mortar for subsequent determination of organic and carbonate content.

Many methods exist for the determination of organic content of sediment. In this particular application the relative rather than absolute amount was of interest. Consequently organic content was determined by weight loss after ignition at 550°C, following initial drying at 100°C (Dean, 1974). This method removes bound water from clay minerals (McCave, 1979) and has been estimated to be about 1.6 times greater than more precisely determined particulate organic matter (Meade *et al.*, 1975). It is, however, a rapid method for large numbers of samples and provides reproducible results.

Carbonate content was measured gasometrically in a carbonate bomb (Schink *et al.*, 1978). Seisser & Rogers (1971) found that, in terms of accuracy and precision, expense, analytical skill and time available for analysis, gasometry is the most suitable method for routine carbonate analysis of large numbers of sediment samples.

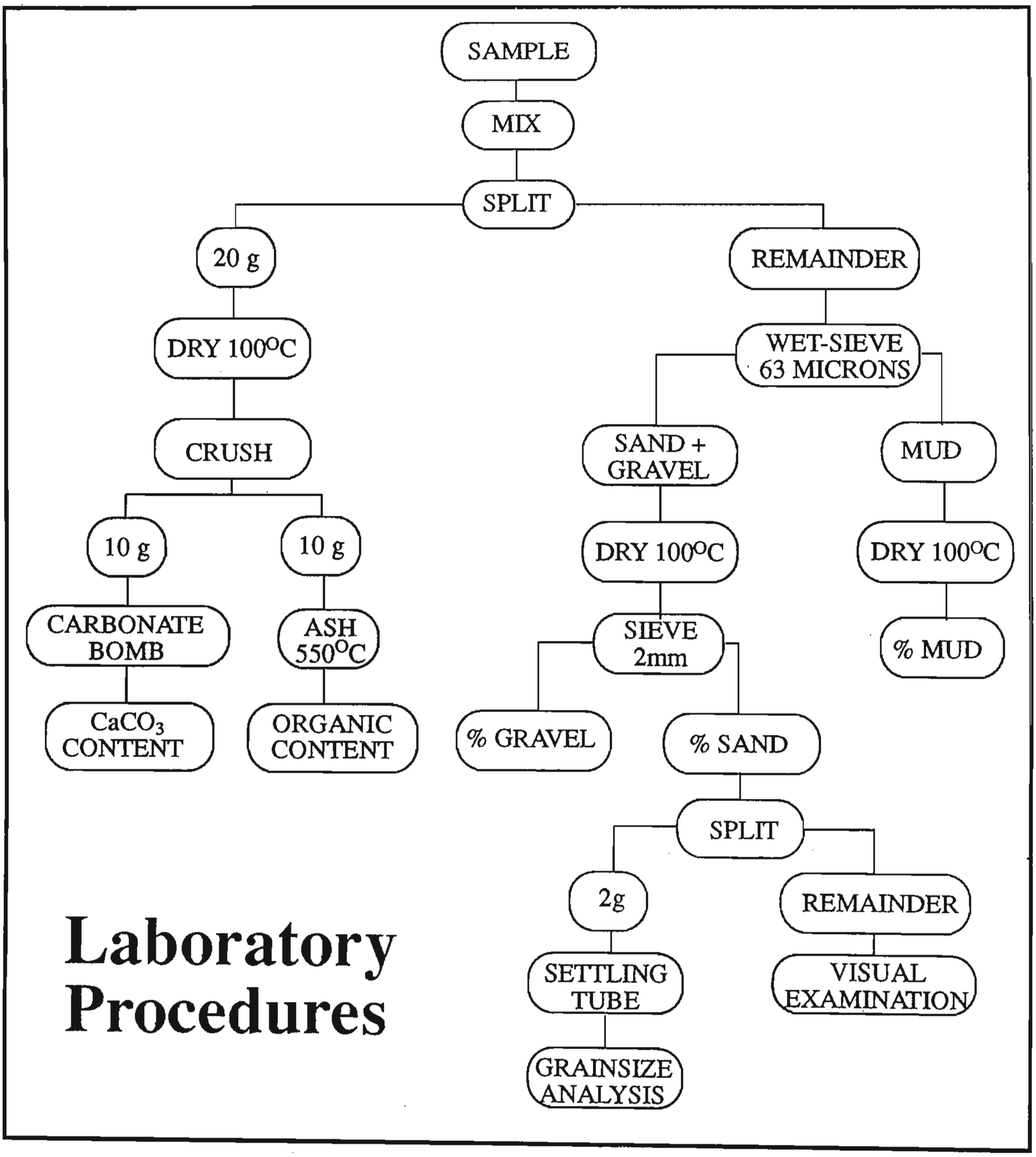


Figure 2.1. Flow chart of laboratory analysis of sediment samples

The remainder of each sample was wet sieved through a 0.063 mm screen to remove the mud component which was dried at 100°C and weighed. This was recorded as a percentage dry weight of the total sample. The remaining sand and gravel fractions were dried at 100°C and dry-sieved through a 2mm screen which removed the gravel fraction. It was recorded as a dry-weight percentage of the total sample. The grainsize distribution of the remaining sand fraction were analysed by settling tube (Esterhuysen & Reddering, 1985). Median, mean, sorting and skewness were routinely calculated using both graphical and moment statistics (Buller & McManus, 1979; McBride, 1971). Flemming (1977) stressed the benefits of settling tube analysis over sieving in the interpretation of sedimentary environments and concluded that settling procedures are the only practical and reliable means by which hydraulically related size parameters can be obtained.

The remaining sand and gravel-sized sediment was stored for visual examination of grains and microfossils.

2.4. HISTORICAL CHANGES: AERIAL PHOTOGRAPH INTERPRETATION

The south African coast has been photographed extensively at several intervals since 1937 In the Durban area, the first vertical aerial photographs were taken in 1930. This provides a long-term data set which is not frequently encountered around the world. In addition, 1:10000 orthophoto maps are produced by the Department of Surveys and mapping. On these, topographical contours at 5 m intervals are overlain on aerial photographs. Extensive use was made of available vertical aerial photography spanning the period 1930 to 1990. The photographs were of varying scale and came from several sources: the state Department of Surveys and Mapping, Mowbray; The Air Survey Company of Africa, Durban; Aerial Photographic Services, Pietermaritzburg; the University of Natal Department of Surveying and Mapping; and the City Engineer's Department of Durban Corporation.

Initial enlargements were obtained as close to 1:10 000 scale as possible. To facilitate comparisons between photographs, these were digitised using a graphics tablet or flat-bed scanner linked to a Macintosh SE30 computer. The digitised images were then printed and rescaled to the 1:10 000 orthophotograph which was used as the base map. The digitised image was then reprinted at the adjusted scale and traced. This enabled close comparison of sequential photographs. Scale aberration and distortion were minimised by selecting photographs in which the river-mouth area occupied the centre of the print. The interpretations from the traced images are illustrated in the appropriate chapters. They are easier to compare than photographs of varying colour and quality.

2.5. CHEMICAL MEASUREMENTS

A few chemical parameters were routinely measured during fieldwork in the selected river-mouths. Water salinity and temperature were measured using a Y.S.I. model 33 S-C-T meter. Dissolved Oxygen was measured using a Y.S.I. model 57 Oxygen meter.

2.6. CHANNEL PROFILES

Because of different channel morphologies, several techniques were employed in the measurement of cross-sectional profiles in the various river-mouths. Channel cross-sections of the deep, cliff-lined Mtamvuna river-mouth were surveyed using a Furuno 3800 echo sounder at measured water levels. Shoreline station positions were fixed by theodolite. Cross-sections of the more shallow Mgeni river-mouth were measured using a theodolite and survey staff which was carried across the channel. Use was also made of published channel cross-sections when available.

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CHAPTER 3.
MGENI RIVER-MOUTH

3.1. INTRODUCTION

The Mgeni River enters the sea through the northern suburbs of Durban (Fig.3.1.). It is the third largest-catchment river in the study area. The lowest 2.5 km of its course experiences tidal water level and salinity fluctuations through a semi-permanent tidal inlet. It has been studied from a sedimentological viewpoint since 1985 (Cooper, 1986a,b, 1988a; Cooper & Mason 1987; Cooper & McMillan 1987) and the fortuitous occurrence in 1987, of a high magnitude flood, enabled assessment of the effects of such events on sedimentology of the river-mouth (Cooper, 1989; Cooper *et al.*, 1990). The results, coupled with an intensive pre-flood study and a set of vertical aerial photographs spanning a 60 year period, permit both long and short term analysis of river-mouth sedimentology.

3.2. CATCHMENT CHARACTERISTICS

3.2.1. Catchment topography

The Mgeni River catchment covers 4400 km^2 (Fig.3.2) The river rises in the Natal Drakensberg, 252 km from the Ocean, at an altitude of 1889 m. Its overall gradient is 1:132 or 0.0075. In its lower 10 km, however, the gradient is reduced to 1: 550 or 0.0018. At maximum Pleistocene lowered sea levels (-130 m), assuming a straight river course, the gradient over the last 10 km would have increased to 1:110 or 0.009. Mean annual runoff is 323 x 10^6 m^3 (NRIO, 1986). 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 occur on the river (Fig. 3.2A). The catchment below Inanda Dam, only 30 km from the coast, is 395 km^2.

Using old rainfall records and established rainfall-runoff relations (Midgley & Pitman, 1969), NRIO (1986) calculated monthly runoff from the catchment since 1921 (Fig.3.3.). The results show that rainfall is highly irregular but that most rain falls in the six summer months (September to February).

Air temperatures are reduced inland but most of the catchment is subtropical and has been since at least the Miocene (Partridge & Maud, 1987). This has produced thick soil profiles.

3.2.2. Catchment geology

The geology of the Mgeni catchment (Fig. 3.4) consists, in its upper reaches, of Ecca and Beaufort Group lithologies which are generally fine-grained lacustrine and fluvial sedimentary rock. These are intruded by Late Jurassic Karoo Dolerite. They are underlain by Dwyka Tillite. In the central part of its catchment, the river traverses a deeply weathered, Proterozoic granite-gneiss complex in the Valley of a Thousand Hills (Plate 3.1). Downstream, the river flows through a downfaulted block of Ecca and Dwyka rocks. Near the coast, alluvium is present on the Springfield Flats and Tertiary and Pleistocene coastal deposits are exposed atop the valley sides.

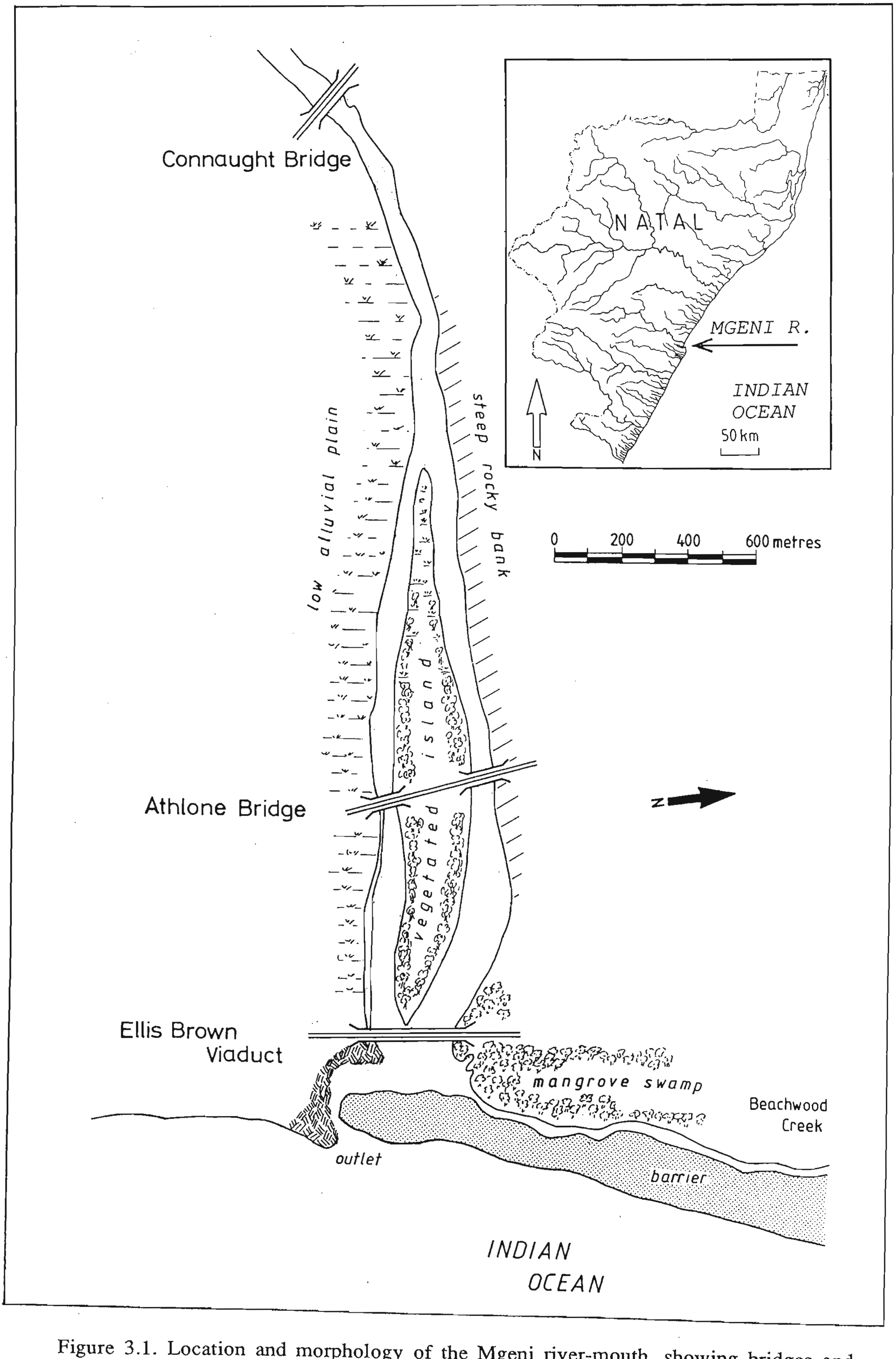


Figure 3.1. Location and morphology of the Mgeni river-mouth, showing bridges and locations referred to in the text.

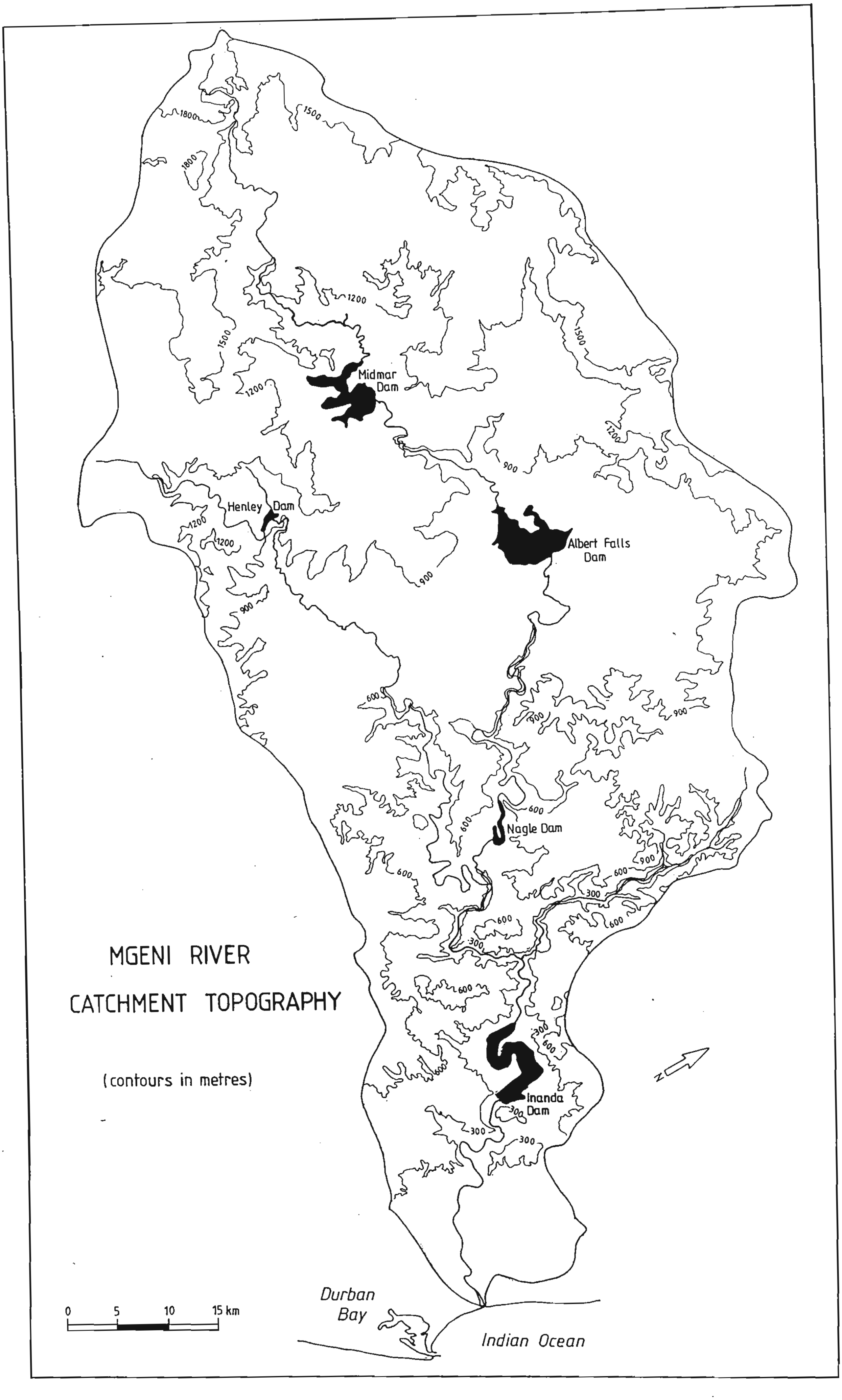


Figure 3.2A. Topography of the Mgeni River catchment area showing the location of major dams on the river.

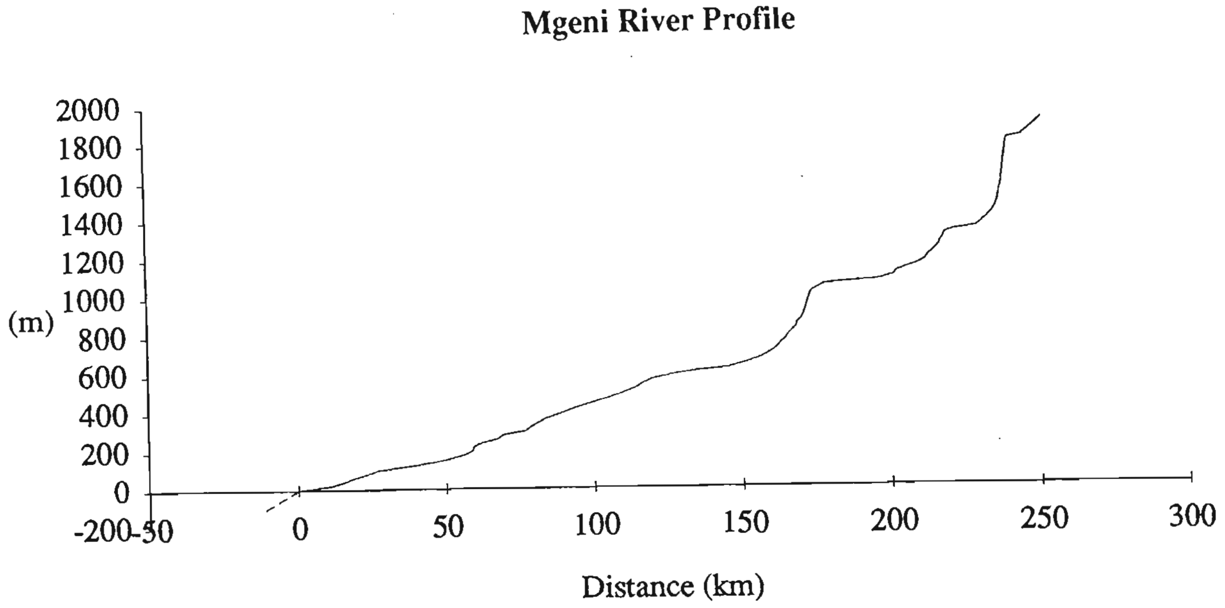


Figure 3.2B. Downstream river profile showing changes in gradient. The dotted line represents the channel extension to the shelf edge during the last glacial maximum, assuming a straight river course.

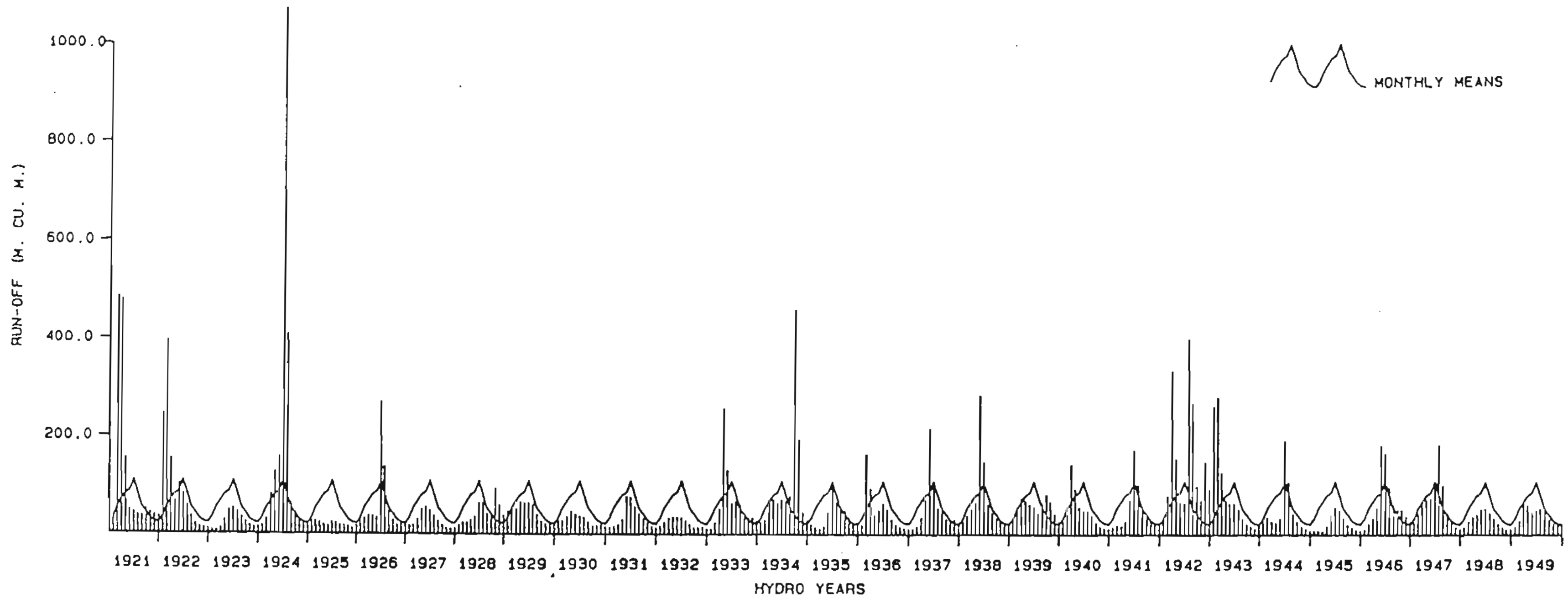
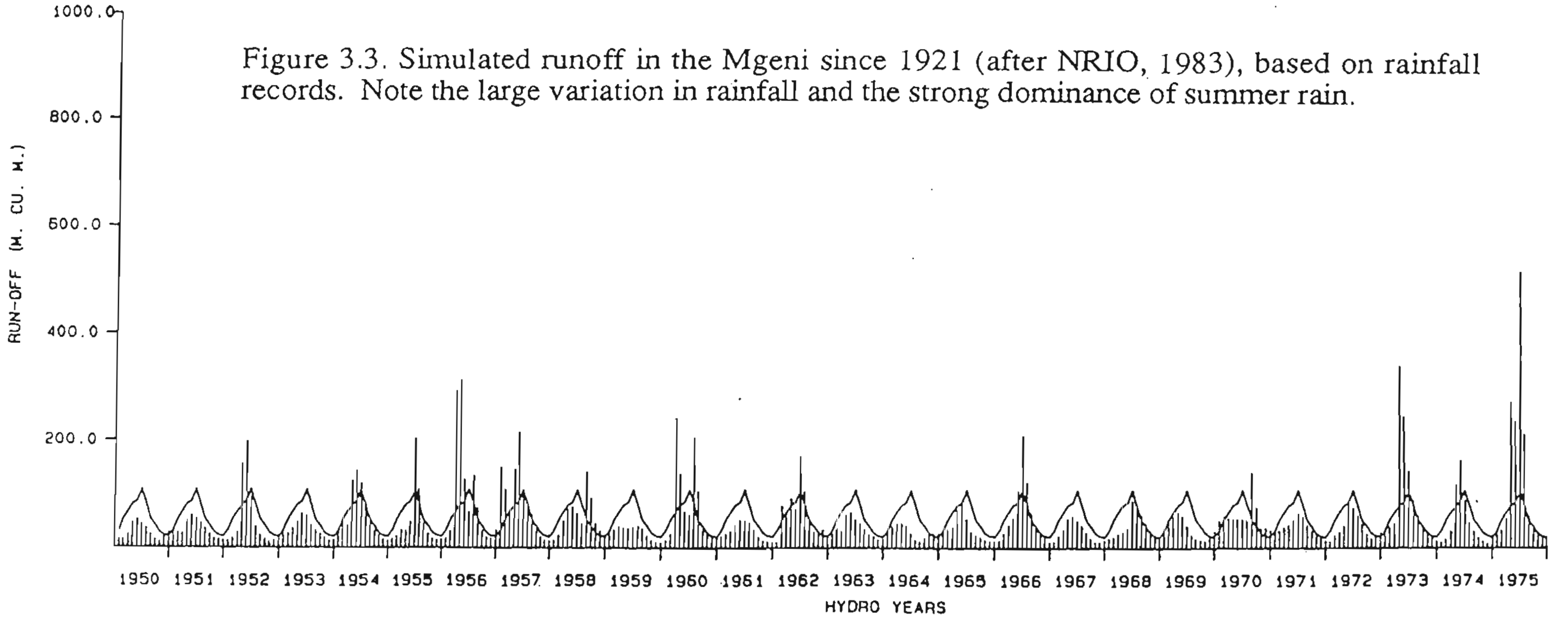


Figure 3.3. Simulated runoff in the Mgeni since 1921 (after NRIO, 1983), based on rainfall records. Note the large variation in rainfall and the strong dominance of summer rain.



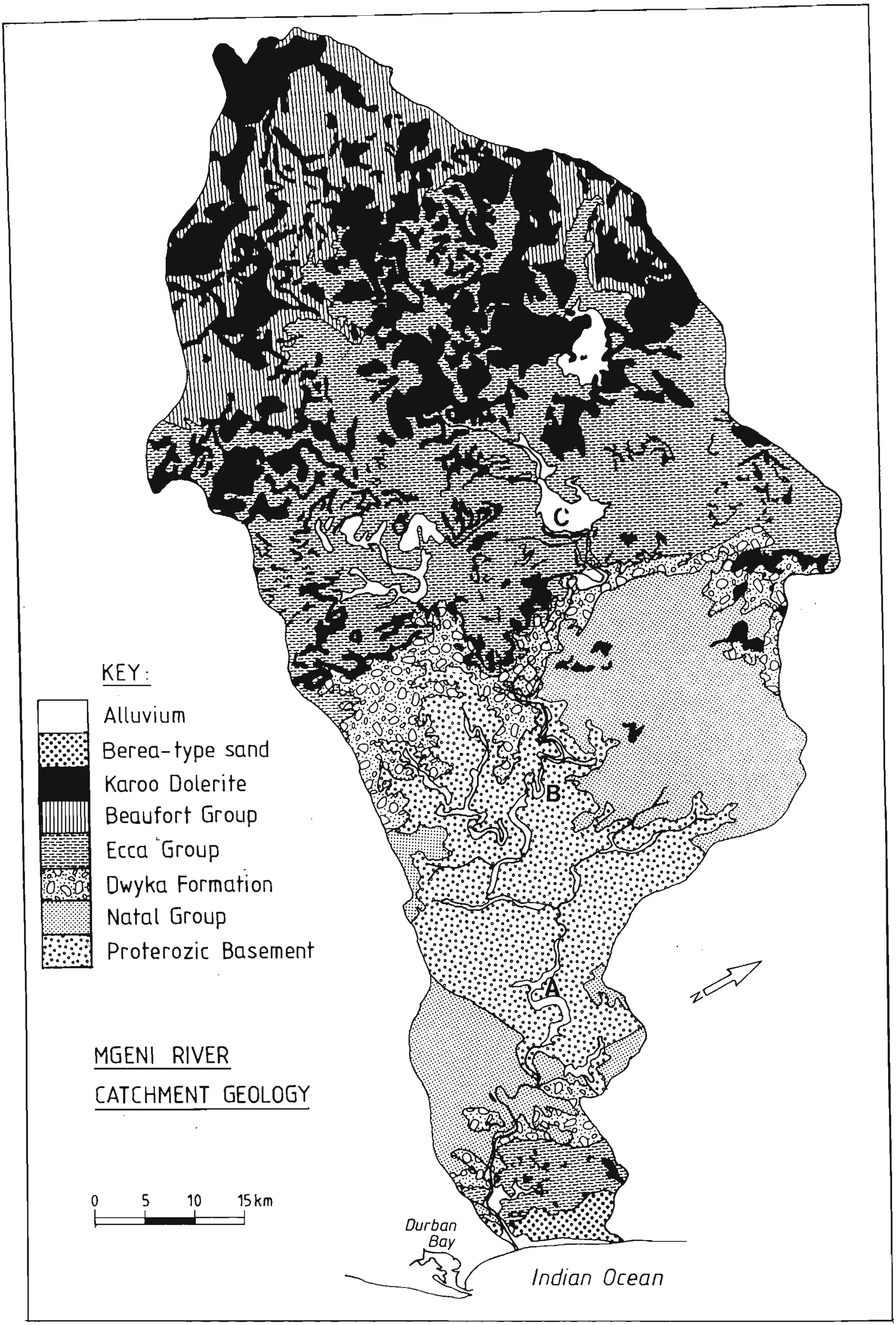


Figure 3.4. Geology of the Mgeni catchment area. The upper reaches are characterised by fine-grained lithologies, while most sand is derived from the granitic facies in the mid-catchment in the Valley of a Thousand Hills. A-Inanda Dam, B- Nagle Dam, C. Albert Falls Dam.

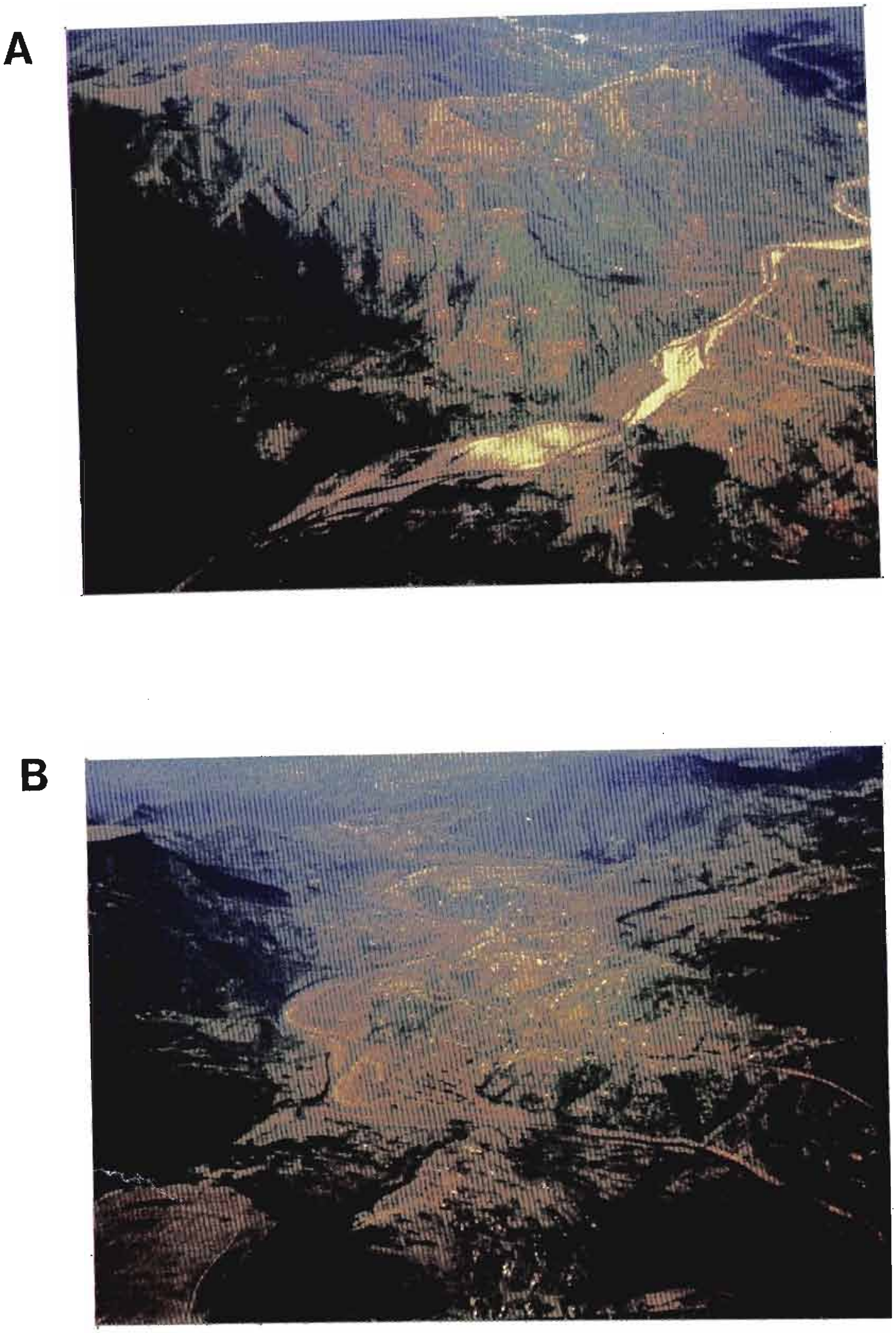


Plate 3.1A,B. Photographs illustrating the deeply dissected topography of the Valley of a Thousand Hills from where most of the gravel and coarse sandy sediment in the Mgeni river-mouth is derived. Note the braided river channel in this locality. The narrow valley offers little storage capacity for eroded sediment.

The annual sediment yield from the Mgeni drainage basin was estimated at 1.6 x 10^6 tonnes (NRIO, 1986) using a sediment yield map compiled by Rooseboom (1975). However, the five dams in the catchment reduce the amount of sediment, particularly bedload, reaching the coast. It is important to assess the volume of sediment reaching the coast and as Inanda Dam was only completed during the latter part of the study period it is excluded from the calculation below. The catchment area below the four dams completed in 1987 (excluding Inanda Dam, completed in 1988) is approximately 1700 km^2 and the sediment yield from this area was calculated at 0.5 x 10^6 tonnes per year from Rooseboom's (1978) map (NRIO, 1986).

Given a mean annual runoff of 323 x 10^6 m^3 and an average suspended sediment concentration of 165 mg/litre (Brand *et al.*, 1967) yields a total suspended load of 53 295 tonnes per year. There has been some debate as to the relative proporations of suspended and bedload in Natal rivers. Some authors (Swart, 1981, Nicholson, 1983) suggest a figure of 12% while others (Alexander, 1976) suggest that it might be as much as 50%. Calculation of the total load using each of these figures give a total load between 59 000 and 106 000 tonnes. This amounts to 12 to 20 % of the figure derived from Rooseboom's map. In the absence of large storage areas in inland basins downstream of Nagle dam, the large discrepancies underline the need for further research on this phenomenon.

Inanda Dam further reduces sediment supply from the catchment but, most importantly, cuts off the source of gravel to the river-mouth. As it was only closed in 1988, the effects of this cannot yet be assessed.

3.3. HISTORICAL DEVELOPMENT OF THE RIVER-MOUTH 1931-1991

Historical changes in morphology of the Mgeni river-mouth are revealed by reference to aerial photographs, the earliest of which dates from 1931. Earlier historical records and old paintings and charts are less reliable but give an impression of river-mouth morphology.

3.3.1. Morphological changes

Changes in morphology discussed below are illustrated in Figures 3.5 and 3.6. For ease of reference the changes in the river-mouth channel and coast-parallel lagoon are depicted separately.

In December 1931 the Mgeni river-mouth had a shallow, braided channel, with largely unvegetated sandy braid bars exposed above water level (Fig.3.5A). A bridge (the Old Athlone Bridge) crossed the middle reaches and road and rail bridges were present near the head of the river-mouth. At the coast, a broad, coast-parallel, back-barrier lagoon extended north of the constricted tidal inlet (Fig.3.6.A). The course of a narrow tidal channel was visible in the lagoon, surrounded by unvegetated, shallow subtidal or intertidal mudflats. Mangroves were present only in the upper reaches. A salt marsh, evidently disrupted by human activity associated with a shooting range, extended through most of the lower reaches. The inlet was prevented from migrating southward by a rocky groyne, south of which was a small lagoon remnant. Historical records suggest that the groyne was constructed in the early 1930s

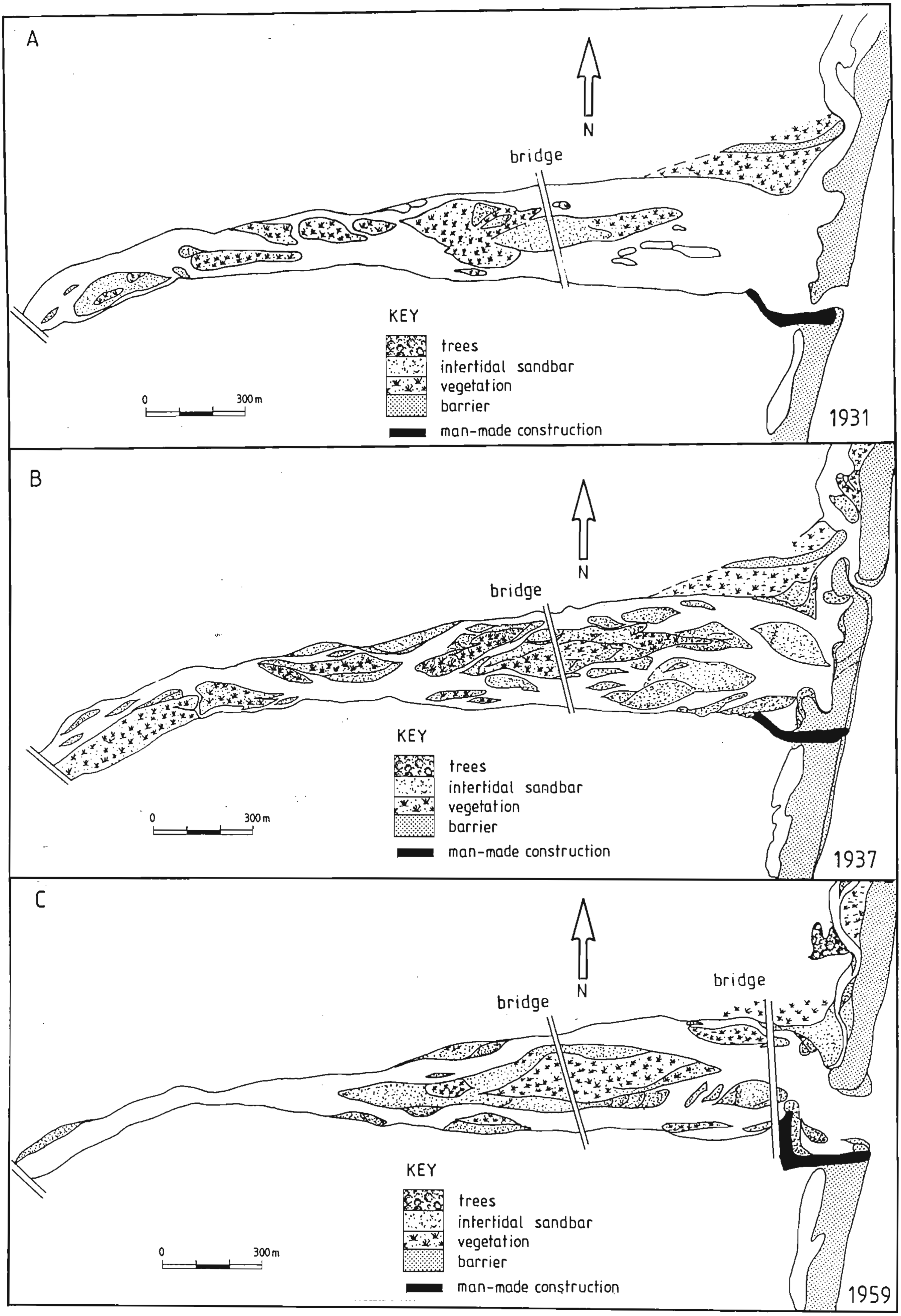


Figure 3.5. A-F. Historical changes in river-mouth morphology 1931 to 1983, illustrating the progressive evolution of the river-mouth from a braided to anastomosing channel.

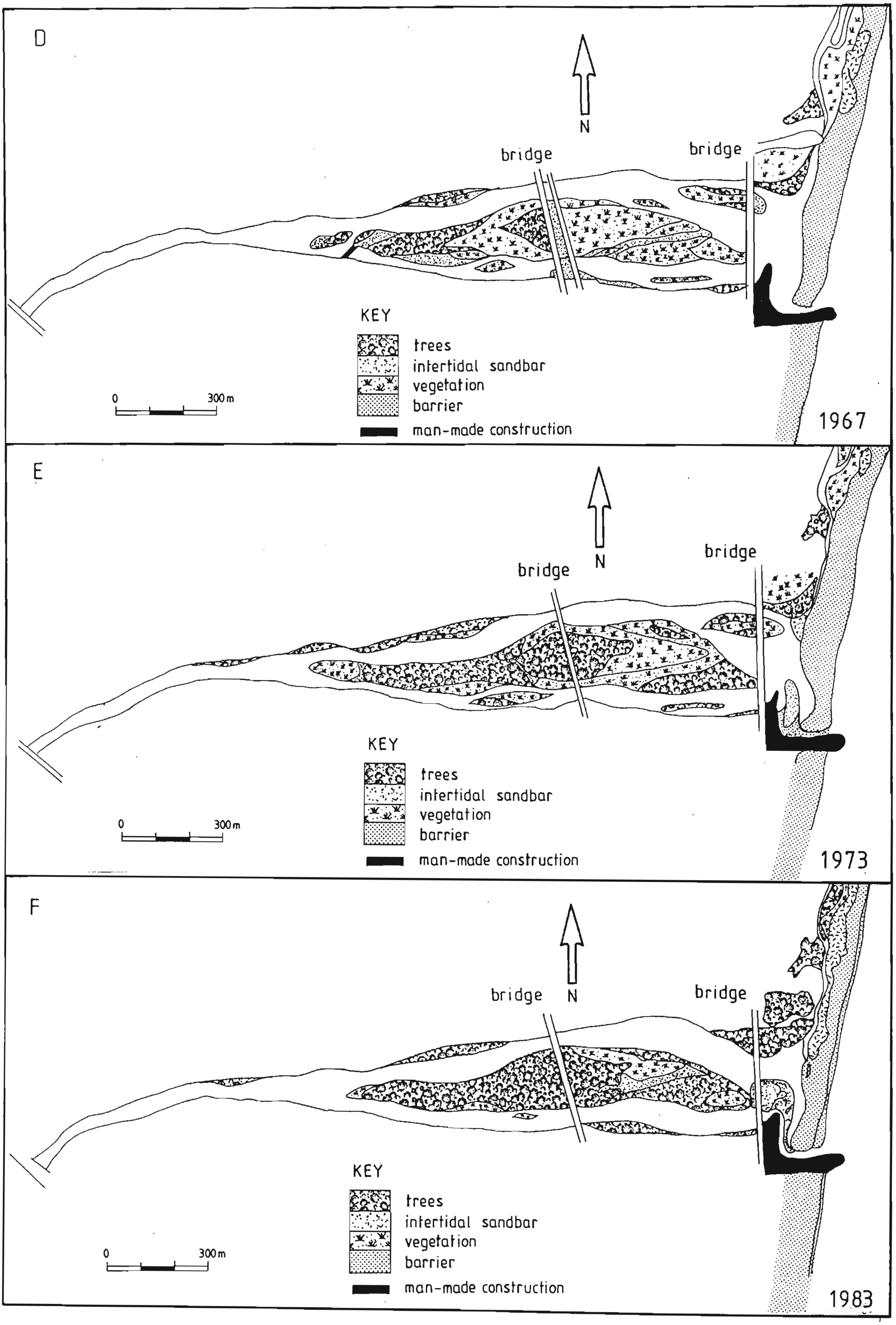


Figure 3.5. A-F. (continued) Historical changes in river-mouth morphology 1931 to 1983, illustrating the progressive evolution of the river-mouth from a braided to anastomosing channel.

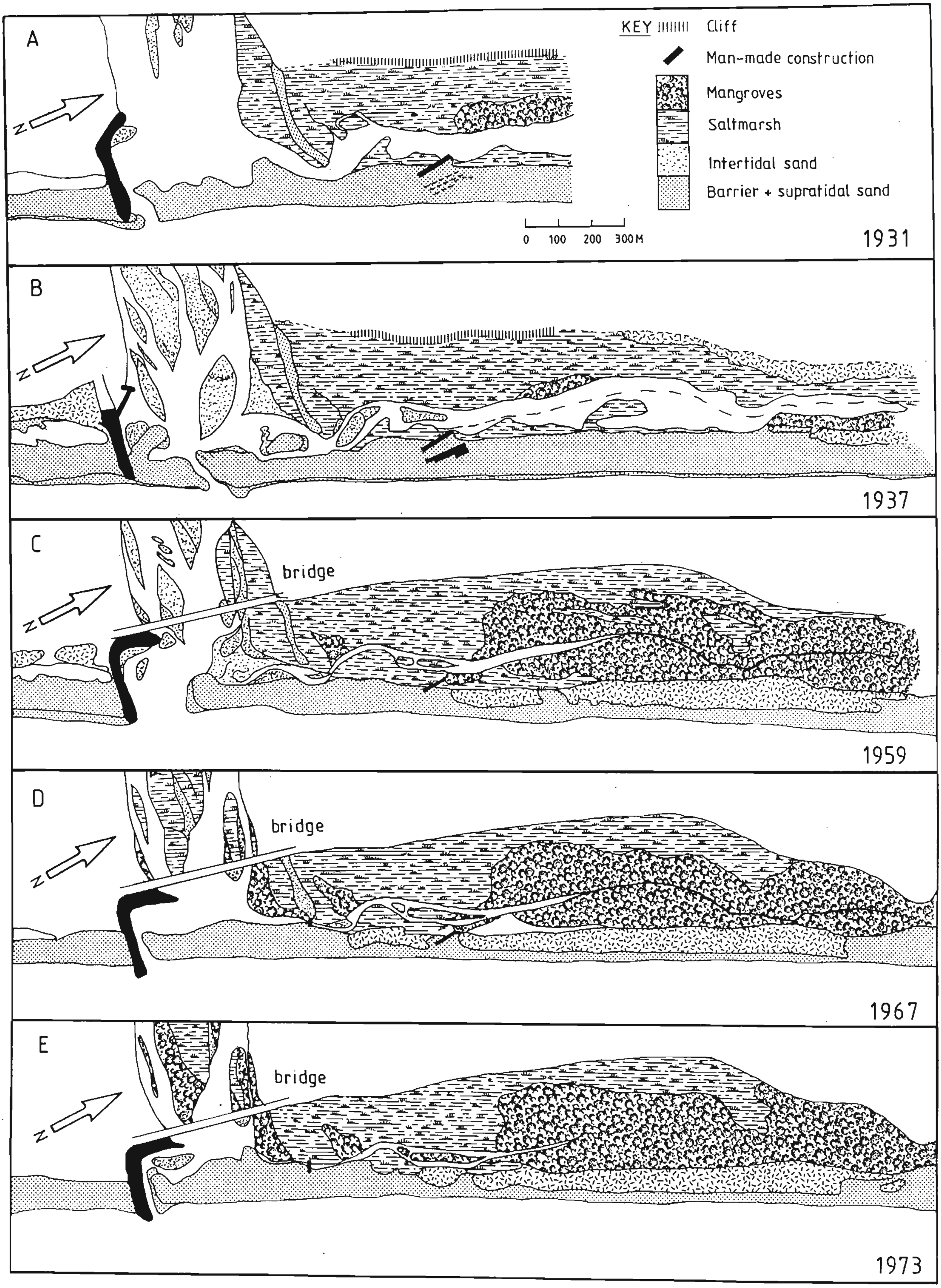


Figure 3.6. A-H. Historical changes in the coast-parallel lagoonal area 1931 to 1985, illustrating the gradual infilling of the area and shoreline retreat, accompanied by growth of an aeolian dune. In Figure 3.6 H successive shoreline positions are compared.

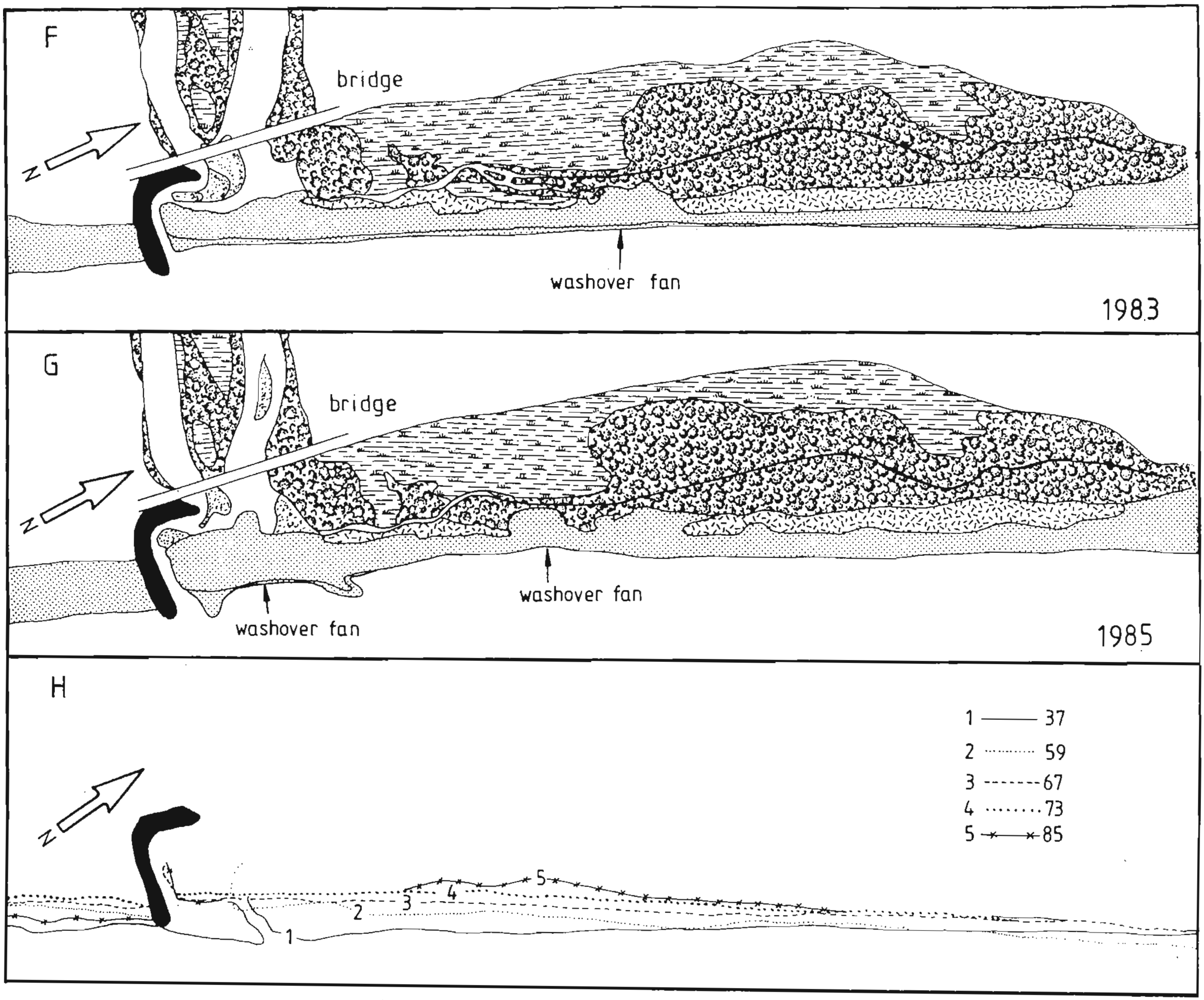


Figure 3.6. A-H. (continued) Historical changes in the coast-parallel lagoonal area 1931 to 1985, illustrating the gradual infilling of the area and shoreline retreat, accompanied by growth of an aeolian dune. In Figure 3.6 H successive shoreline positions are compared. (Key as in Figure 3.6A)

(Pfaff, personal communication) and the photograph was probably taken shortly after its completion. No dunes were present on the barrier north of the groyne. At the northern side of the river-mouth channel an elongate sand spit (Fig.3.5A) extended seaward, across the mouth of the northern lagoon. This was surrounded with mudflats and had probably been inactive for some time.

In 1937 a prominent supratidally-exposed central bar was present. It was sparsely vegetated, as were some side-attached bars in the upper reaches. Intertidal braid bars, which filled most of the channel, were unvegetated (Fig.3.5.B). Photographs taken on 30th April and 16th July 1937 record a change in inlet position. The preservation of intervening barrier features indicates that this did not occur through progressive migration but through inlet closure and re-opening. The barrier also retreated slightly in the same period, suggesting that overwash, coupled with low winter freshwater discharge was the reason for inlet closure. The inlets had small ebb-tidal deltas but no flood-tidal deltas. The lagoonal area showed little change since 1931 (Fig.3.6.B)

In 1959 side-attached bars in the upper reaches of the river-mouth and adjacent to the coast-parallel lagoon were incorporated into the floodplain, causing the channel to narrow (Fig.3.5.C). In the channel many braid bars had coalesced, forming a large, elevated central bar with scattered trees and bushes on it. The river formed two distinct channels around this central island. The isolated pond south of the groyne was reduced in size. The coast-parallel lagoon was reduced to a narrow channel remained, surrounded by sparsely vegetated, supratidal mudflats and mangroves. Mangroves had extended downstream in the lagoon since 1937 (Fig.3.6.C). The coast had retreated and a dune was formed on the barrier. The Ellis Brown Viaduct was constructed 200 m upstream from the inlet.

In 1967 (Fig.3.5D) the central island was enlarged by downstream accretion and upward growth. Channels between braid bars were shallower and intertidally exposed and many side-attached bars were vegetated and incorporated into the floodplain (Fig.3.5.D). Mangroves had colonised some braid bars and the margins of side-attached bars in the lower river-mouth but had not extended their distribution in the lagoon (Fig.3.6D). The latter may have been due to an impervious bridge which was built across the tidal creek and reduced seawater flow to the mangroves (Berjak *et al.*, 1977; Begg, 1978). The upstream end of the central island was densely vegetated with stands of trees. North of the groyne, the coast had retreated. The old Athlone Bridge was being replaced by the new Athlone Bridge adjacent to it.

In 1973 vegetation cover extended across the central island and more braid bars were attached to the island margins as the intervening channels shallowed (Fig.3.5E). Mangroves were present on the lower reaches of the island. Small washover fans were present on the barrier and at the river mouth had caused an increase in barrier width. The inlet was located against the groyne and a flood-tidal delta was present in the river-mouth. The coast-parallel lagoon was reduced to a narrow tidal channel with a mangrove swamp in the upper reaches and salt marsh in the lower reaches (Fig.3.6E).

By 1983 the remaining braid bars in the river-mouth had all become side- or island-attached. The island was completely vegetated by terrestrial vegetation including large trees in the upper reaches (Fig.3.5F). In the lower reaches mangroves formed a fringe around the margin and had colonised former channels. Mangroves were also present along the lower margins of the tidal creek (Fig.3.6F) and had spread through the lower reaches of the river-mouth. A well-defined flood-tidal delta was present in the river-mouth. The barrier had retreated further landward and a small washover fan was deposited north of the inlet.

In July 1985 (Fig.3.6H) the barrier had retreated further landward and impinged on the flood-tidal delta. A large washover fan was deposited in the mangroves infilling part of the mangrove swamp channel system (Cooper & Mason, 1987) adjacent to an area of the barrier beach which had eroded markedly. The flood-tidal delta was smaller than in 1983 but was still distinct, despite floods associated with tropical cyclone Demoina in February 1984. The island had changed little since 1983.

Morphological changes up to 1986 led to the geomorphological conditions under which previous work on the river-mouth was undertaken (Cooper 1986a, 1988a; Cooper & Mason 1986, 1987; Cooper & McMillan, 1987). It had changed little in the preceding 10 years and was apparently stable and in a mature stage of development. The river-mouth morphology and sedimentary framework at that time are briefly described below.

3.3.2. 1986 River-mouth morphology

In its upper 700 m, the river-mouth comprised a narrow, laterally restricted, channel (average width 60 m) confined between prominent bedrock outcrops. In the lower 1.8 km, however, the right bank was bounded by a broad alluvial plain into which the 400 m-wide channel was incised. A central vegetated island, with a mean elevation of 2 m above MSL, caused the channel to bifurcate. The channels recombined in the back-barrier area before reaching a narrow tidal inlet, typically located against the artificial rocky groyne. Beachwood Creek tidal channel drained a low-lying, mangrove swamp which occupied a coast-parallel area behind the beach barrier. Intertidal areas were restricted in extent.

Attenuation of the open coast tide by the constricted inlet, produced a mean tidal range of 1.4 m in the river-mouth, making it microtidal. Tidal salinity changes extended 2.5 km upstream from the mouth and a salt wedge developed in the channel at high tide. Upward mixing of the salinity intrusion by wave action was limited as the long axis of the river-mouth is orientated perpendicular to the predominant wind direction and vegetation afforded protection from the wind. Ocean waves were prevented from entering the river-mouth by the river-mouth barrier.

Sediment distribution in 1985-86 was discussed fully by Cooper (1986a,b) and only a synopsis is given below. River-mouth sediments consisted mainly of fluvially-derived gravel and mud (Fig.3.7). Marine sand, recognised by foraminiferal distributions (Cooper & McMillan, 1987) and textural characteristics (Cooper, 1986a), was deposited in the lower 200 m of the river-mouth by flood-tidal currents and barrier overwash.

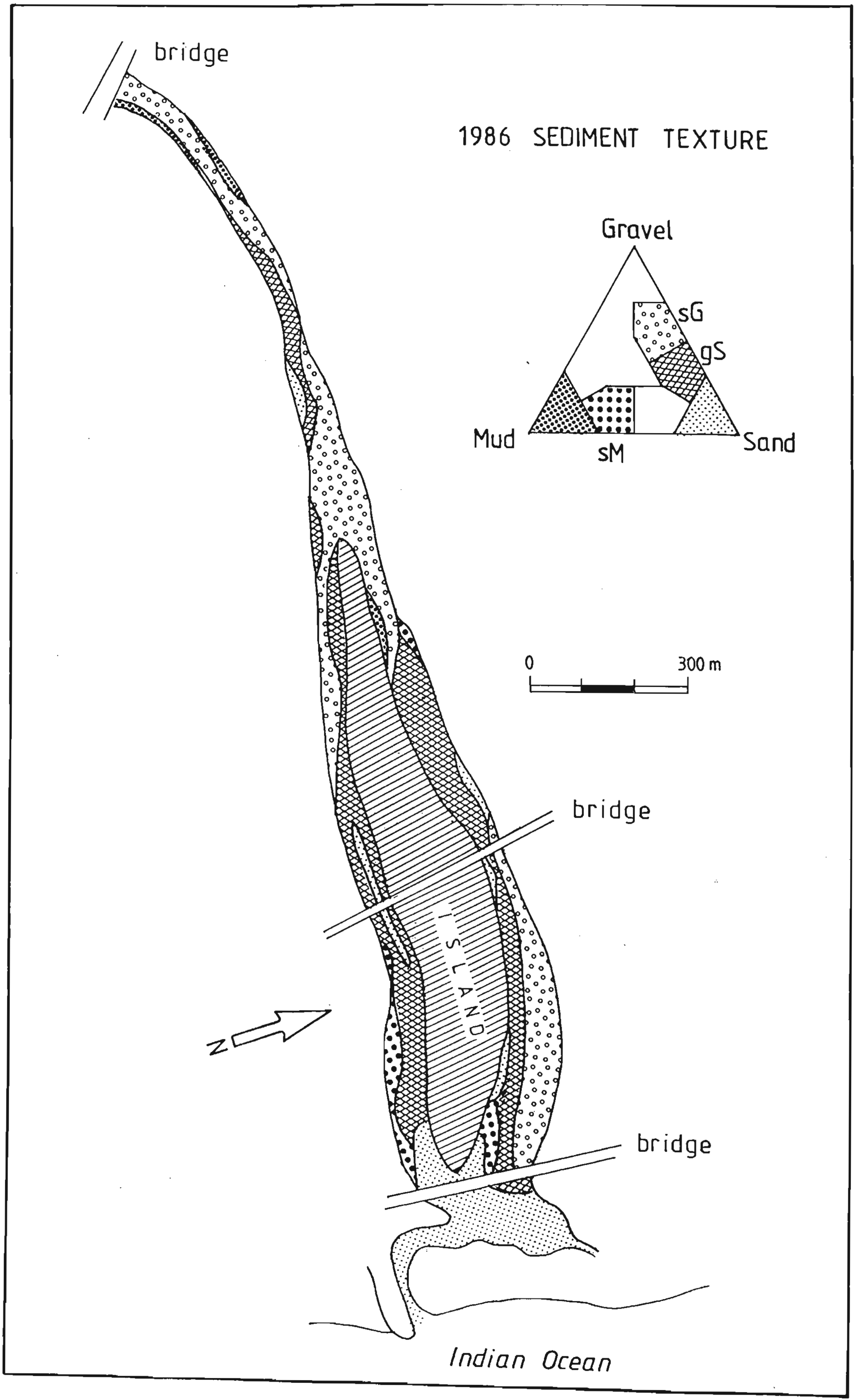


Figure 3.7. Sediment texture in the river-mouth during 1986 Note the abundance of gravel in channel sediments.

Gravel (>2 mm) comprised over 30% of the bottom sediment through most of the river-mouth: sourced from deeply weathered, megacrystic granite gneiss some 30 km upstream. The high gravel content precluded formation of small-scale bedforms but side-attached braid bars were present, particularly in the north channel of the river-mouth.

The channel sediments generally contained less than 10% mud (Fig.3.7). Maximum concentrations of over 50% occurred on small sections of the channel margins where flow velocities were at a minimum. In some areas mud was trapped by algal-coated pencil roots (pneumatophores) of mangroves (Bird, 1986). Even a low mud content adds cohesion to estuarine sediments making them more resistant to erosion under normal flow conditions (Terwindt *et al.*, 1968). Thus much of the bed could be considered moderately erosion-resistant. Mud deposited on the bed was mixed with other grainsizes largely by the burrowing activity of the infauna (Cooper, 1986a).

High concentrations (> 80%) of poorly cohesive, marine sand in the lower 200 m enabled formation of large and small-scale bedforms in the lower river-mouth (Cooper, 1988a). Variations in the volume of the flood-tidal delta revealed by aerial photography indicate that this sediment is more susceptible to erosion by seasonal, low-discharge floods than cohesive sediment upstream.

Depositional environments and sedimentary facies of the 1986, stable river-mouth phase were divided into barrier-associated and back-barrier groups (Cooper, 1986a, 1988a). The barrier-associated facies were similar to those reported for wave-dominated microtidal coasts except that the inlet does not migrate or dominate the barrier stratigraphic sequence as in other areas (Kumar & Sanders, 1975; Reddering, 1987). Barrier stratigraphy is instead dominated by overwash lamination (Cooper & Mason, 1986). The flood tidal delta contained typical current-formed sedimentary structures. Ebb-tidal deltas are rare and small.

Back-barrier depositional environments comprised subtidal channels, intertidal bars, lagoon, several tidal creek subenvironments, mangrove fringe and supratidal mudflats. The subtidal channels and intertidal bars were dominated by coarse sand and gravel, of riverine origin and, but for the presence of reversing bedforms due to tidal flow, closely resemble fluvial channel deposits.

3.3.3. Discussion: Long-term geomorphological changes in the Mgeni river-mouth

The changes in river-mouth morphology documented above may be divided into three categories: river-mouth channel changes, barrier/lagoon changes and groyne-induced beach erosion. Each of these is discussed in this section.

3.3.3.1. River-mouth channel changes. In the period 1931-1986, the Mgeni was transformed from a wide and shallow, braided river-mouth to one with two well-defined anastomosing channels with a vegetated central island (Fig3.5A-F). The change occurred through coalescence and emergence of braid bars and the incorporation of side-attached bars into the bank. Essential conditions for braiding are (i) high sediment transport and (ii) low threshold of bank erosion (Reineck & Singh, 1973, p. 228). In the Mgeni the banks are normally vegetated or muddy and thus unsuitable for braiding. Erodible sandy banks are produced after major floods which erode the channel margins and deposit sandy overbank sediments which are reworked by wave swash, thus producing sandy margins. Channels formed in areas where the bank material is non-cohesive sand or gravel have little chance of stabilising due to continual slumping of the banks and consequently a braided channel develops (Leopold & Wolman, 1957). The subtropical climate of coastal Natal promotes rapid vegetation growth and after floods, vegetation is re-established on the banks. This, combined with overbank and intertidal mud deposition, stabilises the banks thus removing one of the 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 can then be colonised by terrestrial vegetation. Thereafter they are inundated only during high river stages when 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 of the flanking channels is enabled by the now cohesive muddy and partly vegetated banks of the river and of the central island.

One of the most important factors in channel stability is the composition of the channel banks (Leopold *et al.*, 1964 p 201; Gregory, 1977; Lewin, 1977). Rivers and estuaries which flow through cohesive muddy material tend to have laterally restricted channels in which flow is confined to a narrow cross-section: consequently channels are comparatively deep (Reddering, 1988a). Channel margin stability is also enhanced by vegetation, the roots of which bind the sediment and give it increased cohesion. Many engineered responses to stream and river-mouth bank erosion involve artificial planting of vegetation to reduce wave action and impart cohesion to the banks (Knutson & Woodhouse, 1983; Webb & Dodd, 1976; Woodhouse et al., 1976). In one application, Nevins (1969) described the conversion of a braided, shingle channel in a New Zealand river to a meandering channel by planting willows at appropriate bends. Smith (1976) found that stream bank sediment in which vegetation roots comprised 16-18% of the volume and formed a 5 cm root mat, had 20 000 times more resistance to erosion than comparable banks which lacked vegetation. Leopold *et al.* (1964, p 202) state "As the threshold of erosion of the bank material increases, whether by addition of coarse or cohesive sediments, or by the presence of vegetation or bedrock, with no change in bed material or discharge, the channel will be narrower." Thus the Mgeni channels narrowed.

Formation of two channels rather than a single one may be attributed to the rocky northern bank and the early stabilisation of the southern bank against which scour occurred thus concentrating flow at the channel margins. Flume studies of the formation of a central island in a braided channel (Leopold *et al.*, 1964) produced similar results to channel evolution processes observed in the Mgeni (Fig.3.8), although in the flume study only coarse grainsizes were used. Additional stabilisation of banks by muddy sediment enhanced the formation of the island in the Mgeni.

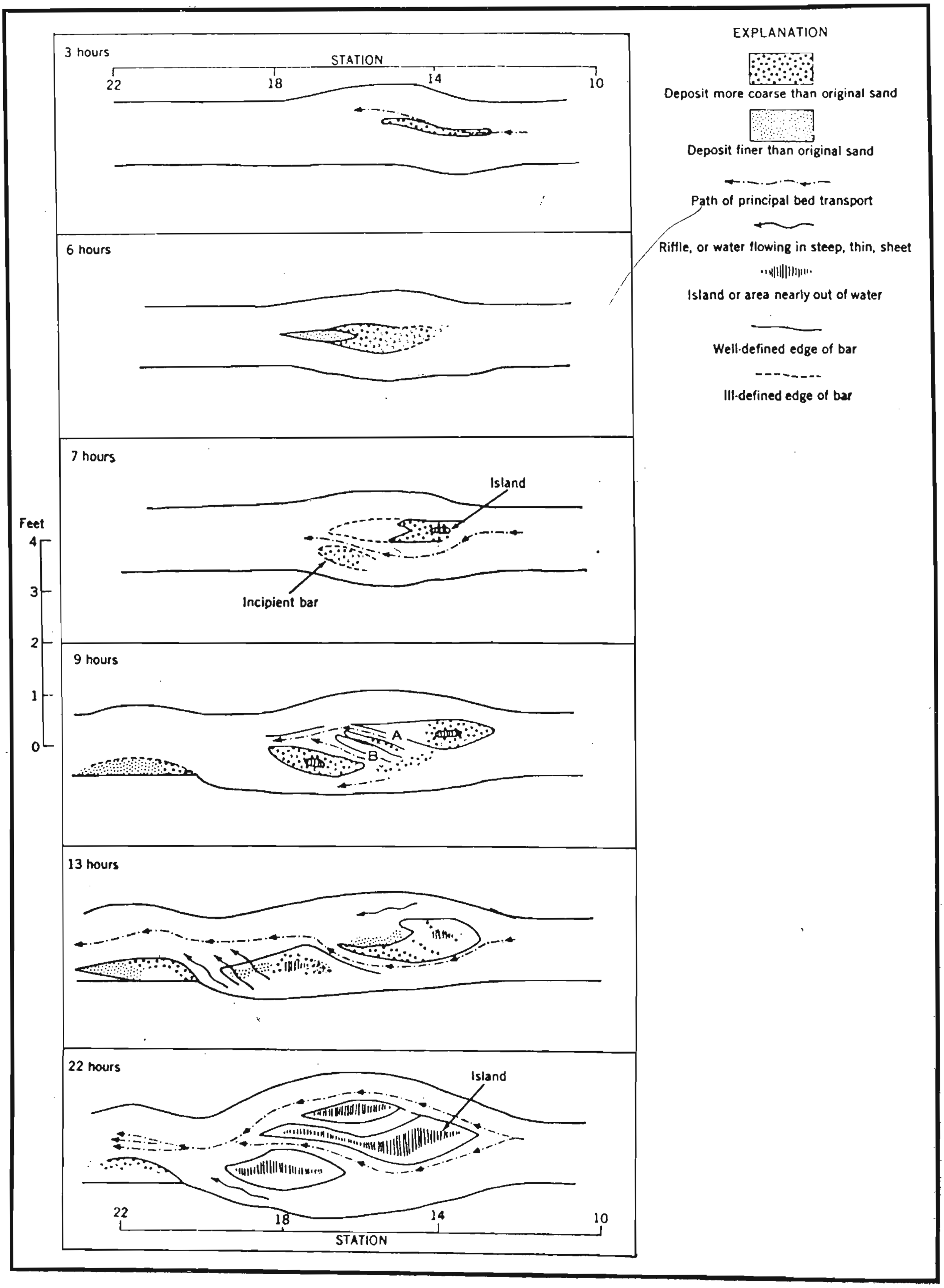


Figure 3.8. Formation of a central island under flume conditions in a braided stream (after Leopold *et al.*, 1964.)

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

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 river-mouth. Planktonic foraminifera carried into the river-mouth (Cooper & McMillan, 1987) also indicated that fine-grained marine sediment was entering the river-mouth in suspension on the flood tide. An increased tidal prism probably also led to a more permanent inlet, although a lack of information on mouth condition prior to the 1980s prevents confirmation of this. The flood-tidal delta material was evidently eroded from the seaward margin of the barrier and transported through the inlet as barrier erosion progressed.

3.3.3.2. Lagoon evolution. During the 60 year period under review, the back-barrier lagoon north of the tidal inlet changed from a shallow, muddy lagoon with unvegetated intertidal mudflats to a high intertidal mangrove swamp and supratidal salt marsh drained by a narrow channel (Fig.3.6A-H). Much of this was accomplished in the period 1937-1959. By comparison with recent observations, mud deposition in the area occurs 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 would have been required to raise it to a supratidal level. Wright (1990) and Wright & Mason (1990) attributed a rise in bed level in a similar environment in the St Lucia Estuary in Zululand, to the same process. After 1959, evolution proceeded with mangrove colonisation of the now elevated muddy areas. This eventually extended into the lower reaches of the channel. Areas higher than the mangrove swamp support a sparse salt marsh vegetation dominated by halophytic succulents and algae.

The groyne at the mouth may have played a role in this decrease lagoonal area through preventing inlet migration and periodic river scour along the lagoon, however, in 1937 the lagoon was very shallow and the groyne may simply have accelerated a natural process.

3.3.3.3. Barrier retreat. A major feature of the long-term development of the Mgeni river-mouth area is the progressive erosion of the barrier north of the inlet (Fig.3.6H). Erosion was concentrated in the 1200m 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 stabilised. 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 which deposited sand in the back-barrier mangrove swamp and filled a former channel (Cooper & Mason, 1986). This overwash was generated by extreme wave action, and because of the narrowed beach, was able to cross the barrier. Forebeach erosion exposed lagoonal muds on the forehore at that time.

The fact that erosion is restricted mainly to the 1200 m north of the groyne is direct evidence that the groyne is the cause of it. The changes therefore reflect an adjustment of the equilibrium planform to a new wave regime which approximates a swash equilibrium. Only minor changes after 1973 suggest that the beach had reached a new equilibrium by that time. Progressive dune growth accompanying erosion, suggests that it was wind action rather than longshore drift which removed beach sand. As this was not replaced continually the beach narrowed and changed its planform. The fact that erosion was comparatively slow in relation to the high littoral drift rates (1.6 x 10^6m^3 per year) calculated by Swart (1987), sugests 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) tends to suggest that the beach was adjusted to an equilibrium and that groyne construction caused only a minor local change in shape.

Swart (1987) linked erosion north of the Mgeni inlet to major changes in the Durban Bight resulting from harbour breakwater extension and groyne construction. These produced a sediment deficit in the area. The deficit did not persist northward due to intersection of a shallow nearshore sediment pathway with the coast some 500 m north of the groyne. This met the calculated demand for longshore sediment supply. Such longshore transport need not necessarily operate in the Durban Bight, particularly as sediment supply is highly episodic. Cooper (1991a) proposed that as the area had a gently curved planform in pre-harbour breakwater times, it was probably in equilibrium with approaching wave fronts. The groyne at the Mgeni mouth disrupted this equilibrium and erosion resulted from the realignment of dominant wave fronts. In this interpretation, the interruption of the incident wave field only extended to about 1000 m north of the mouth and hence the adjacent beaches were unaffected. The resulting planform is similar to the zeta bays which form on the northern side of rock outcrops elsewhere on the Natal coast. Problems with Swart's (1987) interpretation stem mainly from the lack of evidence for current-driven bedforms in the area interpreted as the underwater sediment pathway across the Durban Bight. Additionally, Swart used deep sea wave data from voluntary observing ships to construct wave refraction diagrams for the Durban area. These may not give a true reflection of the nearshore waves which could be refracted so that they always assume a coast-parallel orientation, and produce an equilibrium planform.

This updrift erosion also affected the inlet stability by inducing a change in the nature of the beach plan equilibrium from an essentially drift equilibrium to swash equilibrium (Carter, 1988). As this happens the inlet position is altered. When the beach is wide, littoral drift bypasses the end of the groyne and the position of the inlet is variable as illustrated by the photographs of 1931 and 1937. However, as the coast retreats, the groyne begins to jut into the incident wave field. Wave refraction then causes the inlet to locate against the groyne as reported in other areas by Bascom (1954).

3.4. THE EFFECT OF FLUVIAL FLOODS

3.4.1. Intoduction

The morphology of river channels and floodplains are greatly affected by high discharge (Leopold *et al.*, 1964). Floods might therefore be expected to produce marked geomorphological changes in small river-mouth areas fed by large rivers, particularly if the channel is laterally restricted. Due to their infrequent occurrence, the impacts of major floods on rivers and estuaries are poorly documented and an understanding is still lacking of the role of such floods in long-term sedimentation and their preservation in the stratigraphic record. This will vary according to environmental setting. Events during September 1987 offered the opportunity to study the effects of a high magnitude flood, with a calculated 120 year recurrence interval, on the Mgeni river-mouth. In this section the impacts of the flood are assessed and in the following section the post-flood recovery is documented. Section 3.6. attempts to place flood-associated changes in their historical perspective in terms of sedimentation in the river-mouth.

3.4.2. Flood rainfall and discharge

Natal's annual rainfall exceeds 1000 mm (Tyson, 1987) and periodically, extremely high rainfall during a few days may lead to widespread flooding. Such was the case in September 1987. On 25th September 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 unstable baroclinic systems which slope to the west over South Africa, with increasing height (Stranz & Taljaard, 1965). They are associated with strong convergence and are responsible for many of the flood-producing rains over South Africa (Taljaard, 1982).

The following day (26th September) heavy rain began to fall over Natal. This persisted for 5 days during which up to 800 mm of rain fell (Fig. 3.9). The flood peak occurred at about midnight on the 28th of September (Kovacs, 1988).

During the associated floods, water level in the Mgeni river-mouth 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. Seawater was flushed from the river-mouth and a plume of highly turbid river water extended over 2 km into the Indian Ocean. Suspended sediment concentrations measured 3km upstream from the mouth, reached 5698 mgl^{-1}, compared with a mean concentration of 165 mgl^{-1} under average flow conditions (Brand *et al.*, 1967).

Steep river gradient caused the surface runoff to be transported rapidly to the sea. Surface current velocities of 6 to 7 ms^{-1} were recorded about four hours before the estimated peak by timing floating objects over a fixed distance at the Ellis Brown Bridge.

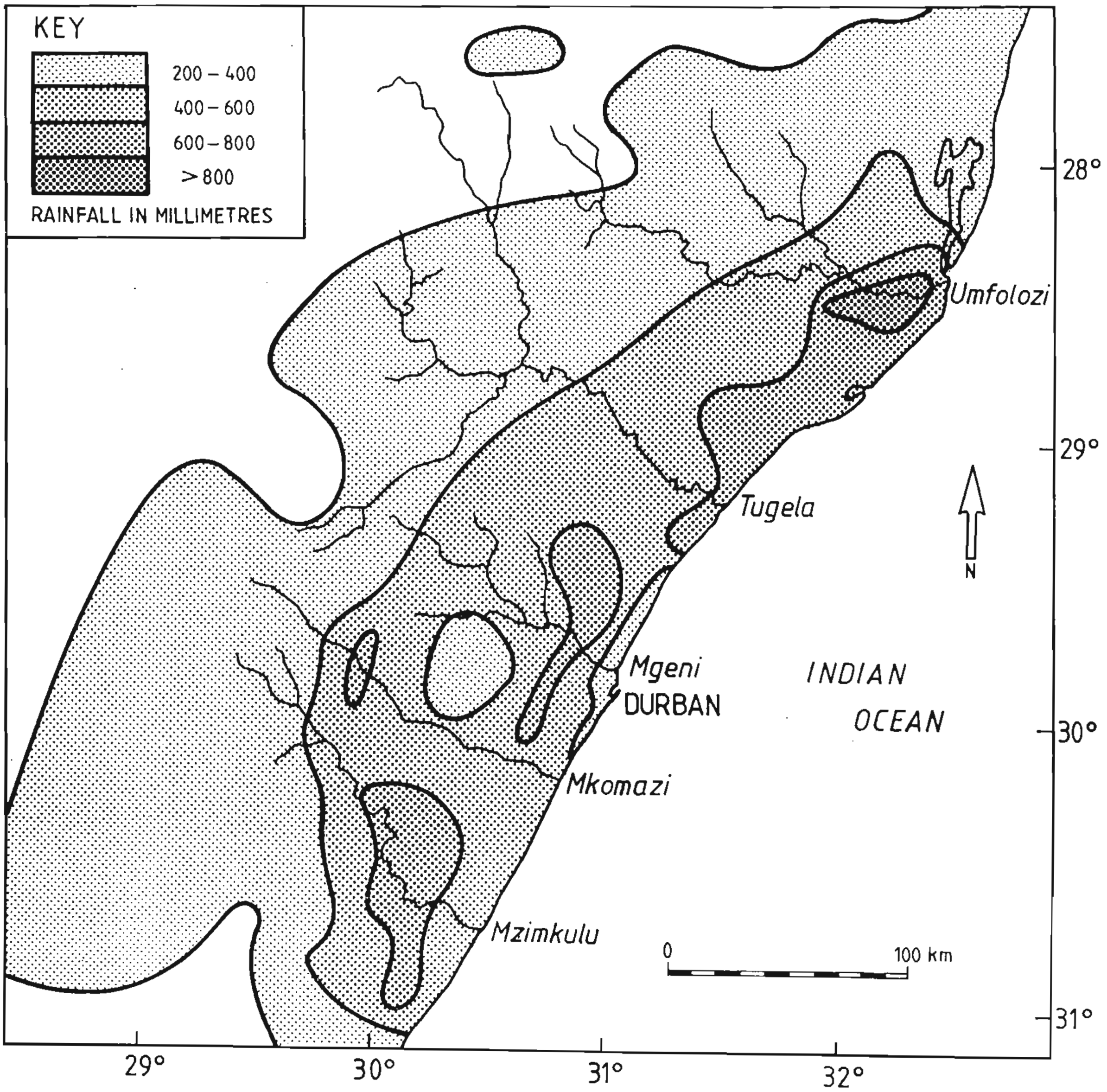


Figure 3.9. Flood-producing rainfall of September 20-25th 1987 over Natal (after Kovacs, 1988).

There are no accurate records of the flood peak as all guaging stations were destroyed. Kovacs (1988) estimated peak discharges at three points upstream but not in the river-mouth itself. Ouryvaev & Lukashenko (1969) demonstrated that an estimate of flood discharge may be made using the cross-sectional area and the estimated surface flow velocity. Application of this method using an estimated velocity of 6.5 ms^{-1} and a surveyed cross-section (Section number 2 (see following section), with a water level of +5 m MSL (2642 m^3) yielded a value of approximately 17 000 m^3s^{-1}. Ouryvaev & Lukashenko (1969) found that the mean velocity was between 0.6 and 1.0 times the surface velocity in flooding rivers. In the Mgeni where the width was relatively large in relation to the flow depth, bed friction is likely to be high and thus the calculated discharge was multiplied by 0.6. This figure has been widely used in South African rivers in engineering design projects (Huizinga, personal communication, 1988). This yields a corrected figure of approximately 10 000 m^3s^{-1} for the peak flood discharge. The potential error due to bed friction is 10-15 % (Ouryvaev & Lukashenko,1969) so the peak discharge may lie between 9000 and 11 000 m^3s^{-1}. The figure is considerably larger than the 5000 m^3s^{-1} discharge calculated for Inanda, 30 km upstream (Kovacs, 1988), but may be attributed to high rainfall and high incidence of impervious surfaces in the urbanised area between Inanda and the coast.

Considering all potential sources of error in the calculation together with the possibility of non-coincidence of the flood peak with maximum bed erosion, the impression gained is that the September 1987 flood of the Mgeni river-mouth was the largest yet recorded. The previous highest recorded discharge (5700 m^3s^{-1} recorded in the river-mouth) was in October 1917. Smith (personal communication, 1990) has recently calculated an ancient flood peak in the Mgeni of 28 000 m^3s^{-1} using palaeoflood hydrology in the Valley of a Thousand Hills. This predated the documented 1856 flood (Barnes, 1984), but because of probable climatic changes during the Holocene such a high discharge may not be attainable under current climatic conditions.

3.4.3. Morphological changes

During the 1987 flood the normally constricted outlet was enlarged by complete erosion of the river-mouth barrier. A plume of turbid water entered the sea and hundreds of tonnes of transported plant debris, including large trees, were thrown onto the adjacent beaches by wave action.

The vegetated island in midstream, together with sections of the bank, particularly on the south side, was completely eroded by the flood. 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.3.10). Although some fine-grained sand had been deposited in the upper reaches, coring revealed a maximum thickness of 4-5 centimetres. Thus the surveyed sections give an indication of the post-flood erosion base of the river-mouth. Comparison of the survey results with channel cross-sections surveyed in 1984 allowed the volume of sediment eroded from the river-mouth to be calculated (Cooper *et al.*, 1990). Aerial photography and field observations showed that in early September 1987 the morphology of the river-mouth had changed little since the 1984 sections were surveyed. They may therefore be considered representative of the pre-flood morphology of the river-mouth.

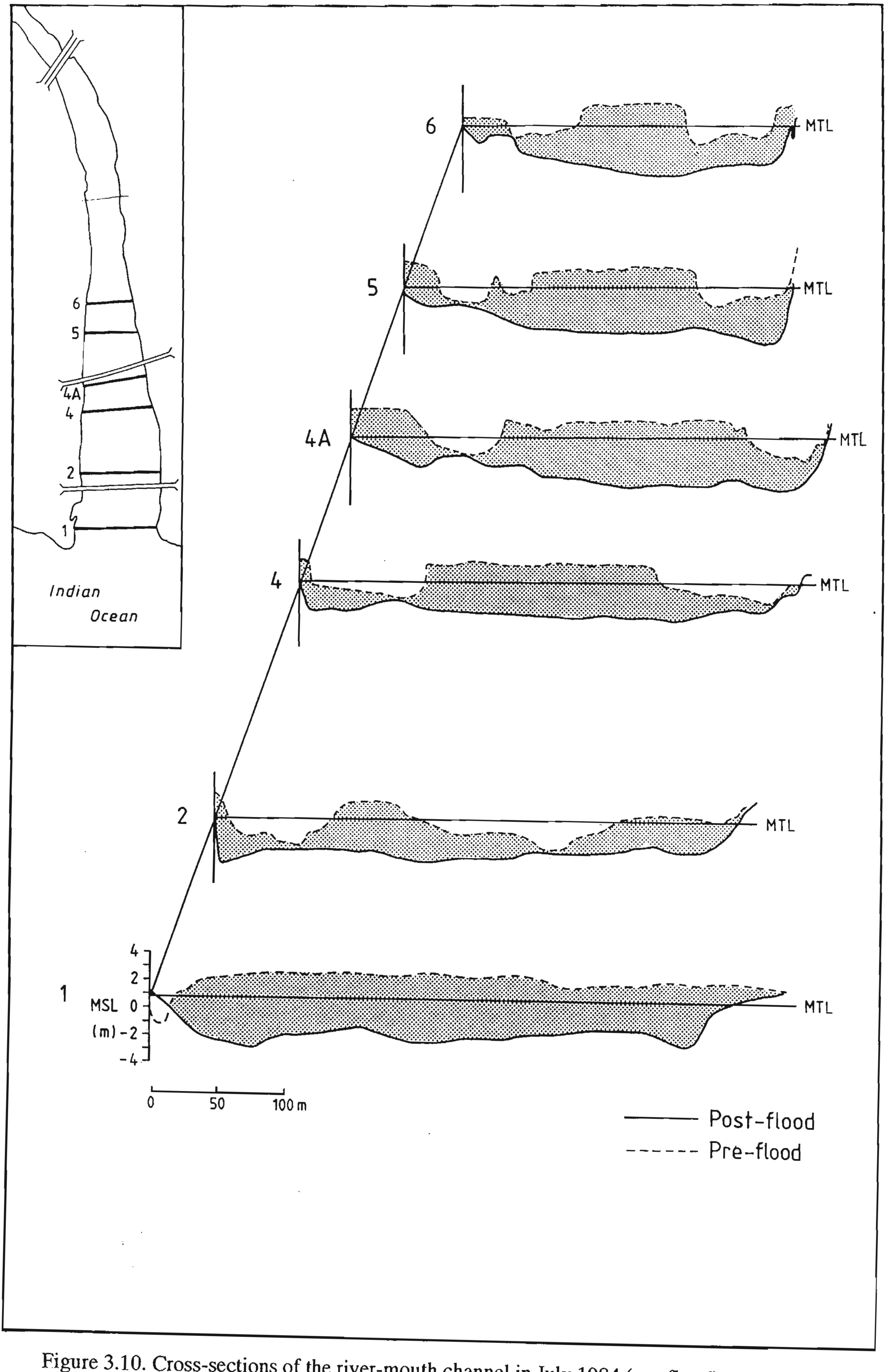


Figure 3.10. Cross-sections of the river-mouth channel in July 1984 (pre-flood) and October 1987 (post-flood), illustrating the volume of sediment eroded during the flood. Positions of transects shown in inset. MTL = Mid Tide Level. (continued overleaf)

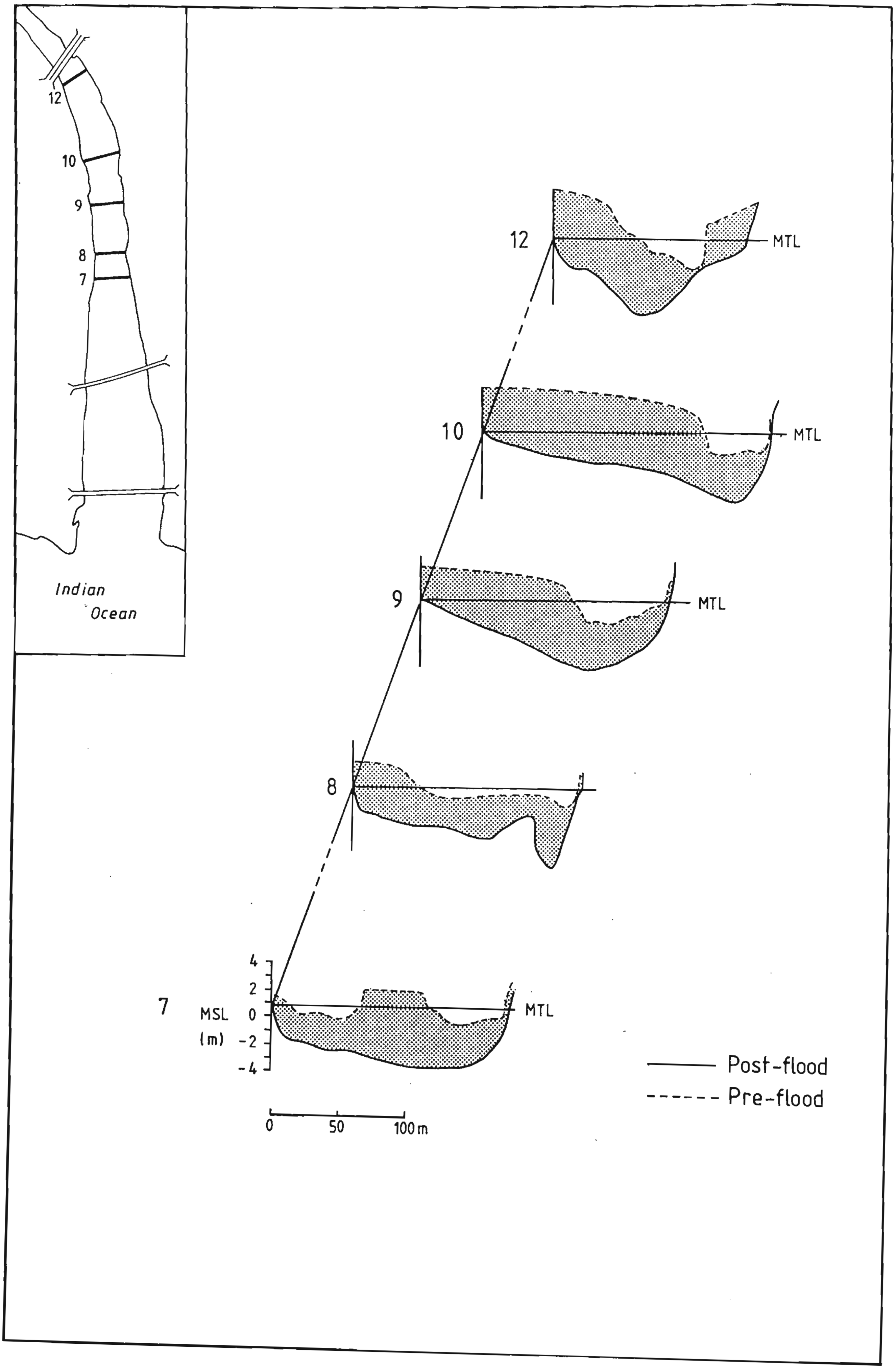


Figure 3.10 (continued). Cross-sections of the river-mouth channel in July 1984 (pre-flood) and October 1987 (post-flood), illustrating the volume of sediment eroded during the flood. Positions of transects shown in inset.

The data from both surveys were processed using the computer programs X-AREA2 and ESTVOL (Reddering, 1985) and the channel cross-sectional area, hydraulic radius and effective width were calculated for mean high tide level (HTL) and mean low tide level (LTL). The volume of sediment eroded from below HTL and LTL could therefore be calculated. The amount of supratidal sediment eroded was calculated by multiplying the difference in surface water area before and after the flood by the mean elevation of the island and banks above HTL.

The post-flood channel cross-sections are superimposed on the pre-flood sections in Figure 3.10. Channel dimensions calculated from these cross-sections are shown in Table 3.1 and the calculated volume changes are shown in Table 3.2.

During the flood a funnel-shaped channel was produced (Fig.3.11A) with near-constant downstream increase in cross-sectional area, produced by widening and deepening of the channel. Erosion of the bed led to an increase in mean depth at high tide from 1.18 m to 2.95 m. Channel width increased by erosion of the south bank in the upper reaches, the island in the middle reaches and the north bank and river-mouth barrier in the lower reaches. Maximum depth increase coincided with minimum increase in width just upstream of the former island.

The flood channel widened and shallowed seaward because erosion of the central island effectively spread the erosive power of the flood over a wider area, thus increasing bed shear stress. The deepest part of the flood channel was adjacent to the north bank in the upper reaches where scouring was enhanced by the presence of rock outcrops. In this area maximum depths of 6.5 m below MSL were recorded. Downstream, the thalweg split, forming two less prominent channels. The outlet could not accommodate the flood discharge and consequently the river-mouth barrier and part of the mangrove swamp were eroded.

A total volume of 1.8 x 10^6 m^3 of sediment was eroded from the river-mouth (Table 3.2). Of this, 309 x 10^3 m^3 (17%) was from areas above HTL (supratidal). The remaining 1.5 x 10^6 m^3 represents the increase in volume of the river-mouth due to the erosion of sediment from below HTL. The increase in subtidal volume (below LTL) was 1.28 x 10^6 m^3. An increase of approximately 271 x 10^3 m^3 (15% of the total volume increase) in intertidal volume (tidal prism), established a post-flood tidal prism of 425 x 10^3 m^3 (Table 3.2).

3.4.4. Sediment distribution

Sampling of the channel bed was accomplished by diving 8 days after the flood peak. The channel base comprised poorly sorted, coarse sand and gravelly sand (Fig.3.12), and local bedrock outcrops. All mud had been eroded from the river-mouth 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. Flow velocities were still high (1-2 ms^{-1}) and freshwater extended to the outlet.

Section number	X-area HTL (m^2)	X-area LTL (m^2)	Volume HTL ($\times 10^3$ m^3)	Volume LTL ($\times 10^3$ m^3)	Volume Intertidal ($\times 10^3$ m^3)
1984					
1	18·1	13·2			
2	310·8	160·5	32·3	17·6	14·7
4	243·0	105·1	88·4	42·2	46·2
4A	162·2	79·9	38·6	17·7	20·9
5	165·0	70·4	32·7	15·0	17·7
6	145·4	56·3	34·1	13·9	20·2
7	120·3	48·2	18·9	7·3	11·6
8	123·2	38·2	17·4	6·0	11·4
9	100·8	53·1	27·7	11·3	16·4
10	81·2	46·9	20·3	11·2	9·1
12	86·5	51·4	35·2	20·6	15·4
Total			345·6	162·8	182·8
1987					
1	1204·8	909·0			
2	1085·5	818·4	274·6	207·2	67·4
4	969·3	714·8	328·5	245·1	83·4
4A	1029·6	791·3	191·9	144·5	47·4
5	908·5	713·0	193·7	150·4	43·3
6	726·4	558·5	179·5	139·5	40·0
7	658·8	540·1	96·9	76·9	20·0
8	541·6	429·0	83·9	67·7	16·2
9	596·3	462·7	141·0	110·5	30·5
10	600·1	458·5	133·9	103·2	30·7
12	460·0	363·7	221·9	172·3	49·6
Total 1987			1845·8	1417·3	428·5
Less 1984 volume			345·6	162·8	182·8
Volume increase			1500·2	1254·5	245·7

Table 3.1. Cross-section and volume data for 1984 and 1987. X-area is the cross-sectional area at high and low tide levels (HTL and LTL respectively). The volume of the estuary contained between successive sections are given for high and low tide levels and the intertidal volume in each section is calculated

	Volume increase (m^3)			
Section no.	Intertidal	Subtidal	Supratidal	Total
1				
2	52 629	189 615	61 095	303 339
4	37 138	202 941	44 365	284 444
4A	52 629	100 597	32 110	185 336
5	25 622	135 342	31 306	192 270
6	19 733	125 612	23 331	168 676
7	3 649	74 316	9 332	87 297
8	4 817	61 654	5 216	71 687
9	14 042	127 003	17 884	131 199
10	21 672	91 981	27 424	141 077
12	35 117	151 642	43 324	230 083
Total	271 128	1 281 523	309 306	1 861 957

Table 3.2. Cross-sectional data indicating the increase in volume of the estuary between various surveyed sections as a result of the flood

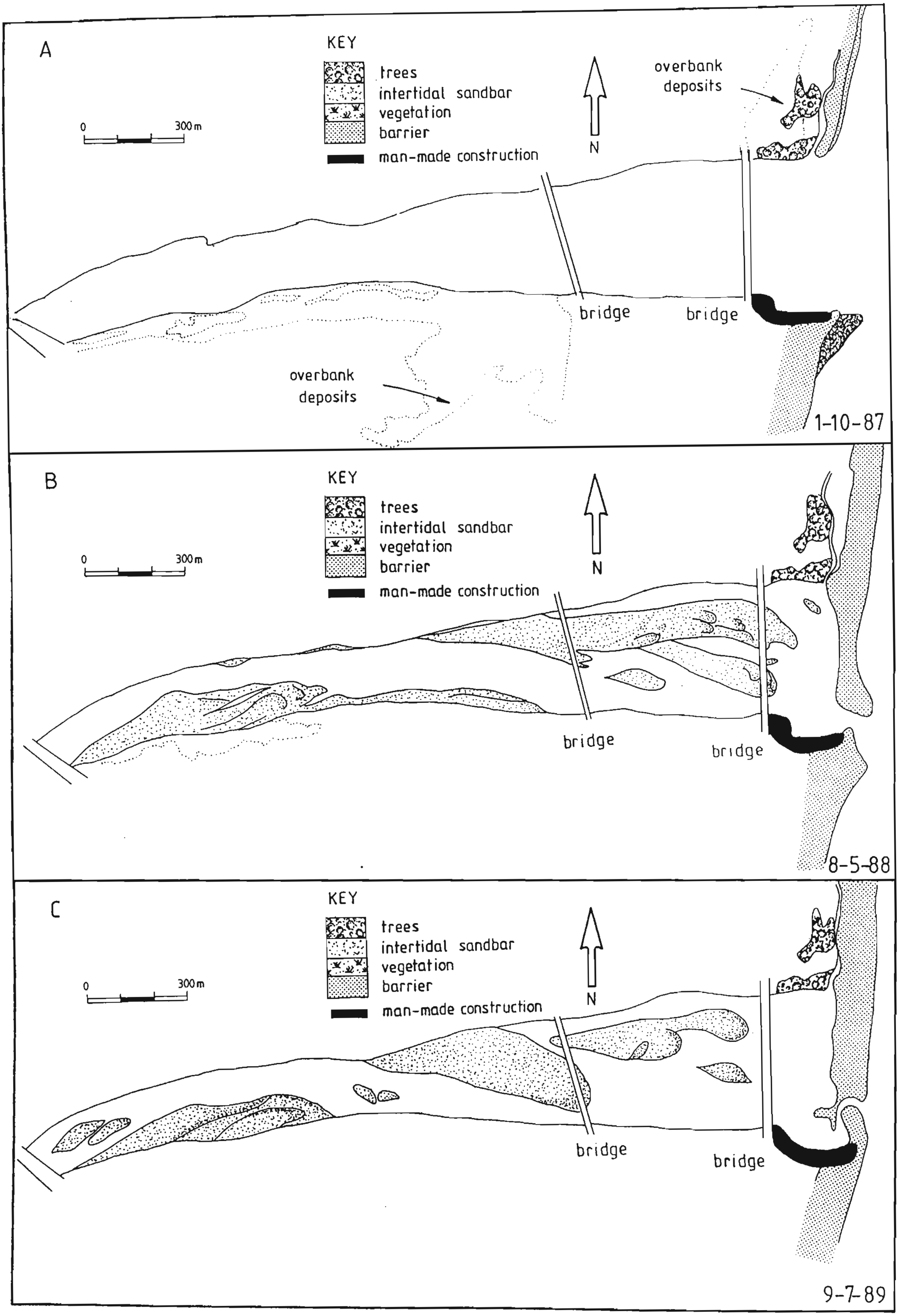


Figure 3.11.A-D. Post-flood changes in the river-mouth channel October 1987 to April 1990, illustrating post-flood recovery. (Continued overleaf).

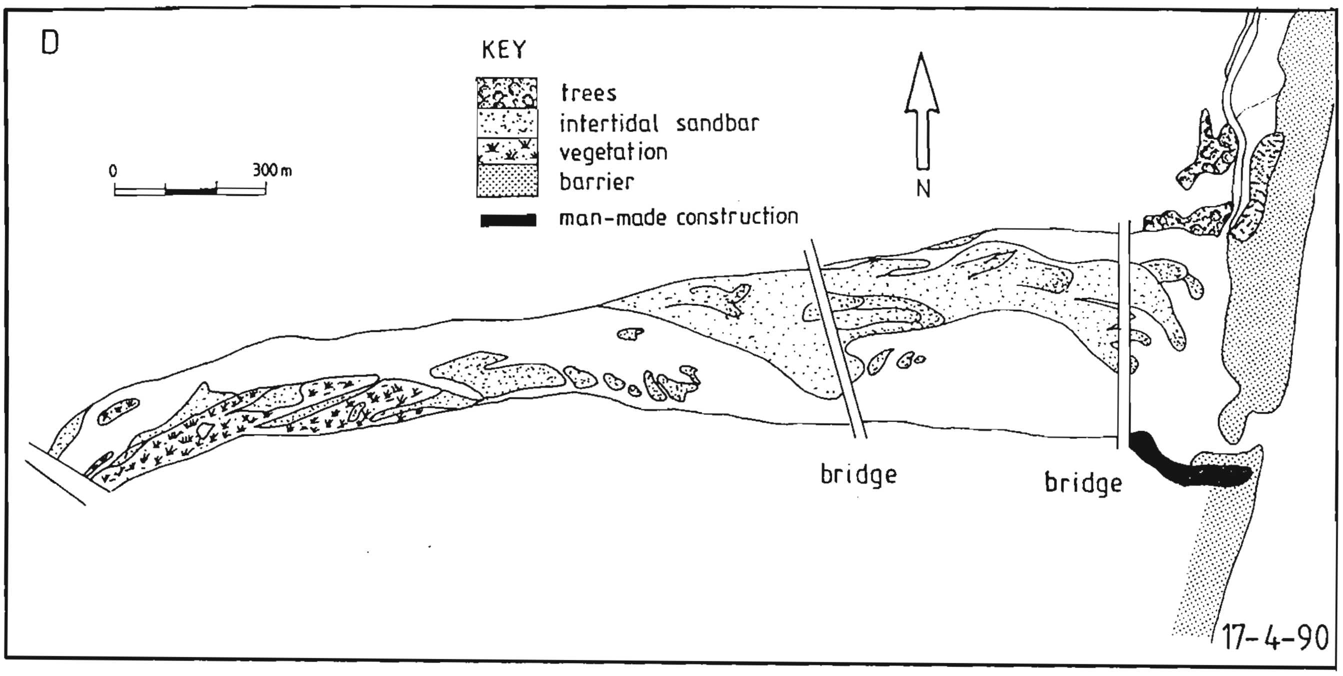


Figure 3.11.A-D (continued). Post-flood changes in the river-mouth channel October 1987 to April 1990, illustrating post-flood recovery.

The gravel content of the channel sediments was lower than under pre-flood conditions. Examination of the grainsize characteristics of the sand fraction showed that the lower reaches were dominated by coarse sand, the middle reaches by medium-grained sand and the upper reaches by fine sand. Around the Athlone Bridge, greatest variation was noted. In general the sediments were only moderately to moderately well sorted (Fig.3.12) In the upper reaches the fine sand was well sorted and sand of various grainsizes were well sorted at Athlone Bridge. Grainsize distributions were generally near-symmetrical. The upper channel sediments tended to be coarse-skewed and the lower reaches, fine-skewed. Skewness bore little relationship to other variables.

Overbank deposits (Fig 3.11A) consisted of either well-sorted fine 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 (Plate 3.2). Thinner mud deposits (<10 cm thick) filled depressions to the south of the river-mouth. Overbank deposits of fine, angular, well-sorted sand (mean grainsize 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 (Plate 3.3). Similar features were noted by Hiller & Stavrakis (1982) and Reddering & Esterhuysen (1987b) in overbank deposits.

3.4.5. Discussion: Flood scour

The pattern of flood-induced erosion in the river-mouth was controlled by the geomorphology of the system. Rock outcrops prevented erosion of the northern bank and enhanced downward scouring of the bed at cross-sections 9-12 (Fig.3.10). The gently dipping bedrock surface is close to surface in this area (see Fig.3.17) and consequently the semi-consolidated, muddy south bank was preferentially eroded. Downstream, at sections 7 and 8, bedrock occurs at greater depth and downcutting occurred. Consequently the banks were little eroded in that area. Downcutting was enhanced by high gravel concentrations in that area which were associated 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 topographic 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 river-mouth was facilitated by the non-cohesive nature of the barrier and flood-tidal delta. Reddering & Esterhuysen (1987a) ascribed maximum erosion near the mouths of flooding estuaries in the eastern Cape Province to this phenomenon.

Post-flood sediment distributions revealed areas of coarser sediment which may have indicated the main flow directions during the flood peak. All the grainsizes (excluding bedrock) were within the range of grainsizes 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 sand in the upper reaches. As erosion is controlled by both current velocity and the available 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.

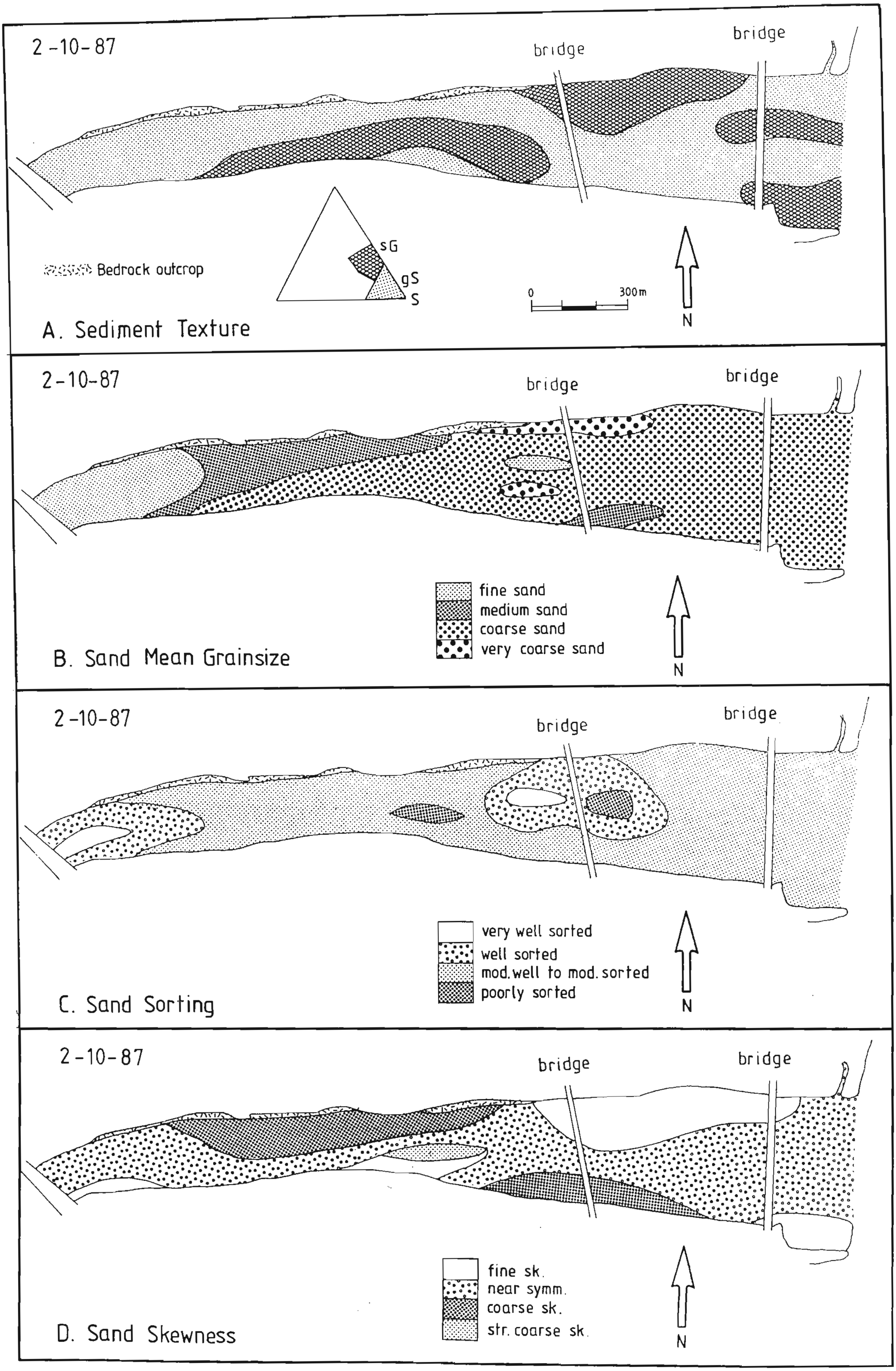


Figure 3.12. Post-flood sediment distribution (2/10/87). Showing: (A) sediment texture; (B) mean grainsize of the sand fraction; (C) sorting in the sand fraction; and (D) Skewness of sand grainsize distributions.

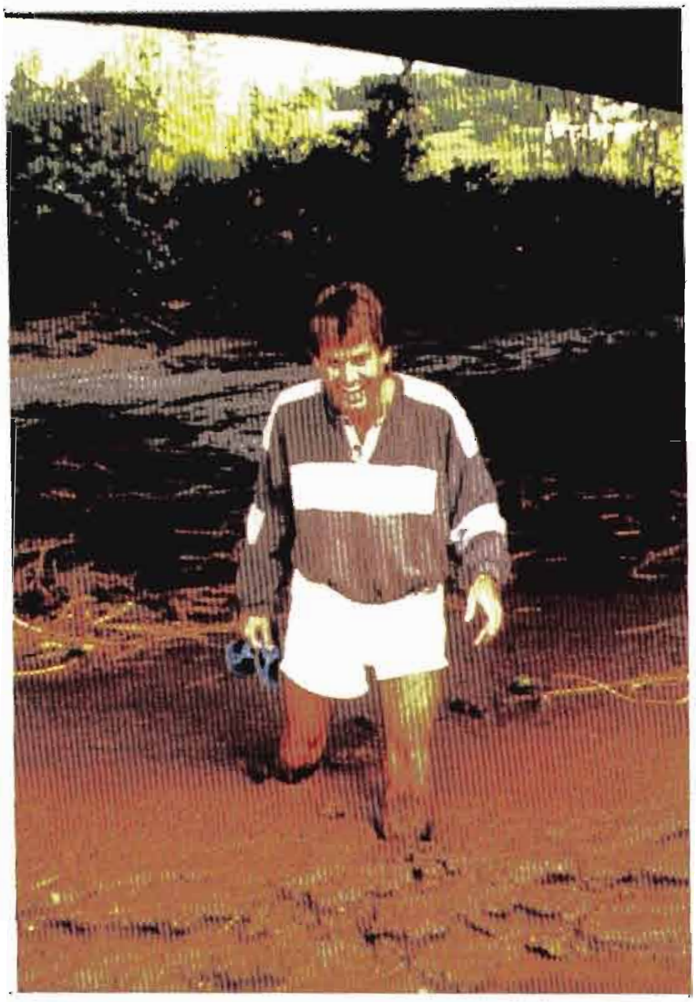


Plate 3.2. Thick layer of organic-rich mud deposited in overbank areas of the Beachwood mangrove swamp during the September 1987 flood.

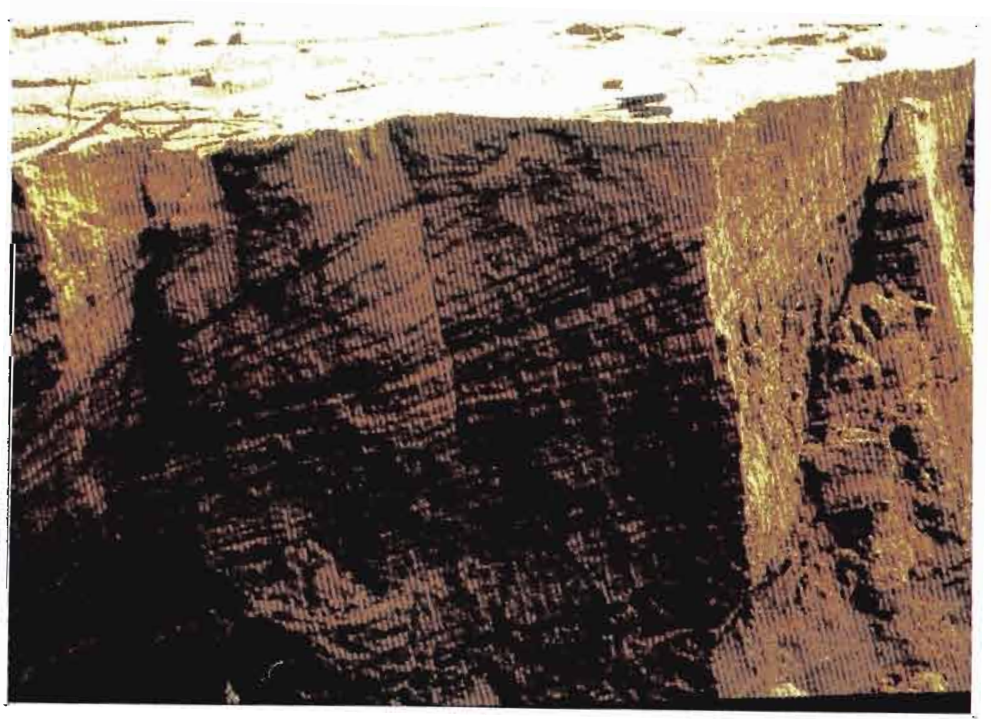


Plate 3.3. Upstream-dipping cross-bedding in overbank deposited fine sand adjacent to the coast-normal river-mouth channel. The bedding orientation suggests formation of eddy currents in the marginal channel areas during the flood. Car keys on top of bank for scale.

The complete erosion of all accumulated organic detritus, fine-grained fluvial sediments and marine sand from the river-mouth was evidenced by a lack of organic material, fine sediment and carbonate in post-flood sediments. The sediments sampled on October 6th were largely a lag deposit. During the flood stage all the bed was in motion and the sediments preserved after the flood are representative of material which stopped moving as the flow velocity dropped. Fine-grained sand in the upper reaches, however, was deposited from suspension during the waning stage. It is mainly confined to deep scour pits in the upper reaches.

3.5. POST-FLOOD RECOVERY

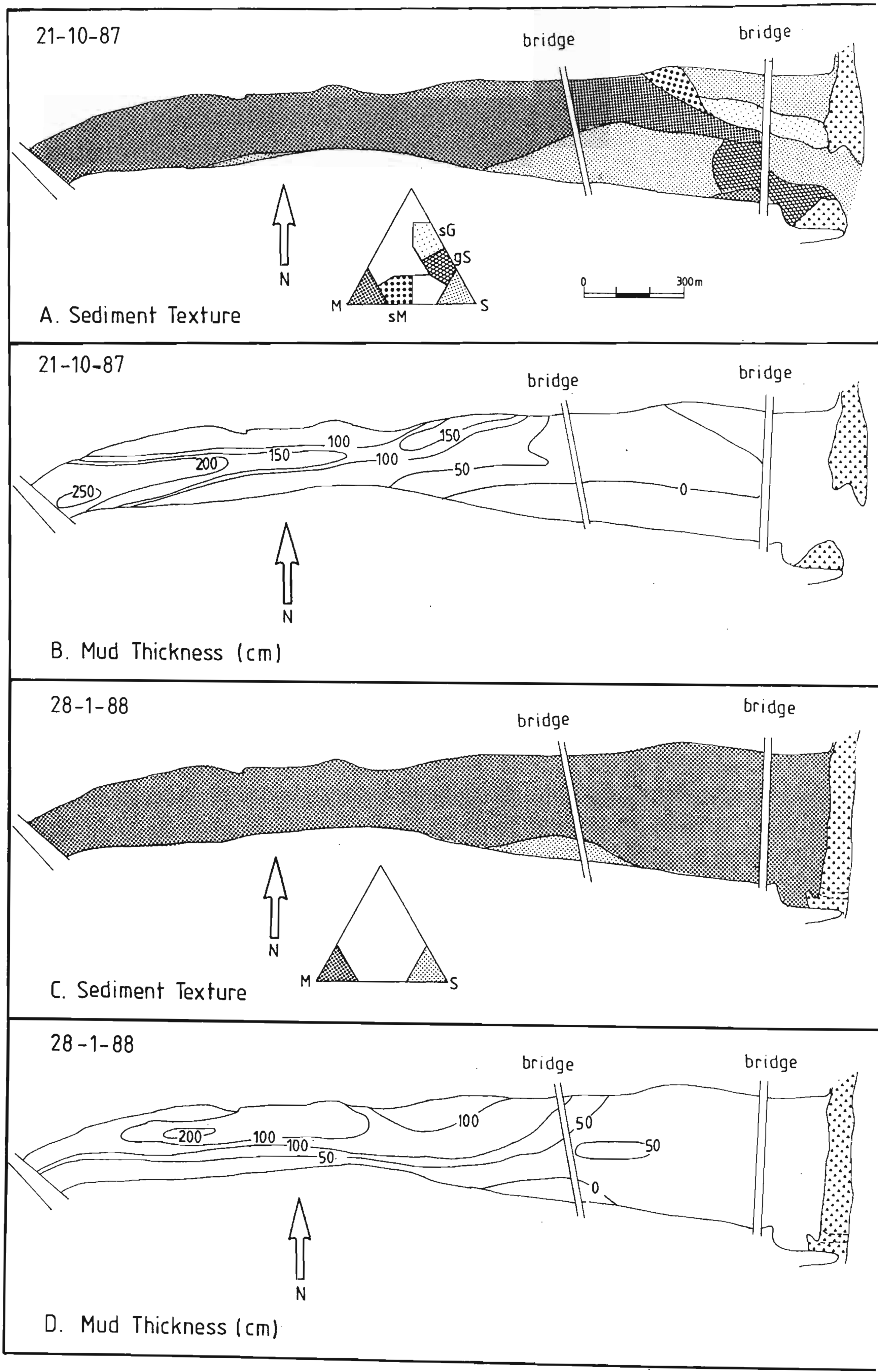
In order to assess the relative importance of the flood event, the river-mouth was visited on several occasions after the flood. Several post-flood aerial photographs were also examined. The situation on each occasion is described below.

3.5.1. Post-flood river-mouth changes

10/10/87. No barrier was present but slight shoaling was noted at the north side of the mouth. Sand was also accumulating adjacent to the groyne. Southeasterly waves were entering the river-mouth, eroding the northern bank near the mouth and a sandy beach was produced there. Beachwood Creek had been cut off by sand deposition. The river channel was dominated by gravelly sediment and no sampling was undertaken. Water in the river-mouth was fresh.

21/10/87. At this time the barrier was partly emergent. A small sand body (150m x 30m) had formed with its long axis nearly parallel to the coast. Wave approach was from the southeast, at a small angle to the coast. A second small sand body had formed in the southern margin of the channel, attached to the groyne. The larger of the two sand bodies was welded to the barrier remnant on the northern margin of the flood breach by the end of October. Small upstream-directed current ripples (wavelength 10 cm, amplitude 8 cm) were present in the river-mouth opposite the inlet. Most of the river-mouth bed was covered in a layer of soft, organic-rich mud, except in the lower reaches where the bed remained sandy (Fig.3.13A). The thickness of mud was measured by pushing a rod through the soft mud until resistance was encountered from the underlying gravelly bottom. It averaged 0.4 m in thickness, with a maximum of 2.5 m in the upper reaches (Fig.3.13B) and thinned seaward. The mud had a near-constant organic content of about 20%. The post-flood topographic variation in the channel was subdued by mud deposition in the deeper parts. Salinity was becoming re-established in the river-mouth.

19/11/87. The barrier was accreting seaward and a runnel was present between the previously deposited barrier segment and the new part. A subtidal portion of the northern barrier extended almost to the soutern barrier segment . Aeolian sand was accumulating in the lee of debris on the more elevated ridge. The seaward ridge was composed of coarse sand and gravel and covered with mollusc shells transported over the berm by overwash and deposited in shore-parallel lines in the back beach. The


A. Sediment Texture

B. Mud Thickness (cm)

C. Sediment Texture

D. Mud Thickness (cm)

Figure 3.13. Grainsize distribution (A) and mud thickness (B) on 21/10/87 (A and B). and grainsize distribution (C) and mud thickness (D) on 28/1/88 (C and D). Note the downstream extent of the muddy sediment and its apparent decrease in thickness, attributed to compaction between the two periods.

shells were all thick shelled varieties typical of the shallow nearshore and indicated landward transport of sediment from the shoreface (Table 3.3). Upstream-directed ripples produced by flood-tidal currents were present in the inlet and 250 m up the channel. The salinity regime on the spring high tide was that of a stratified estuary with bottom salinities exceeding 30‰. The thickness of the mud layer in the river-mouth had increased slightly and had extended further downstream of the Ellis Brown Bridge.

Mollusc	**Habitat**	**Abundance**
Bivalivia		
Crassostrea margaritacea	sand at extreme low tide and below	abundant, some articulated
Anadara natalensis	muddy sand	abundant
Fulvia papyracea	muddy sand	rare
Tivela natalensis	surf zone or sandy beaches	common
Glycmeris queketti	sand in 20-100 m	common
Gastropoda		
Tonna variegata	inshore sandy bays	abundant fragments
Ficus ficus	sand at low tide to 30 m	broken shells present
Phalium areola	sand, shallow	common
Bufonaria crumenoides	sand among submerged rocks	whole shells present
Thais bufo	mid-tidal rock pools	present
Cymatium parthenopeum	rocks in shallow water/buried in sand	common
Cyprea tigris	overhanging sides of deep rock pools	whole shells present

Table 3.3. Mollusc shells from the Mgeni river-mouth barrier, 18/11/87.

28/1/88. The mouth was virtually closed and only a small outlet channel was maintained across the barrier. Water levels in the back-barrier were high and most of the Beachwood area was inundated. The seas were rough due to a passing cyclone. Mud deposition in the river-mouth had extended downstream to the barrier (Fig.3.13C). In the upper reaches the mud thickness was reduced compared to November (Fig.3.13D). Increased resistance to pushing the stick through the mud layer suggests that this was due to compaction. Water salinity was low due to the nearly closed mouth and was only 0.7‰ behind the barrier.

28/3/88. In March 1988 the barrier had been re-established in a position seaward of that in 1985. The adjacent beaches to the north had accreted seaward by over 100m. The river-mouth was shallow throughout its length (typically < 0.5 m) and the bed was composed of micaceous, fine-grained sand (mean grainsize 0.2 mm) (Fig.3.14). 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 upsteam during waning flows and, with the return of normal flow conditions, migrated downstream as bedload. Very fine sand was more common in the lower reaches, particularly on the intertidal areas (Fig.3.14B), suggesting less active currents in those areas. Sorting (Fig.3.14C) followed the reverse trend, due also to stronger current action and selective winnowing of very fine sand. Very-well-sorted sands occurred in the upper reaches and in the tidal inlet and these tended to be coarsely skewed (Fig.3.14D).

The bed was intertidally exposed between the Ellis Brown and Athlone Bridges and the channel thalweg ran obliquely across the river-mouth (see 8/5/88 aerial photographic interpretation, Fig.3.11B). In the upper reaches a large unvegetated sandbar was exposed at all tides on the right bank. Bedforms in the

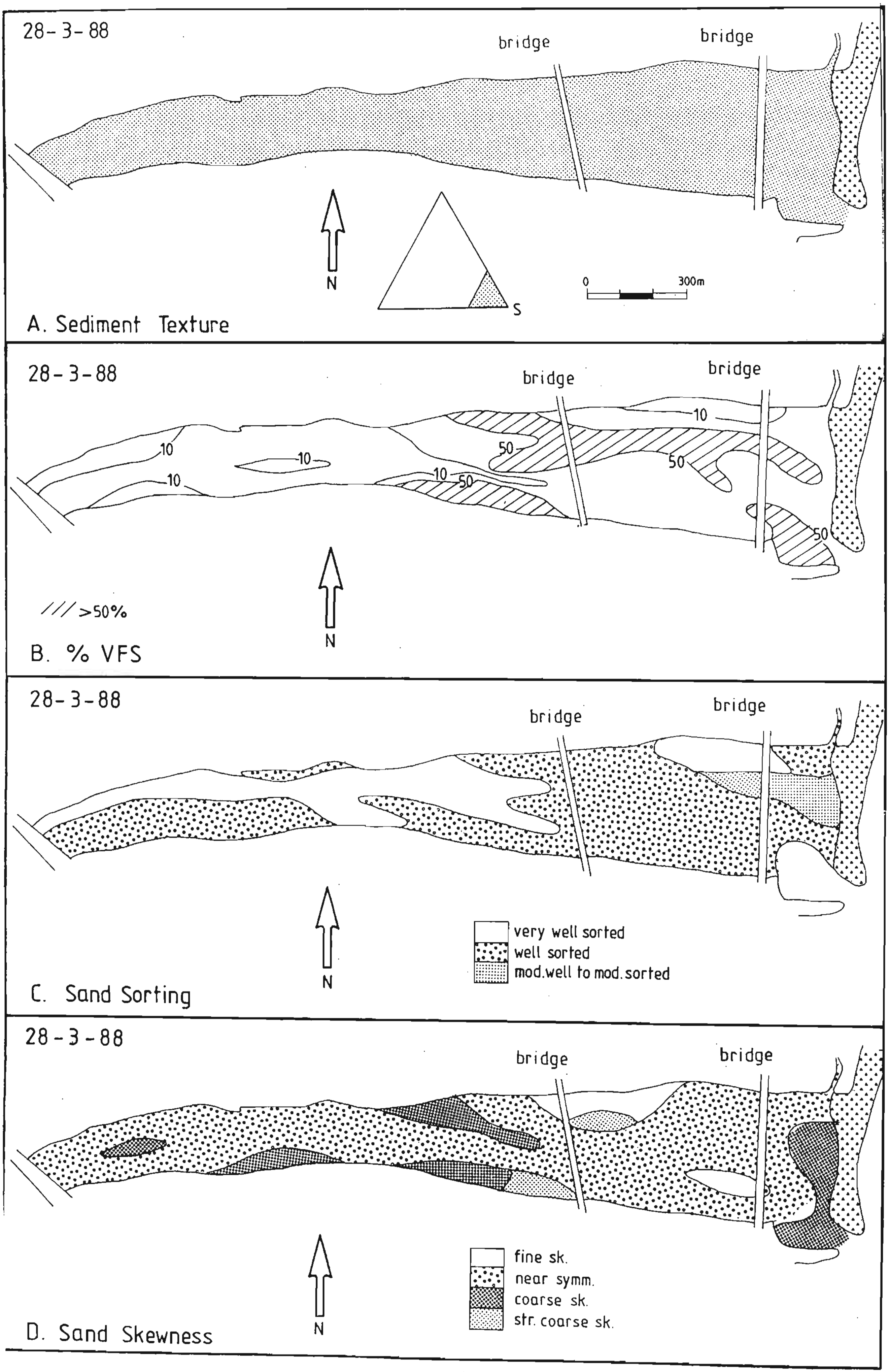


Figure 3.14A-D. Sediment grainsize distribution in the Mgeni river-mouth on 28/3/88. The river-mouth is completely sandy (A) and grainsize variation is best illustrated by variation in proportions of the very fine sand fraction (B). Sorting of the sand fraction (C) and skewness of the sand grainsize distributions (D) are also shown.

channel comprised straight-crested sandwaves, (20-30 m wavelength; 0.7 m amplitude) with small, superimposed linguoid, current ripples (Plate 3.4). The inlet was located adjacent to the groyne.

30/5/89. River-mouth morphology had not changed appreciably but the sandy surface of intertidal flats began to be exposed above high tide as a result of swash action. The settling of mud on the intertidal flats had occurred during low tide exposure and surfaces comprised laminated and thinly interbedded sand and mud. The intertidal surfaces seaward of the Athlone Bridge were colonised by algae which helped bind the sediment (Plate 3.5). Their distribution in the lower reaches suggests that the algae were marine. The more elevated parts of the sand bars were vegetated with *Scirpus* grass. 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 (wavelength, 10 cm, amplitude 2 cm) 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 stabilisation of the right bank.

A survey of several cross-sections was carried out in June 1989. These enabled calculation of river-mouth dimensions and the volume of sediment deposited since the 1987 flood. A comparison of the cross-sections with those measured immediately after the flood are shown in Figure 3.15. The results are tabulated in Table 3.4 and show that during the 21 months since the flood, a total of 1.36 x $10^6 m^3$ of sediment was deposited in the river-mouth. Of this, 93% was deposited subtidally while only 7% (0.95 x $10^6 m^3$) represented intertidal deposition. The tidal prism was calculated at 332 x 10^3 m^3, almost twice that which existed before the flood. The pre-flood, flood and post-flood channel dimensions are compared in Table 3.5. Aerial photography of July 1989 (Fig.3.11C) depicts the river-mouth morphology close to the time of the survey. The channel contains a large volume of intertidally-exposed sand. The apparent reduction in downstream extent of the sandbars is due to a higher tidal level than the 8/5/88 photograph.

17/4/90. Aerial photography from almost a year later (fig.3.11D) showed that the river-mouth channel was virtually unchanged. Vegetation was better established on the elevated parts of the intertidal flats and a small bar near the tidal head was densely vegetated. A former intertidal bar in the upper reaches was thickly vegetated and almost incorporated into the floodplain. Small parts of the sandbars were supratidally exposed. Two channels were present, one on either side of the elevated central area, although the southern channel was better defined and evidently carried more flow.

3.5.2. Discussion: Post-flood recovery

The recovery of the river-mouth after the flood may be divided into barrier and back-barrier channel sections, each of which are discussed below.

3.5.2.1.Barrier recovery. Coarse sediment deposited offshore as a subaqueous stream-mouth bar was rapidly reworked by wave action and transported landward to reconstruct the sandspit. The mechanism

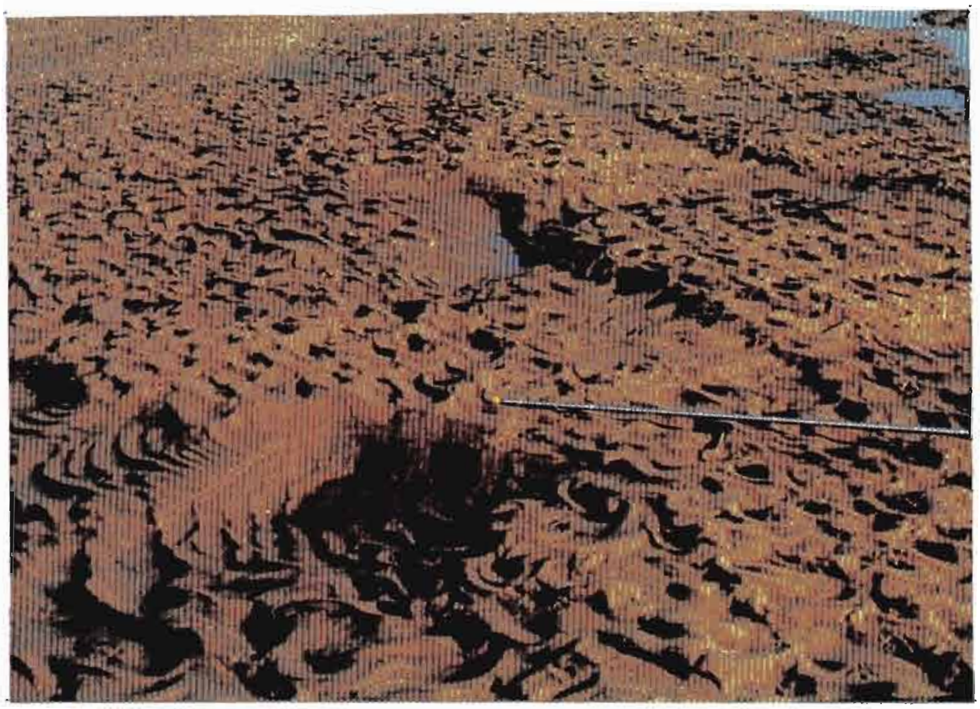


Plate 3.4. Fine-grained sand forming sandwaves in the river-mouth. These migrated rapidly downstream after an initial post-flood suspension settling phase and filled the subtidal channel, producing large intertidal areas. Portion of current meter rod shown is 1.3 m long.

Plate 3.5. Algae and reeds colonising sandbars in the lower reaches of the river-mouth. The downstream location of the algae suggests that they are marine. Algae binds the sandy sediment surface, giving it increased cohesion. Eroded lumps of algal-bound sand were noted in the channel at this time.

Section Number	X-AREA HTL m^2	X-AREA LTL m^2	VOLUME HTL $x10^3m^3$	VOLUME LTL $x10^3m^3$	VOLUME Intertidal $x10^3m^3$
JUNE 1989					
Section no.					
1	116.9	30.2			
2	277.8	23.1	65081	26580	38501
4a	215.2	8.1	163111	53448	109663
5	109.8	3.2	73373	20310	53063
7	137.2	1.8	47421	12930	34491
8	104.6	4.5	40995	13238	27757
9	87.4	0.58	40939	11967	28972
10	60.7	0.1	35999	10718	25281
11	30.9	0.2	15714	3299	12415
12	0	0	2850	285	2565
Total			485483	152775	332708

TABLE 3. 4 Cross-section and volume data for Mgeni river-mouth in June 1989. X-AREA is the cross-sectional area at high and low tide level (HTL and LTL respectively). The volume of the estuary between successive sections are given for high and low tide levels and the intertidal volume (tidal prism) is calculated.

Year	HIGH TIDE VOLUME $(x10^3m^3)$	LOW TIDE VOLUME $(x10^3m^3)$	TIDAL PRISM $(x10^3m^3)$
1984	345.6	162.8	182.8
Oct '87	1845.8	1417.3	428.5
June'89	485.5	152.8	333.0

Table 3.5. Comparison of volume data for the Mgeni river-mouth under pre-flood conditions in 1984, immediately after the flood (October 1987), and after rapid sediment infilling in twenty-one months (June 1989). During the flood approximately 1.6x 10^6 m^3 was eroded. In the twenty one months after the flood the river-mouth volume was reduced by 1.3 x 10^6 m^3.

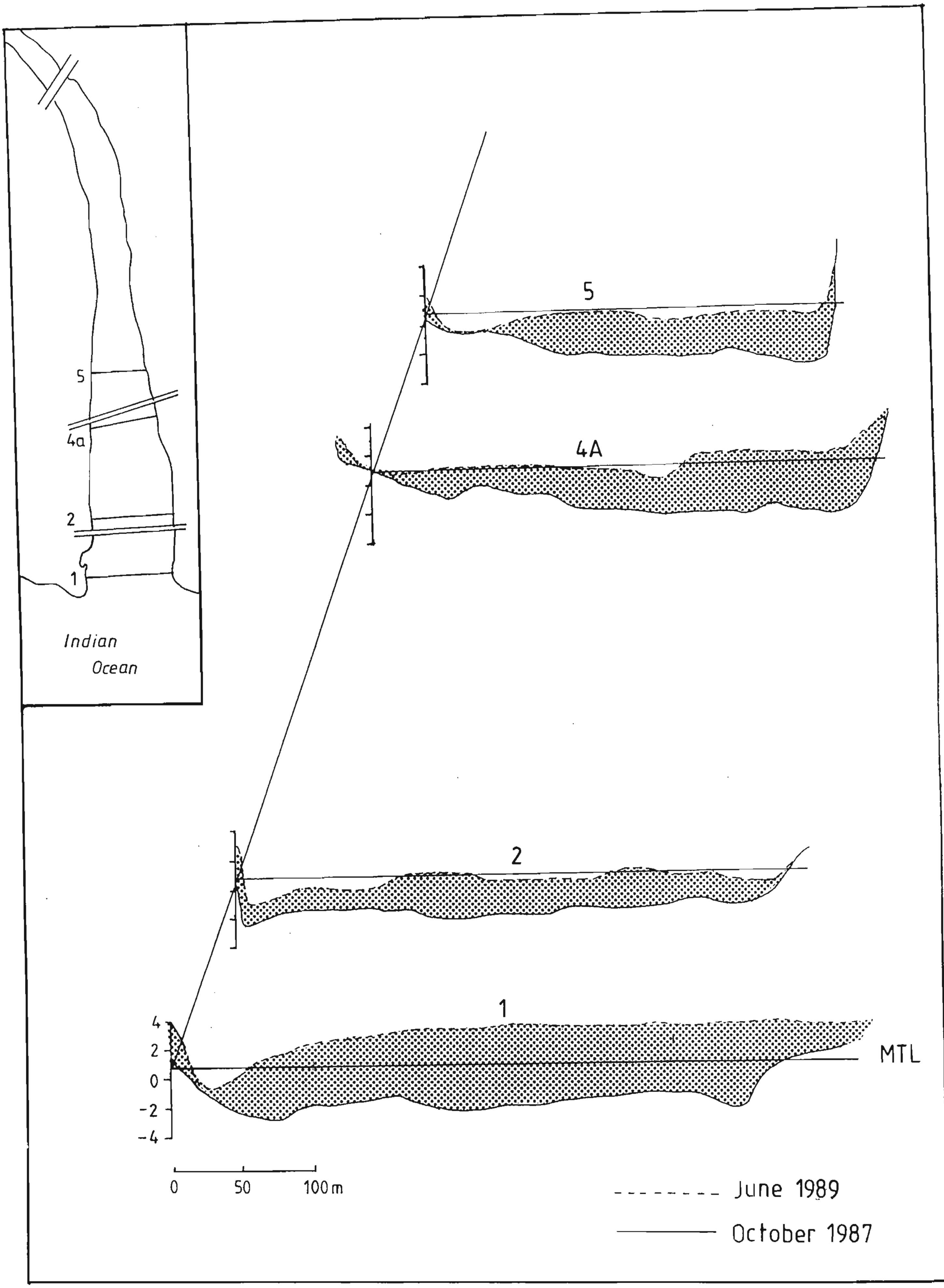


Figure 3.15. Comparison of post-flood scoured channel (October 1987) and cross-sections surveyed in June 1989. Not all the cross-sections were surveyed and only those which coincide with the earlier cross-sections are illustrated. Note the volume of sediment deposited since the flood (shaded area). MTL = mid-tide level. (Continued overleaf).

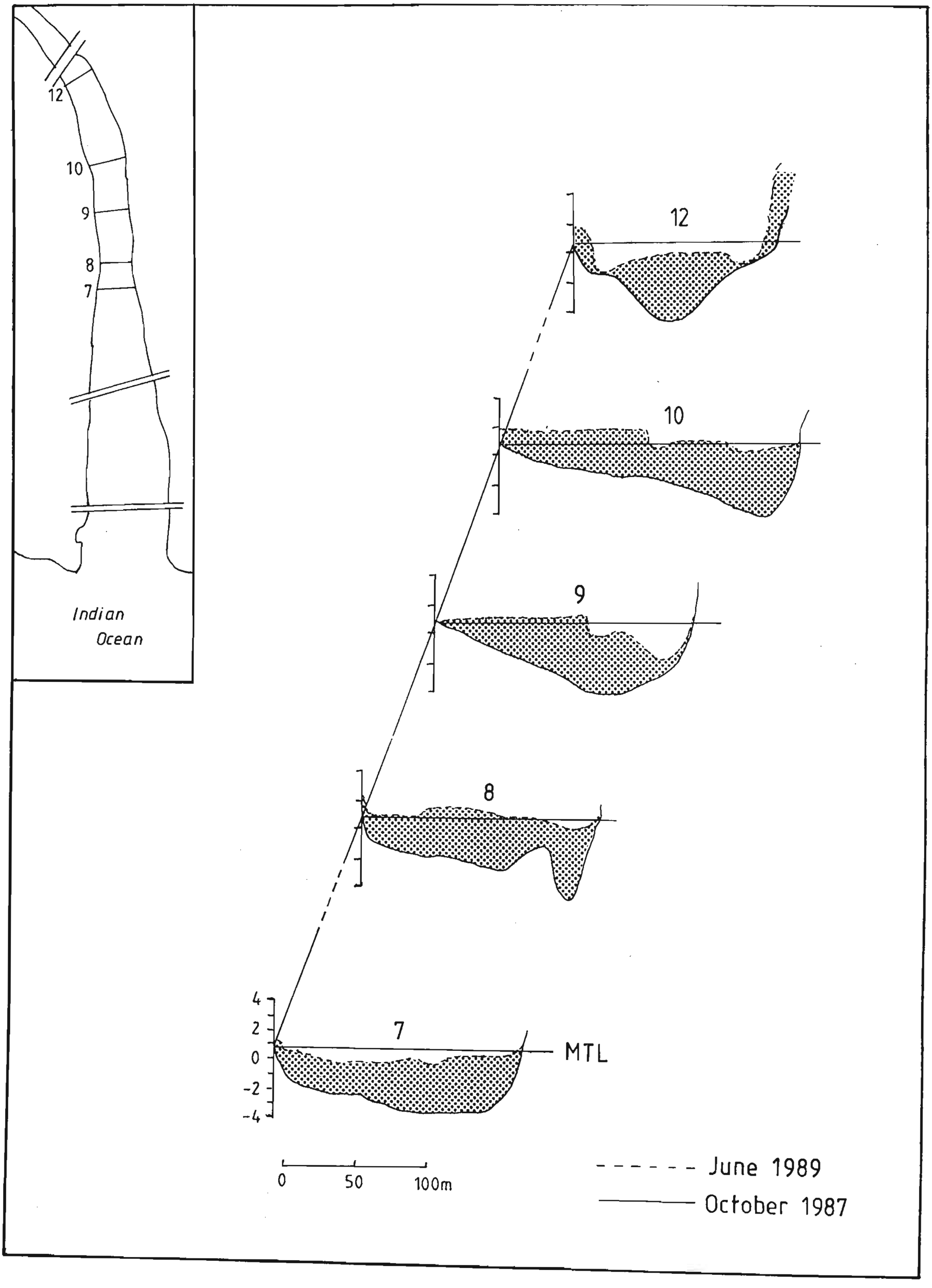


Figure 3.15 (continued). Comparison of post-flood scoured channel (October 1987) and cross-sections surveyed in June 1989. Not all the cross-sections were surveyed and only those which coincide with the earlier cross-sections are illustrated. Note the volume of sediment deposited since the flood (shaded area). MTL = mid-tide level.

of mouth bar modification and barrier reconstruction was described by Cooper (1988b, 1990d). When flood velocities dropped, 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 sandbars was stressed by Reddering (1983).

Within three weeks after the flood peak, stream-mouth bar sands had already become emergent, though wave-induced turbulence and landward transport of 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 mouth formed in its former southerly position. The large quantity of sand in the littoral zone caused progressive accretion of beaches north of the river-mouth (Fig.3.16) restoring the shoreline position to near that of the 1930s (Compare with Figure 3.6).

3.5.2.2. Back-barrier channel recovery. In the 8 months after the flood, the river channel underwent rapid accretion. Overbank deposits were artificially removed from the surrounding area, except in the mangrove swamp where they were colonised by a populous burrowing crab community. Three phases of post-flood recovery may be recognised in the three year period elapsed since the flood: Waning flood deposition, suspension-settling of mud, downstream sandwave migration, and braid bar coalescence and emergence.

The waning flood deposition lasted only a few days after the peak and left the bed covered in a moderately sorted, unbedded mixture of sand and gravel. Fine-grained sand deposition from suspension in the scoured upper reaches was associated with the falling stage and did not persist. Suspension settling of muddy sediments began after October 10th and by the 26th (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 next sampling period at the end of March 1988 (180 days after the flood) the entire river-mouth was full of fine-grained sand which had migrated rapidly as bedload from upstream. This is interpreted as formerly suspended sediment carried during the flood and deposited upstream as the flows subsided. Subsequently it moved downstream as bedload and rapidly filled the river-mouth. Blatt *et al.*. (1980) noted that fine sand is the most easily transported beload fraction. By the end of May 1988 (240 days after the flood) the fine sand deposited in the upstream area during the previous two months was thickly vegetated, a fact ascribed to rapid vegetation growth in the subtropical climate. Within the next year little sedimentation occurred in the river-mouth and the major changes which occurred involved vegetal stabilisation of the intertidal bars and the initiation of mud deposition at low and high tide slack. The river-mouth 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 was in October 1917 when a discharge of $5700 m^3 s^{-1}$ was recorded.

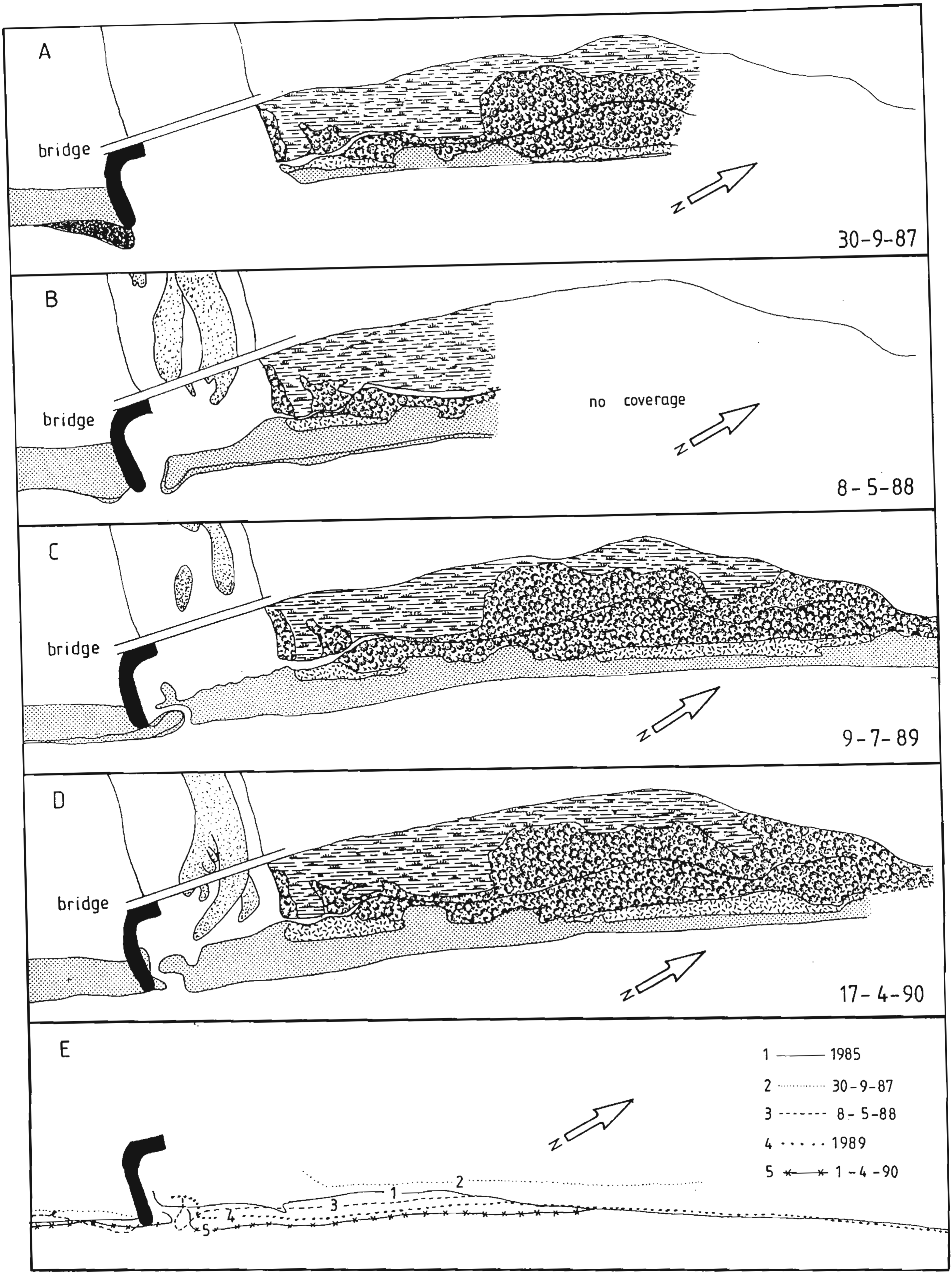


Figure 3.16. (A-E) Post-flood changes in the coast-parallel lagoon. These are restricted mainly to changes in the shoreline position shown in the composite diagram (E). The coastline prograded rapidly after the flood and assumed a position similar to that of the 1930s, as a result of the increased sediment supply in the nearshore. If the past repeats itself it should take about 70 years to erode to the pre-flood position when washover occurred.

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 sand followed by up to 2.5 m of organic-rich muds becoming thinly interbedded with very fine 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 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 general sequence was produced throughout the river-mouth (Fig.3.17). 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 likely to dominate the sedimentary record in river-mouths of this type.

Within less than 21 months the scoured river-mouth channel was infilled by rapid deposition, as the river-mouth channel returned to an equilibrium 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 x 10^3 m^3 of sediment is required before the river-mouth approximates its pre-flood morphology. The smaller volume in the river-mouth 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.

3.6. LONG AND SHORT-TERM SEDIMENTION IN THE MGENI RIVER-MOUTH

The combined results of the historical aerial photographic interpretation and observations following the 1987 flood show several similarities which relate to the long-term sedimentology of the river-mouth. The aerial photographs from 1931 record a long period of slow geomorphological change from a shallow, braided river which through bar emergence and vegetation eventually formed an anastomosing pattern with a vegetated central island and comparatively deep marginal channels. This change may be related to increasing margin stability, not only on the left bank but also through mud deposition and eventual vegetation on the central island. This bank stability enabled downcutting and deepening of the channels. Similar changes in channel morphology through bank stabilisation and vegetation have been widely reported. Under these stable conditions the river-mouth accommodated variation in discharge through temporary deposition, either in the channels or on side-attached bars which characterised both anastomosing channels before the flood (Cooper 1986a). 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 river-mouth. Events during and since the 1987 flood have transformed this apparently stable morphology by exceeding normal thresholds of sediment erosion and transport and over a few days eroded over 1.8 million cubic metres of sediment from the river-

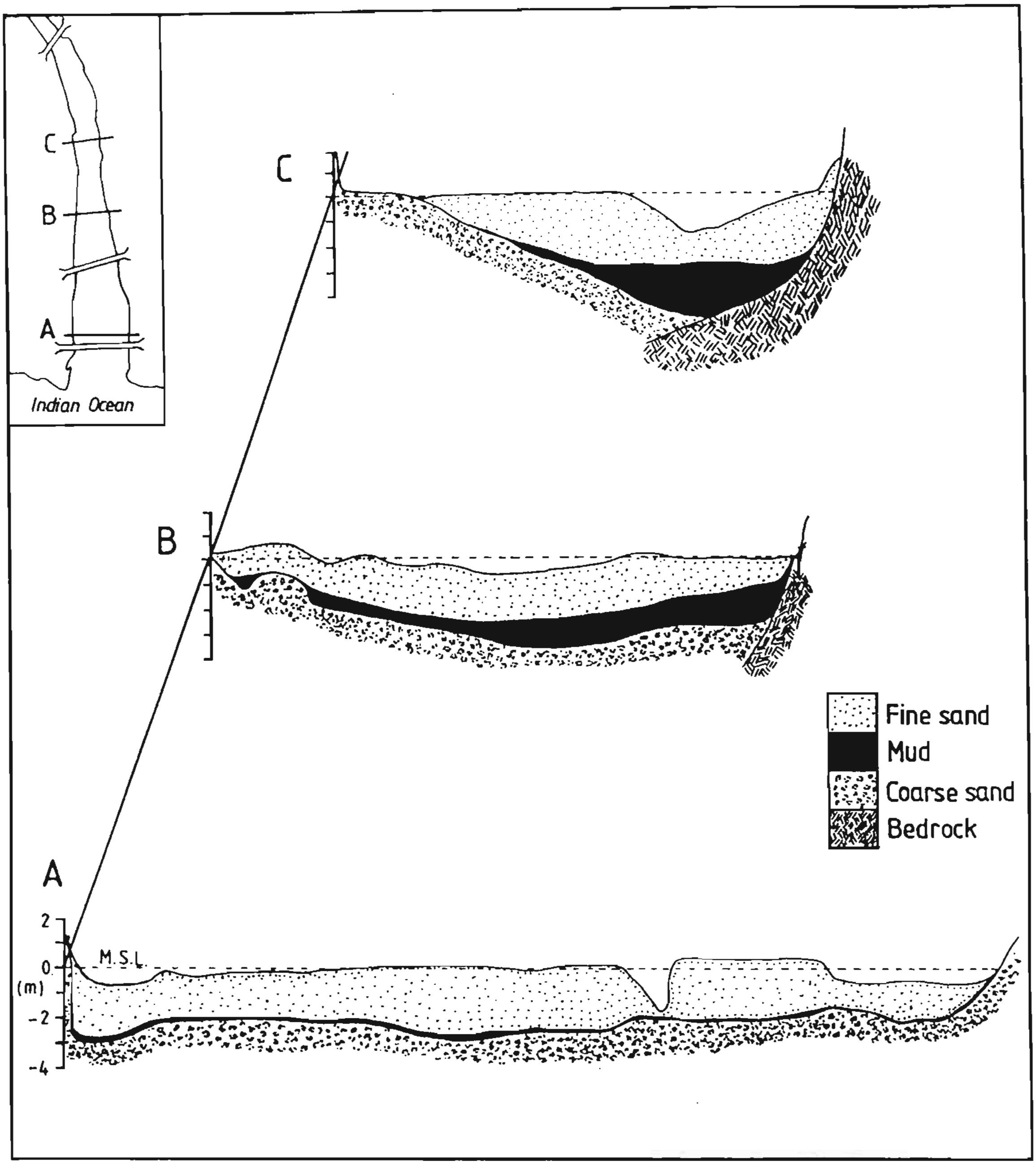


Figure 3.17. Post-flood sedimentary successions in the river-mouth, based on consecutive sediment sampling and cross-sectional surveys. Note the downstream thinning of the mud layer and the effect of the fine-grained sand in reducing gradients along the channel. Cross-section positions shown in inset.

to calculate the net proportion of sediment retained in the river-mouth annually. Marine-derived sand is excluded from the calculation as it is subject to rapid erosion and accumulation.

The total amount of sediment eroded from areas upstream of section 2 during the 1987 flood, (ie upstream of the flood-tidal delta) was approximately 1.5 $\times 10^6$ m^3 (Table 3.1) which could be considered equal to the net amount of sediment accumulated since 1917. This yields a mean sediment accumulation rate of 21.4 $\times 10^3$ m^3 per year since 1917. Considering only the supratidal sediment upstream of section 2, the accumulation rate is 3.4 $\times 10^3$ 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 1.24 x 10^6 m^3 (1861957-(303339+309306)) or 17.8 $\times 10^3$ m^3 per year. This is approximately 46% of the predicted annual bedload sediment yield based on Rooseboom's 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 (1978) map, reported in Section 3.2, it may be that all of the bedload sediment is retained in the river-mouth in interflood periods and bedload supply to the coast at such times is negligible.

This chapter shows that sediment accumulation and erosion in the Mgeni river-mouth is strongly episodic and thus consideration of mean sedimentation rates is unrealistic. The erosion of 1.8 x 10^6 m^3 of sediment from the river-mouth in a few days and its almost instantaneous deposition in the Indian Ocean clearly illustrates the importance of catastrophic floods not only in the river-mouth environment but also on the adjacent shelf and nearshore zone where large influxes of sediment dramatically influence beach accretion and shelf sedimentation patterns. Connell (personal communication, 1988) reported that much of the shallow marine environment off the Natal coast was covered with a layer of organic-rich mud for several months following the floods. The relative importance of such events in nutrient export to Natal's nutrient-poor continental shelf also requires investigation.

3.7. HOLOCENE EVOLUTION OF THE MGENI RIVER-MOUTH

The Holocene evolution of the Mgeni river-mouth may be assessed at a preliminary level at this stage by reference to several lines of evidence. These include borehole cores from foundation investigations below Durban, fossil sea-cliffs and beachridges north of the present mouth, a change in barrier and dune orientation near the present inlet, the surrounding geomorphology, the incised river-mouth channel and comparison with other rivers.

Several cores have been drilled in the valley of the Mgeni River in the course of bridge-building operations (Kantey & Templar, 1964; Francis, 1983) and under the City of Durban in foundation investigations. Information on cores is contained mainly in engineers reports. Some cores were examined sedimentologically by Orme (1974, 1975). The cores reveal a buried bedrock channel extending to 56 m below sea-level under the modern river-mouth. Investigations in the area underlying the City of Durban found the sub-Quaternary surface to lie at depths between 25 and 40 m

(Maud, 1978). The incised valleys of several rivers are incised into Cretaceous siltstones under the unconsolidated alluvial sediment. It is uncertain how much of the overlying material is Pleistocene but on the basis of a radiocarbon date of 24 000 BP (King & Maud, 1964) it seems likely that at least some of it is. The former lagoon under Durban is infilled by silts and clays in its lower part but upwards it passes into more frequent horizons of coarse sand and gravel (King, 1962; King & Maud, 1964).

The vertical sequence revealed beneath the Mgeni River channel indicate that in the middle stages of its Holocene inundation it was characterised by relatively deep water in which suspension settling was the dominant depositional mechanism. The incursion of marine sediments in the upper part of the sequence indicates a marine period in which coarse-grained (transgressive?) sediment, probably barrier-related, extended into the lower reaches of the river valley. At depths of -12 to -8 m below the modern river-mouth, extensive deposits containing marine molluscs are present but these are overlain by gravel, sand and mud layers.

The overlying riverine sediment of the modern river-mouth reflects the influx of catchment sediment which has entirely filled the palaeovalley. The high sediment yield has filled the channel and it appears that this may have kept pace with transgression as the valley fill is composed almost wholly of sands.

The Mgeni river-mouth is adjacent to an extensive, low-lying area to the south on which the city of Durban is built. In the early part of the 19th century the Mgeni was reported to flow south into Durban Bay when water levels rose (Begg 1978; Barnes, 1984). It appears that this may have been the end of an evolutionary phase. The late mid-Holocene Mgeni river may have been diverted southward behind a transgressive coastal barrier in the same way as the Nkomati River is in the Bay of Maputo (Plate 3.6). Evidence for this comes not only from the morphology of the Durban area but also from the fact that coarse-grained river sands are commonly encountered in the shallow subsurface of the low-lying area between the modern river-mouth and Durban Bay (King, 1962; Francis, personal communication, 1989). The modern river-mouth position had been assumed by the mid 19th century, either as a result of a particularly severe flood or by meander cutting of the inner margin of the barrier, or by formation of overwash channels. The inlet was fixed artificially in its present position by a groyne in the early 1930s.

The rear of the lagoonal area at Beachwood Creek is backed by a cliff cut into Berea-type red sands. Below this area red sands extend to at least 11m below the surface and rest on a boulder bed (McCarthy, personal communication, 1991). In the vicinity of the Athlone Bridge the base of the red sand is at 5-6 m above sea level where it rests on bedrock. The red sand is interpreted as a regressive coastal dune of probable latest Pleistocene age resting on a transgressive boulder beach deposit. The cliff cut into it is of Holocene Age and is aligned with a forested dune which extends south of the modern inlet and another which extends north of the cliff, beyond Beachwood Creek. The modern barrier is offset from this earlier shoreline and its orientation indicates a change in plan morphology in the Durban Bight. It is tentatively correlated with a late mid-Holocene regression of about 1.5 m. This drop in sea-level was responsible for formation of the coast-parallel lagoon when the river-mouth, newly incised into its

Plate 3.6. Mouth of the Nkomati River where it enters the Bay of Maputo, Moçambique. The channel is diverted south behind a transgressive sandy barrier which has a plan form in apparent equilibrium with approaching waves. This is proposed as a modern analogue for the Mgeni river-mouth about 7000 years BP. The open water area shown is seen as an analogous environment to that which existed in the area where Durban now stands. In the case of the Mgeni, the former large lagoon is now filled with sediment and a new mouth has been formed at the point where the river formerly diverted behind the coastal barrier.

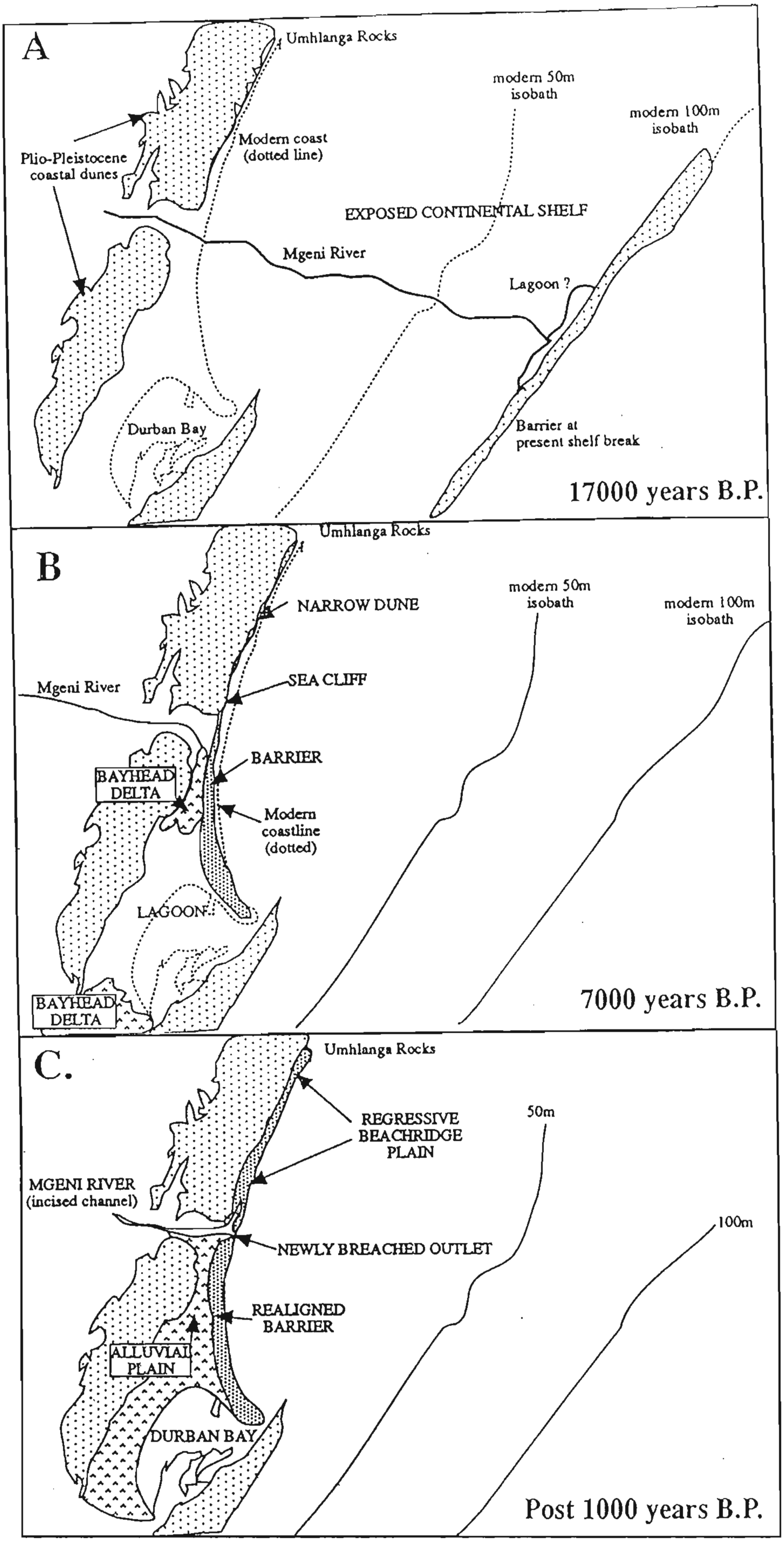


Figure 3.18. Schematic Holocene development of the Mgeni river-mouth area, based on geomorphological and borehole evidence. (A.) River course runs across continental shelf during last glacial maximum 1700 years BP. (B) Sea-level crosses its present level about 7000 years BP and a transgressive barrier extends from north of the present Mgeni river-mouth to Durban Bay. (C) Sea-level drops from its late Holocene highstand, incising the river channel into alluvial deposits and forming the present river-mouth outlet. Coastal progradation to the north is accompanied by barrier realignment to maintain equilibrium with ambient wave field.

CHAPTER 4.
MTAMVUNA RIVER MOUTH

4.1. INTRODUCTION

This chapter documents the sedimentology of the deep, cliff-bound, lower reaches of the Mtamvuna River and the adjacent coast, and determines both the reasons for, and the implications of, its apparently youthful state. The physical characteristics of the river-mouth are assessed in the context of the controlling environmental factors, both temporal and spatial, and a sedimentary model is constructed.

The lower reaches of the Mtamvuna River (31°04'S; 30°11'E) in the extreme south of Natal (Fig.4.1) were selected for study as the river is unusually deep, in contrast to most other shallow, fluvially-dominated river-mouths in Natal. The salinity structure, circulation patterns and tidal exchange render the Mtamvuna's lower reaches worthy of definition as an estuary. The depth of the Mtamvuna has been noted by other authors concerned with its biological characteristics (Day, 1981; Begg, 1978, 1984a). Day's (1981) review of South African estuaries indicates that the Mtamvuna is among the deepest on the South African coast, a fact which he suggested must be due to low rates of siltation. The great depth also inhibits vertical mixing in the water column, which promotes low aquatic oxygen levels and was blamed for an apparently impoverished fish and benthic invertebrate fauna by Hemens *et al.*, (1986).

4.2. CATCHMENT CHARACTERISTICS

4.2.1. Catchment topography

The Mtamvuna River catchment is 161 km long and its source is at an elevation of 1920 m (Kemp *et al.*, 1976). The catchment topography is shown in Figure 4.2A. The overall river gradient is 1:84 or 0.012 but significant downstream changes in gradient are evident (Fig.4.2B). These have been linked to former relative sea levels in the Cretaceous and Tertiary in several Natal rivers (Maud, 1968; Matthews & Maud, 1988).

In a regional context the Mtamvuna has a relatively large catchment area (1570 km^2) with a correspondingly large discharge (M.A.R. =303 x 10^6 m^3). Average recorded flow was calculated at 8500 l/s (Kemp *et al.*, 1976) or 8.5 cumecs. No dams are present in the catchment. An annual sediment yield estimate of 434 000 tonnes (NRIO, 1986), was calculated on the basis of a sediment yield map (Rooseboom, 1978). A crude assessment of the validity of this estimate may be made by comparing it with measurements of suspended sediment concentrations. Mean annual runoff divided by the total annual sediment yield should give an indication of the suspended sediment concentrations required to transport such a volume of sediment. Assuming that sediment transport is constant and that all sediment transport is in suspension the average concentrations of suspended sediment required are about 1400 ppm. The assumptions made are clearly invalid as runoff is strongly seasonal and thus suspended sediments would be expected to occur over a wide range. However, suspended sediment concentrations reported in Begg (1984a) range from 2 to 41 ppm. These low concentrations compared to the average

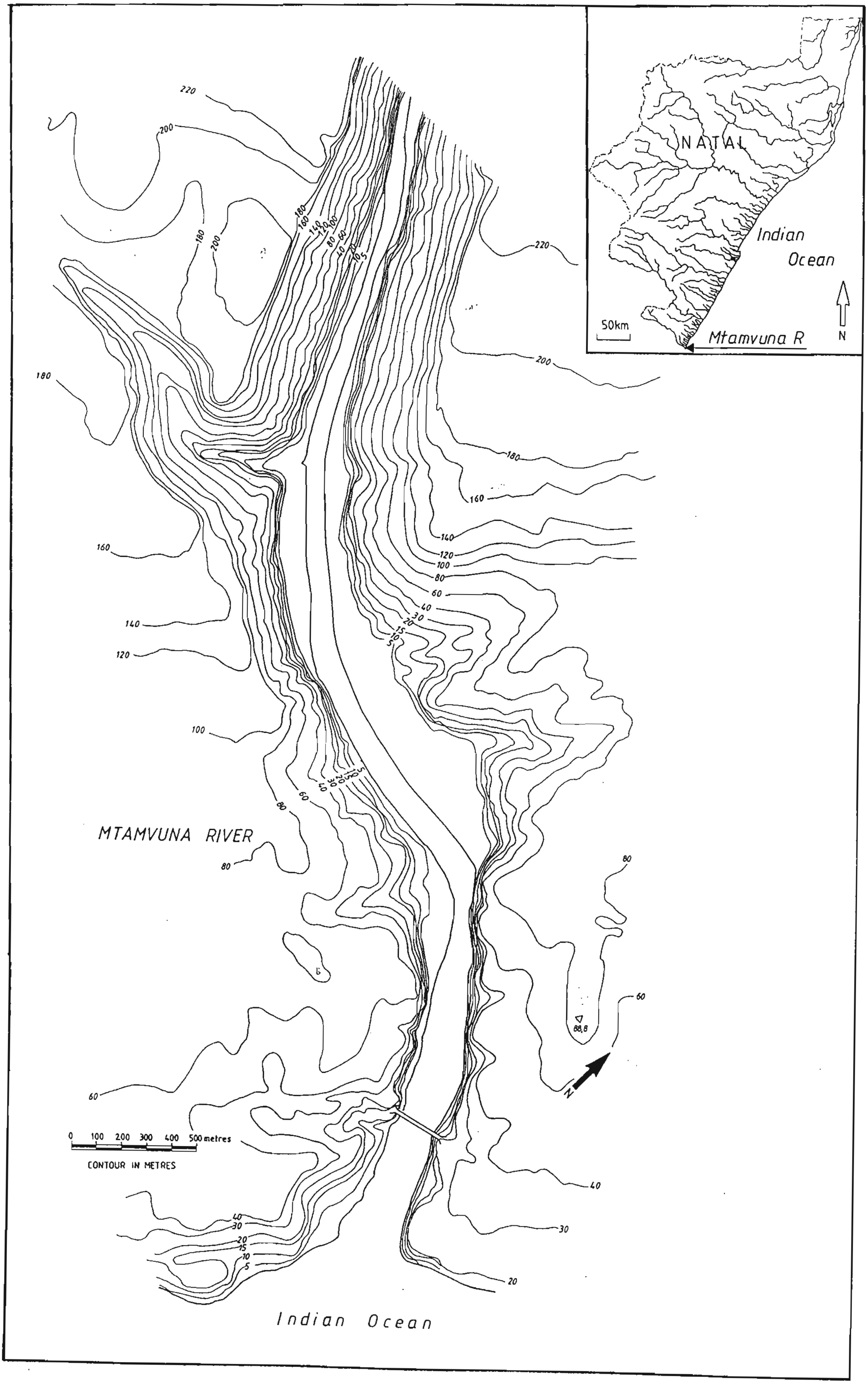


Figure 4.1. Locality map of the Mtamvuna river-mouth showing surrounding topography. Note the long, narrow channel and cliff-bound margins.

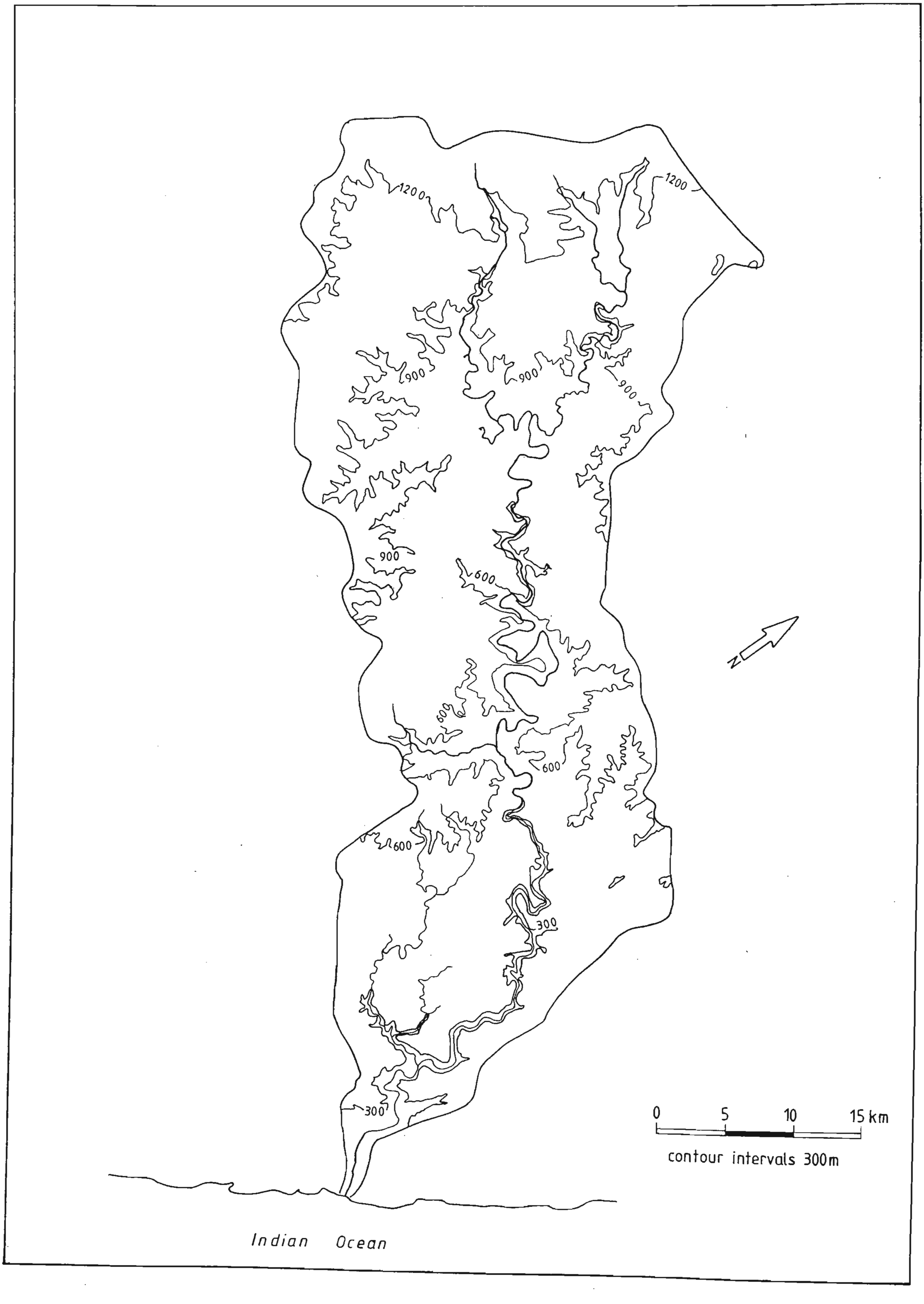


Figure 4.2. A. Topography of the Mtamvuna River catchment.

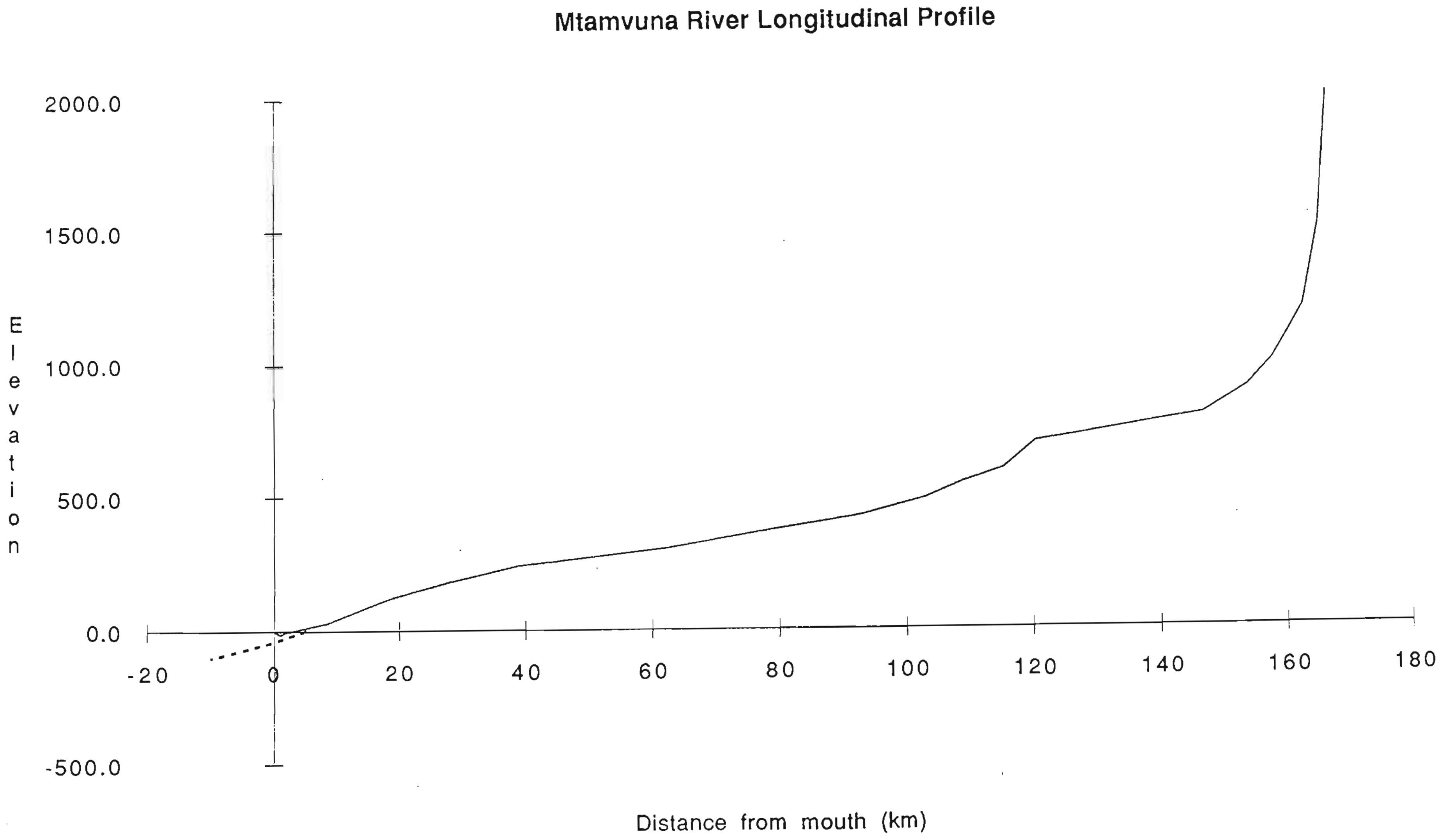


Figure 4.2. B. Downstream channel profile of the Mtamvuna River, showing changes in gradient. The dashed line shows the channel profile extended directly to the shelf break at -100 m and gives a maximum estimate of the gradient during the last glacial maximum.

required, suggest that the calculated sediment yield may be an overestimate, an argument which is borne out by the sediment-starved, rocky nature of the river channel immediately above the river-mouth. Under flood conditions even the noticeably muddy rivers of Natal seldom exceed suspended sediment concentrations of 5000 ppm and in the exceptional case of the Mtamvuna this is considered highly unlikely.

4.2.2 Catchment geology

The geology of the catchment shows three well-defined divisions (Fig.4.3). In its upper reaches, the river traverses shales and fine-grained sandstones of the Ecca Group. Coarse-grained deltaic sandstones are locally present in the middle Ecca Vryheid Formation in the area (Thomas, 1988). The Ecca Group lithologies in the upper catchment are intruded by numerous sills of Karoo dolerite (17% of the entire catchment). Resultant contact metamorphism has increased the shales' resistance to erosion.

In its middle reaches a broad area of the river catchment (35 %) is underlain by the Dwyka Formation and in its lower reaches the river valley is cut through resistant, coarse-grained sandstones of the Natal Group. In the area around the Mtamvuna River soil horizons formed on this lithology are typically 3-4 m thick (Thomas, 1988). A small area of the underlying Proterozoic basement complex is exposed in cliff sides in the lowest 5 km of the river course.

Small outcrops of Late Tertiary to Pleistocene coastal facies, including Berea Formation dune sands are exposed at the coast. These ancient coastal dunes are underlain by a boulder horizon at the Mtamvuna river-mouth, (McCarthy, 1967).

4.3. RIVER-MOUTH MORPHOLOGY

The Mtamvuna river-mouth is situated in a deep gorge flanked by cliffs of Natal Group Sandstone up to 200 m high on either side (Fig.4.1, Plate 4.1), a factor attributed by King (1972) to repeated uplift of the Natal hinterland. This may be associated with tectonism triggered by hotspot activity in the Cretaceous to Tertiary (see Chapter 1, and Smith, 1982). The adjacent coast is mainly rocky and unconsolidated sandy coastal lithosomes occur mainly as barriers across river mouths or as pocket beaches in sheltered embayments. These characteristics control the river-mouth morphology which is considered below in two sections; the river-mouth, and the barrier.

4.3.1. River-mouth morphology

The river-mouth channel is straight to slightly sinuous and located within a narrow steep-sided gorge. Cross-sections of the river-mouth channel were surveyed at 10 positions (Fig.4.4) on two occasions (June 1988 and January 1990) and no noteable change was observed between these periods. Comparison with cross-sections measured in 1970 by Hemens *et al.*, (1986) suggests that while much of the river-mouth has remained stable, the three upper sections of the river-mouth may have reduced in volume over the 20 year period. Low accuracy in positioning makes absolute comparison of the same

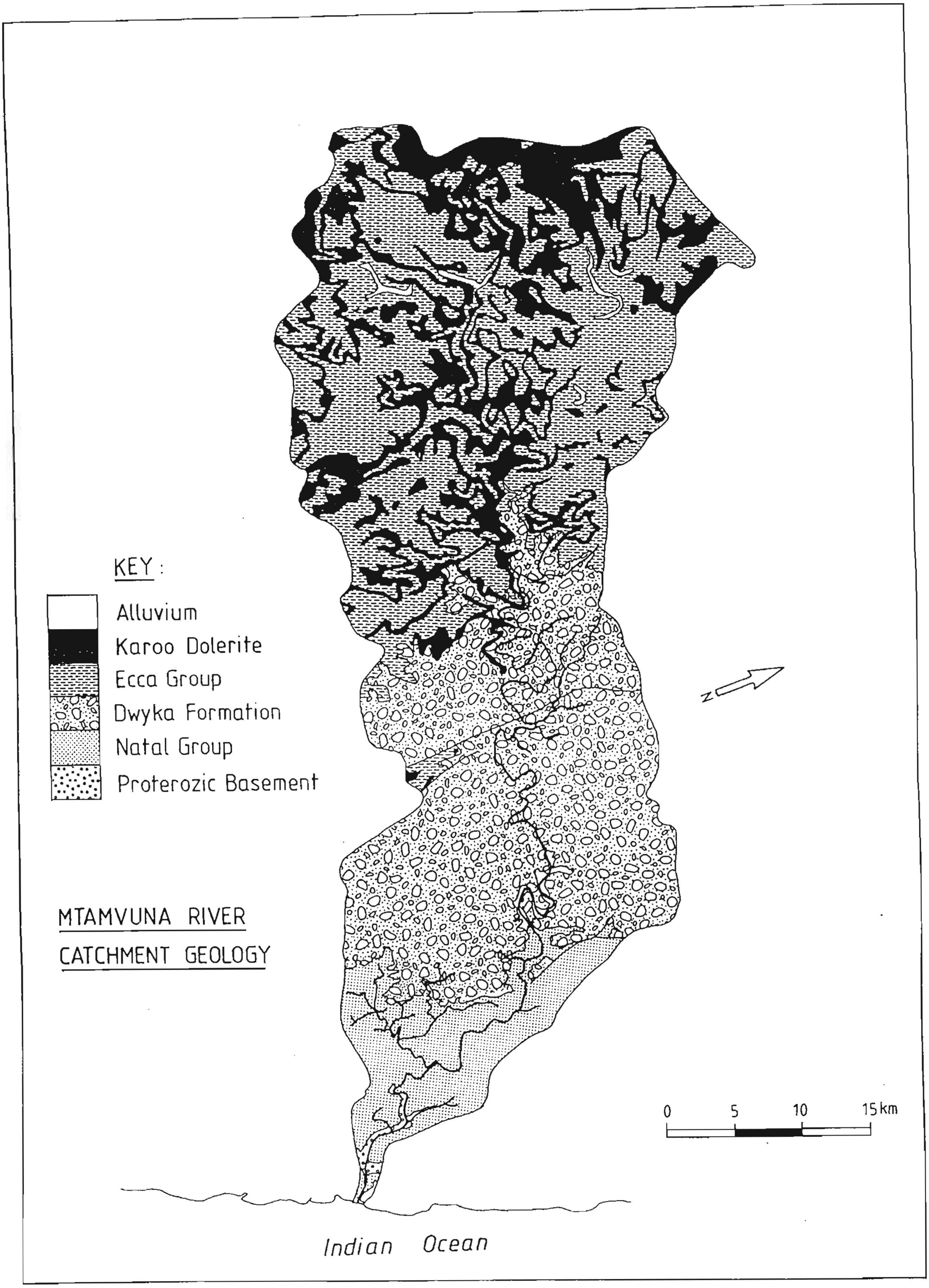


Figure 4.3. Geology of the Mtamvuna catchment based on South Africa 1:250 000 sheets 3030 Port Shepstone and 3028 Kokstad. The catchment is underlain by Ecca Group mudrocks in the upper reaches, Dwyka Tillite in the middle reaches and Natal Group Sandstone in the lower reaches. Note the intensity of dolerite intrusion in the Ecca Group shales.

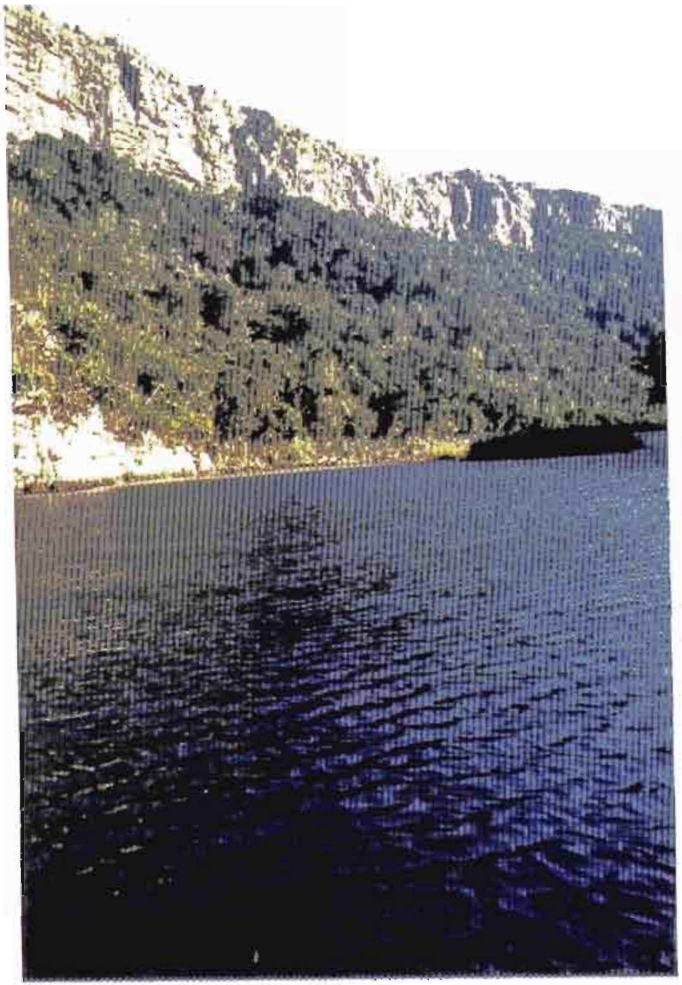


Plate 4.1. Photograph looking upstream, showing cliff-bound nature of Mtamvuna river-mouth. The cliffs are composed of Natal Group Sandstone, which is resistant to erosion.

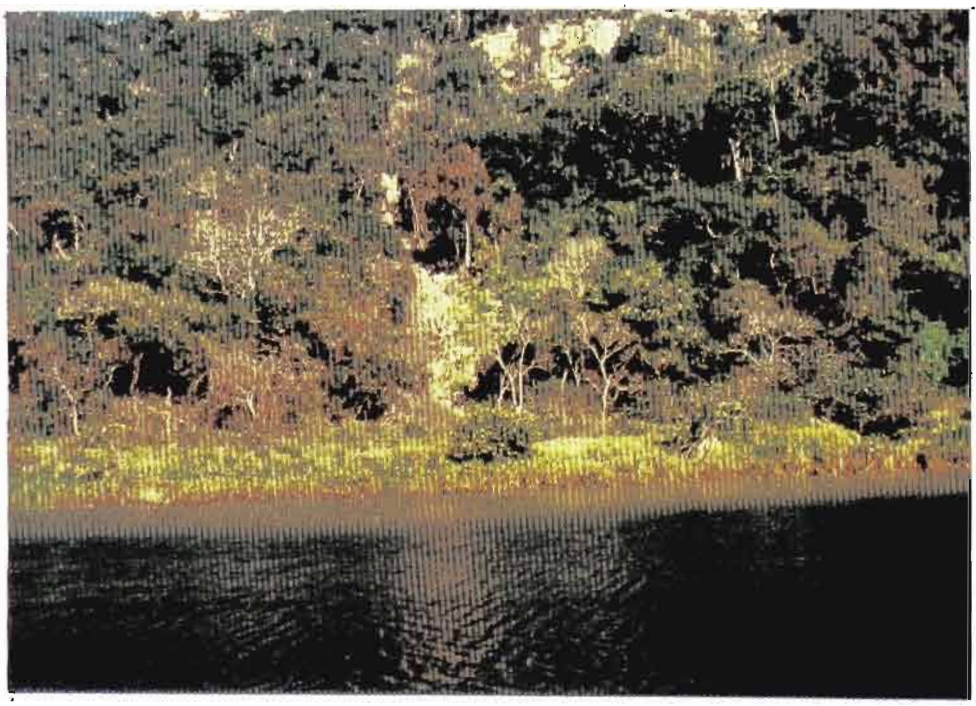


Plate 4.2. Photograph of a recent rockfall following heavy rains in January 1990. This mode of sediment deposition appears to be important in this and other cliff-bound river-mouth environments.

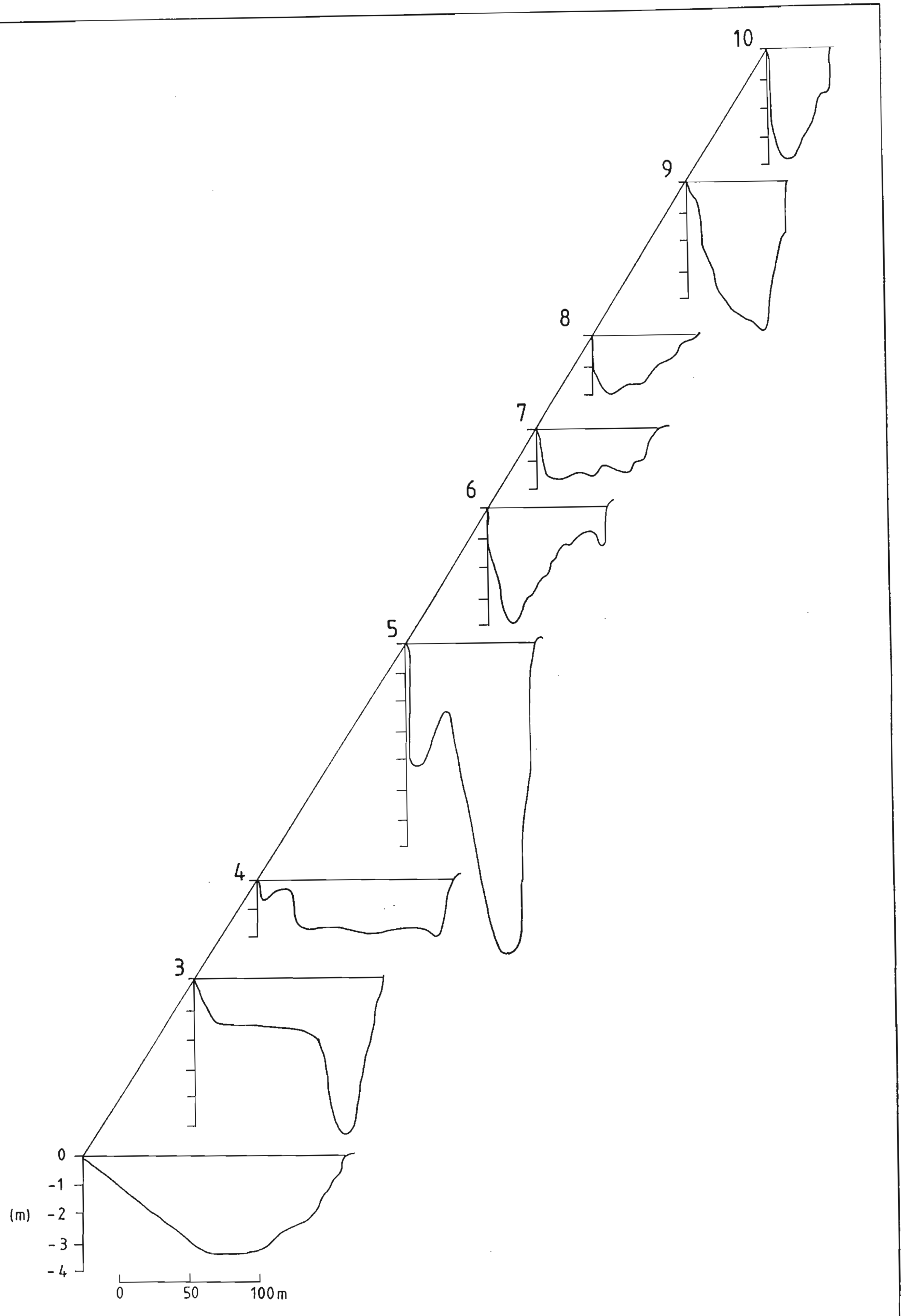


Figure 4.4. Bathymetric cross-sections of the Mtamvuna river-mouth, measured at low tide. For cross-section locations see Figure 4.6. Note the deep middle reaches and shallow lower and upper reaches.

sections difficult but the volume of the river-mouth could be calculated using both the 1970 and the 1988/1990 data sets.

The 1988 and 1990 surveys revealed that the channel is up to 13 m deep and is typically over 3 m deep at low tide. The landward limit of the river-mouth area is situated some 4.9 km upstream from the sea and is defined by a bedrock channel blanketed with boulders. Calculations of the cross-sectional area at each transect for different water depths (Table 4.1) showed that the river-mouth has a volume of just over 1 x 10^6 m^3 at low tide. The spring tidal range is reduced inside the river-mouth to 0.8 m, compared to 2.2 m in the open sea, and the spring tidal prism is approximately 0.35 x 10^6 m^3.

Elevation		**Volume (m^3)**
0	low tide	1 000 312
0.4	mid tide	1 222 879
0.8	high tide	1 355 847
	tidal prism	355 535

Table 4.1 Mtamvuna Estuary Volumes

Direct comparison of cross-sections measured during this study and those measures in 1970 (Hemens *et al.*, 1986) was not possible due to inadequate position-fixing control in the earlier survey, however, an estimate of the river-mouth volume and tidal prism at that time could be made using only the 1970 data. Calculations based on the 1970 cross-sections indicate that the subtidal volume was then 1.05 x 10^6 m^3 and the tidal prism was approximately 0.35 x 10^6 m^3. These figures are broadly comparable with the results obtained in this study and indicate little overall change in dimensions within the Mtamvuna river-mouth during the 20 year period, except possibly in the upstream areas. More closely-spaced cross-sections would be required to determine whether the apparent loss of 0.05 x 10^6 m^3 is real, however Hemens *et al.* (1986), missed the deepest sections and the apparent small reduction in volume may be due to this.

Both sets of observations suggest low sedimentation rates in the river-mouth, a fact borne out by the lack of sediment in the river channel immediately upstream of the tidal head.

Tidal exchange occurs through a small inlet formed in a sandy river-mouth barrier. Seawater intrudes into the river-mouth in the form of a bottom wedge Day (1980) and salinity in the river-mouth reaches 33‰ at high tide. Upstream, at the tidal head, salinities are lowered to 7‰.

The great depth of the river-mouth coupled with its limited wave fetch and protection from cross-channel winds (which reduces vertical mixing) causes the river-mouth to develop marked vertical stratification in the deeper sections. Anoxia has been reported in the deeper parts of the river-mouth when mouth closure occurs (Hemens *et al.*, 1986) and on a few occasions during the fieldwork for this thesis, free sulphides, highly toxic to the aquatic fauna, were recorded in the bottom waters even when the river-mouth was open and full anoxic conditions were not achieved.

The elongated, sinuous river-mouth almost fills the entire valley and precludes the formation of an extensive floodplain. This morphology may be attributed to the erosion-resistant nature of the Natal Group Sandstone which prevented lateral erosion by the river during multiple incisions of the valley. Vertical erosion may have been accomplished by concentration of the flow in a narrow strip, possibly exploiting a joint or fault, although no fracture is mapped in the area with this orientation. Laterally restricted river valleys are typical of valleys cut in the Natal Group Sandstone and several other examples occur in upstream portions of several Natal rivers, including Oribi Gorge on the Mzimkulu River.

4.3.2. Barrier morphology

As the Mtamvuna lies some 100 km south of the limit of Holocene beachrock formation in Natal, no beachrock cementation has occurred in its barrier or the adjacent mainland-attached beaches and these are composed entirely of unconsolidated sandy sediment in the medium-grained sand category.

The Mtamvuna river-mouth barrier was surveyed on eleven occasions between 1972 and 1974 by Fromme (1975). Much of the following discussion results from analysis of his data but the interpretation is entirely that of the author. Additional data from surveys conducted by the author and from aerial photographic interpretation is also used. Analysis of this data reveals that the berm typically slopes from a maximum elevation of 5 m in the northern part to 3 m in the south of the barrier with respect to chart datum. Mean tide is 1.35 m compared to the same datum and mean high water spring tide is 1.72 m, so even at its lowest part the berm crest is still at least 1.3 m above spring tidal level.

The barrier is located between two rocky headlands, one on the south side which interrupts the sand supply through littoral drift from the south and one on the north against which the barrier abuts and continues northward as a mainland-attached beach. The total length of the embayment in which the barrier is located is 1475 m, of which the barrier occupies 300 m. Under normal (non-flood) circumstances, inlet migration is restricted to the southernmost 400 m of the embayment. Following severe floods the barrier may be entirely eroded, as in September 1987, but in common with other barriers along the Natal coast it is rapidly reinstated by landward reworking of the eroded sediment under wave attack. This is discussed further below.

Fromme's surveys revealed that the barrier morphology remains nearly constant, with only minor vertical and horizontal erosion and accretion. It maintains an average width of about 150 m, increasing to over 200 m when flattened by overwashing during storms. The forebeach slope averages 3^{o} but can be as steep as 8^{o} during storms.

In the winter of 1975 the morphology changed significantly due to a severe storm (Fromme, 1975). The forebeach was cut back to form a scarp in the berm and the lower forebeach accreted by almost 90 m at a low angle. At the same time, overwash across the southern low-lying part of the barrier deposited an extensive washover fan in the river-mouth. This appears to be a typical storm response according to aerial photographic evidence.

While the morphological changes associated with this storm event were great, the volume of sediment in the barrier environments was unchanged, material moved offshore during the storm was subsequently re-incorporated into the beach, while the overwash material remained on the inside of the barrier until the next major flood.

Analysis of Fromme's data may be used to calculate the approximate volume of sand in the Mtamvuna barrier. This involves the extrapolation of the selected traverses to the entire barrier using survey-contemporary aerial photography. A contour map of the barrier, constructed using this means is presented in Figure 4.5.

Cross-sections of the beach and barrier may then be constructed within certain limitations. The lack of mobility of the dune at the rear of the southern and northern beaches suggests that it rests directly on rock. This is verified by field mapping and certain of the cross-sections of Fromme (1975). The southern beach area is entirely underlain by rock outcrop as indicated by variations in sand cover in different aerial photographs (section 4.8) and in this area the covering beach sand forms only a thin veneer (Fig 4.5). The elevation of a terrace on top of the bedrock at 4.5 m CD is comparable to a wave-planed Late Pleistocene terrace near Durban (Cooper & Flores, 1991). This level is approximately at the same level of the modern back beach which makes it highly suitable for the accumulation of wind-blown sand dunes. This results in a decoupling of the aeolian component from the littoral sediment body and subsequent loss of this component from the overall sediment budget. Migration of the mouth across the barrier, and the almost permanently open inlet, may be attributed in part to turbulent flow and scour by tidal currents against this rock. It can also be linked to a low sediment influx and recycling of sediment in the embayment, points which are discussed in more detail below.

The beach adjacent to the northern bank of the river-mouth displays similar characteristics and the coastal dune appears to rest directly upon bedrock. The occurrence of outcrops in the river-mouth at low elevations, and on the coast at the mouth of the Zolwane River in the north indicate that bedrock again underlies this beach at shallow depth, although its non-exposure during erosive phases suggests that it lies at slightly greater depth than in the south. This may be linked to a considerably wider backbeach area in this part of the embayment. A cross-section through this part of the beach is shown in Figure 4.5.

A cross-section of a portion of the barrier across the mouth of the river is shown in Figure 4.5. The offshore extrapolation of the nearshore slope may be constructed from bathymetric data given in Hay (1984) and Flemming & Hay (1988). These papers indicate that a water depth of 10 m lies approximately 300 m offshore of the Mtamvuna River. Boreholes indicate that the medium- to coarse-grained sands of the Mtamvuna River barrier overlie silts at a depth of about 13 m below the berm (Orme, 1974) or about 8 m below chart datum. The upstream extent of barrier-associated sand bodies varies with time but the depth to which barrier sediments persist in the lower river-mouth is important for volumetric calculations of the barrier sand. Sediment distribution patterns (Section 4.5) show that silt and mud characterise the middle reaches of the river-mouth from a distance of about 400 m upstream

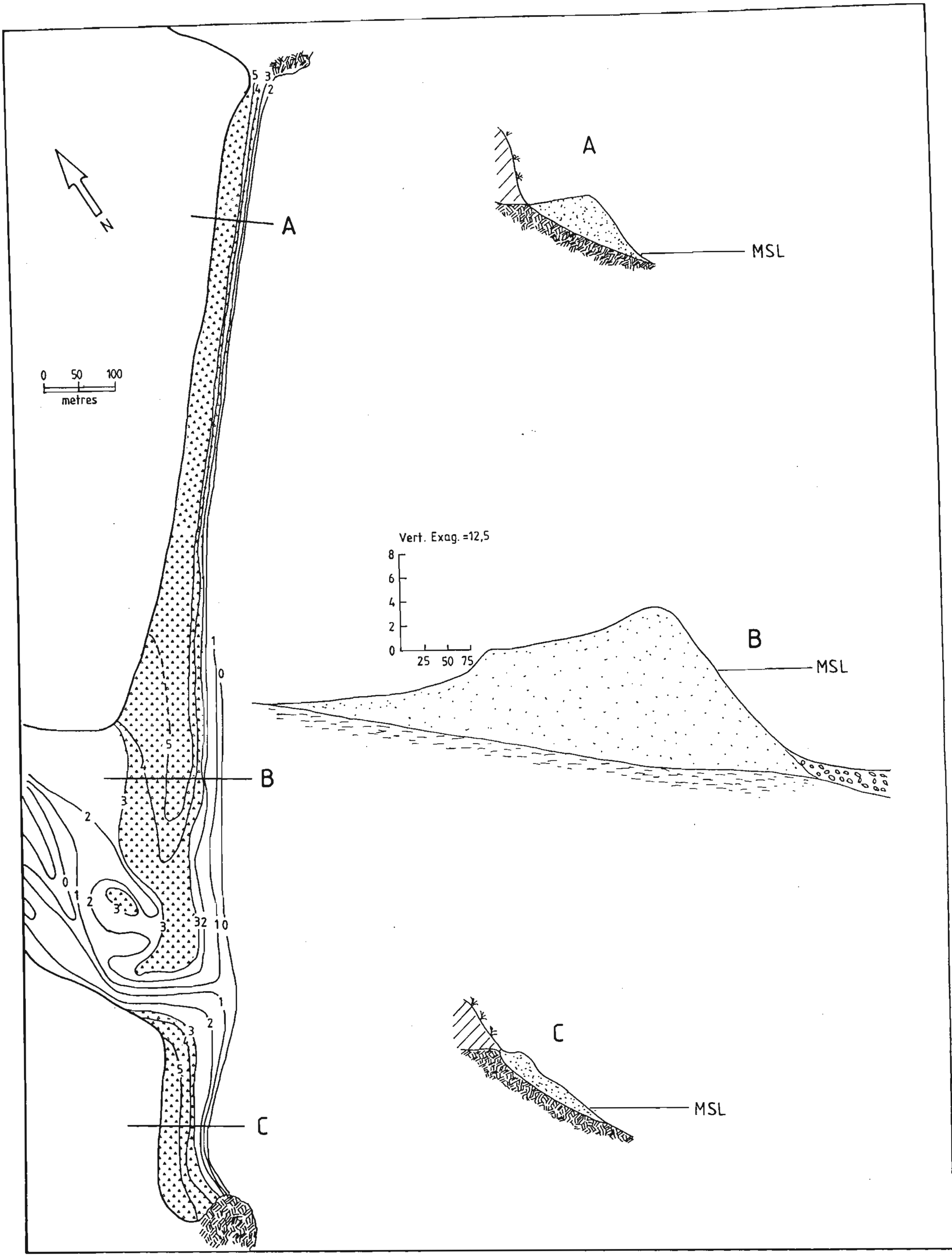


Figure 4.5. Morphology of the Mtamvuna river-mouth barrier. The barrier is located in a shallowly indented embayment. Contours shown are with respect to MSL. Barrier cross-sections for the three locations shown are depicted on the right. The northern and southern barrier sections rest on bedrock while the area directly opposite the river-mouth rests on fine-grained back-barrier sediments.

of the mouth at water depths of 4 to 8 m (= -2.5 to -6.5 m CD). This may be used to reconstruct the slope of the underlying silts thus allowing the cross-sectional structure of the barrier in this vicinity to be assessed (Fig 4.5).

Measurement of the cross-sectional areas of the various embayment beach components (Table 4.2) indicates that the greatest cross-sectional area in the embayment occurs in the barrier section which alone accounts for over 30% of the entire littoral sand in the embayment. The adjacent southern beaches contain only 9 % of the entire littoral sediment volume in the embayment and almost 60% of it in the northern sector.

	Cross-sectional area (m^2)	Shoreline length (m)	Volume (m^3)	% of Total
Barrier	368.3	350	128 905	31.7
S. Embayment	166.0	225	37 350	9.3
N. Embayment	266.4	900	239 760	59.0

Total littoral sediment volume			406 015	

Table 4.2. Volume of littoral sediment in the components of the embayment at the Mtamvuna river-mouth.

Given that the low tide volume of the river-mouth is approximately 1 x 10^6 m^3, the barrier sediment itself could fill in only a small portion of the remaining space, even when at its maximum upstream extent. It is generally prevented from doing so because of other factors detailed below (Section 4.8.2).

The morphology of the modern coastal dune has not changed noticeably since 1937, indicating a low recent accumulation rate of aeolian sand at the rear of the beach. The lack of aeolian sand accumulation is reflected in the near constant volume of sand in the embayment at any time.

4.4. COASTAL AND SHELF MORPHOLOGY

In the vicinity of the Mtamvuna river-mouth the coast is mainly rocky and sand deposits are restricted to narrow beaches, typically located in the inter- to supratidal zone in shallowly indented embayments and resting on bedrock. This sand is liable to be transported mainly by wind.

The continental shelf is narrow (10 km), and the shelf break occurs at approximately 100 m depth. Shelf sediment thicknesses are generally low, although a small depocentre exists off the Mtamvuna mouth in water depths between 10 and 50 m. Flemming & Hay's (1988) study of continental shelf sediments, showed that offshore of Port Edward, sediments were dominated by the medium sand fraction which they attributed to fluvial sediment supply from rivers around Port Edward. While the authors suggested that this was Holocene sediment, the current low sedimentation rates, particularly of bedload material, in both the Mtamvuna and adjacent Mzamba River mitigate against this. It is more likely that the depocentre represents a deposit formed after channel incision and deposition of the eroded material in an ancient delta at lowered sea-level, during the latest Pleistocene. The modern barrier sediment probably represents a transgressively reworked fraction of this sediment body.

4.5. RIVER-MOUTH SEDIMENTS

4.5.1. Sediment distribution patterns

Sediment samples were collected in the Mtamvuna river-mouth during July 1988 on the same cross-sections on which echo-sounding profiles were made (Fig.4.6A). Samples were collected at evenly spaced intervals across each transect.

Textural variation in channel sediments is depicted in Fig. 4.6.B. following the classification of Shepard (1954). This shows a well-defined tripartite division of bottom sediment textures in an upstream direction. Sediment in the barrier and the channel margins up to 300 m upstream of the mouth is mostly sand with only small proportions of mud. This sand is medium-grained, very well-sorted, and has a near-symmetrical grainsize distribution (Fig.4.7.A-C). It has a low organic content. The composition of these sands differs from most other Natal river-mouths in that they contain a high proportion of lithic fragments, probably derived from Dwyka Tillite. These sands contain the only carbonate in the river-mouth sediment (Fig.4.6D) and values average about 10%. The carbonate is skeletal in origin and fragments of molluscs and abraded foraminifera were identified, proving a marine origin for this component.

In the area between the barrier and a point 2000 m upstream, the channel sediments are mostly mud (up to 98%) and sandy mud (Fig. 4.6B) of which organic material comprises about 10 %. A near linear relationship with a correlation coefficient of 0.81 between organic and mud content of sediments throughout the river-mouth indicates that approximately 12% of the mud fraction comprises organic material. In this area of the river-mouth the sediment sand fraction has mean grainsizes almost exclusively in the very fine sand category although some fine sand occurs at the upstream end of this channel section. The sand is generally very well-sorted, but along the north bank sorting is poorer and falls in the moderately to poorly sorted category of Folk (1954). The sand fraction grainsize distribution is generally near-symmetrical except along the north bank, where a strongly coarse-skewed sediment was noted.

In the upper reaches of the river-mouth between 3000 and 5000 m from the inlet, the channel sediments are sand and muddy sand (Fig 4.6B). Organic content is reduced in comparison to the middle reaches but locally values of up to 13 % were recorded. The sand fractions are dominated by the medium to fine grades but differ from those in the lower reaches in having a coarse sand fraction and occasionally a very coarse sand or gravel fraction. The sand fraction has mean grainsizes in the medium to coarse sand range and is moderately to moderately well-sorted. Skewness is generally coarse but on a convex outer bend on the south bank the sand is finely skewed.

The highest gravel concentration was recorded in this area at Section 9 where it was overlain by a thin (2-3 mm) layer of mud. The gravel fraction was composed of subangular to subrounded grains up to 18 mm in maximum diameter. Larger grains included shale (probably Dwyka Tillite matrix), Natal

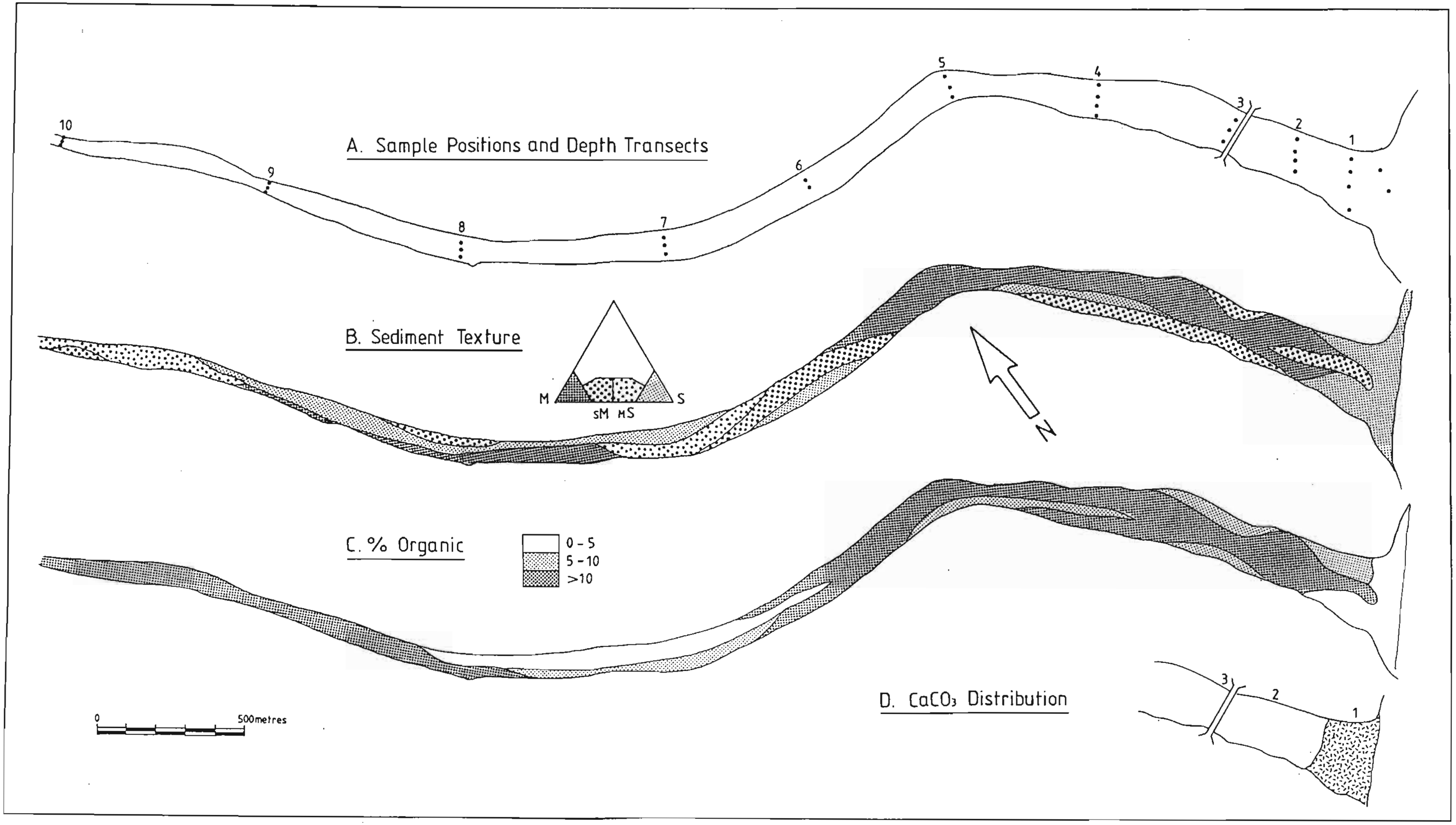


Figure 4.6. Sampling stations and sedimentary characteristics of the Mtamvuna river-mouth channel. (A) Sample locations. (B) Variation in sediment texture. (C) Proportion of organic material in channel sediment, (D) areas containing over 1% carbonate in bottom sediments.

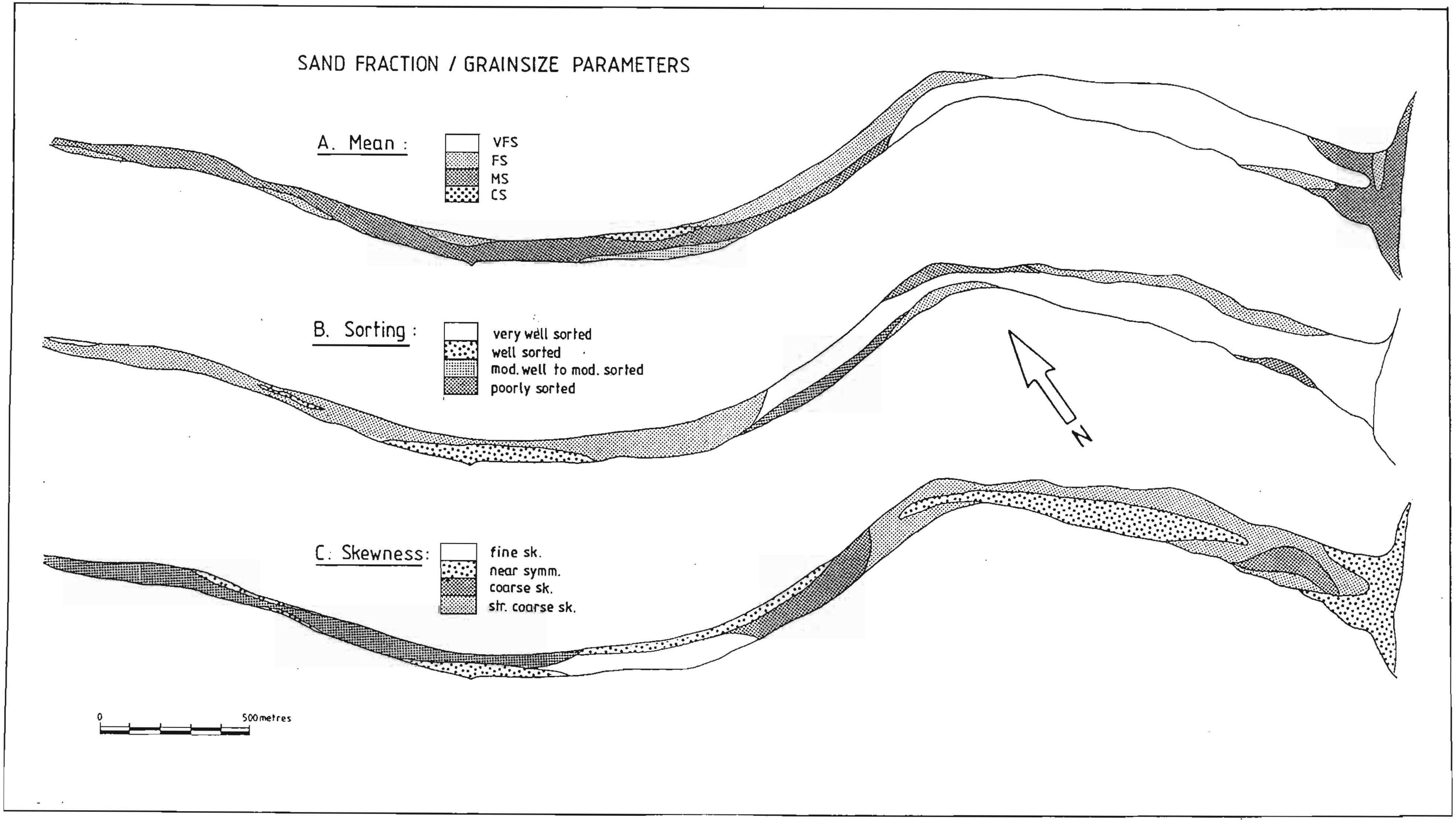


Figure 4.7. Characteristics of the sand fraction of estuarine sediments. (A) Mean sand grainsize, (B) Sorting of the sand fraction, (C) Skewness of the sand grainsize distributions.

Group Sandstone and granitic fragments while the smaller grains comprised quartz, feldspar and occasional mica grains.

4.5.2 Discussion

The above results clearly illustrate that there is an upstream zonation of sediments in the Mtamvuna river-mouth. This may be interpreted in terms of sediment provenance and sedimentary processes within the river-mouth. The upstream area, which comprises medium to coarse, poorly sorted sand and muddy sand, is typical of many fluvial deposits in Natal. The sediment grainsize reflects the catchment geology of the area which is Natal Group Sandstone and gneisses of the Proterozoic basement complex. This is borne out by the composition of identifiable grains in the gravel fraction. Bottom current velocities required to transport gravel-size grains of 18 mm diameter are in the region of 1 ms^{-1} and it is unlikely that these have been transported far since entering the river-mouth.

The coarsely skewed grainsize distribution of sand in the upper reaches of the river-mouth suggests that fine sediment has been winnowed from the channel and this has preferentially concentrated sand and gravel in this area. The bedrock and boulders exposed in the river upstream of the river-mouth suggests little fluvial bedload sediment input from upstream and therefore an alternative provenance must be sought for the upper channel sediments.

Landslides are common along the upper reaches of the Natal Group Sandstone gorge through which the Mtamvuna flows. The lower parts of the gorge are lined with scree slopes and it therefore appears likely that much of the river sediment is derived from this source. King (1980) documented sediment supply from talus as up to 17% of the total in a cliff-bound estuary in south Wales. Recent landfalls were much in evidence in the Mtamvuna in early 1988 (Plate 4.2) following the heavy rainfalls and floods of September 1987 and the presence of large angular blocks in the upper channel provides incontrovertible evidence of periodic rockfalls. Maud (1988) noted that slope failure and resultant earthflows are common in the Natal Group Sandstone after prolonged rainfall and saturation of the overlying soils. This he attributed to permeable soils overlying either an impermeable subsurface clay-rich horizon or bedrock. In the Mtamvuna river-mouth gorge earthflows of this type are unlikely due to the cliffed nature of the gorge sides which do not carry a soil horizon. In this case collapse of the cliff faces is more likely to take the form of a rockfall. The Natal Group Sandstone is well jointed (Maud, 1988) and excess pressure in the joints arising from rainfall will promote cliff failure. Weathered scree material washed off the screes into the river channel by overland flow may be the source of the medium-grained sand in the upper reaches of the river-mouth. Weathered Natal Group Sandstone typically produces a fine to medium-grained sandy soil (Beater 1970; Maud,1988; Partridge and Maud,1987). Areas in the upper reaches of the river-mouth which contain mud within the bottom sediment probably do so as a result of suspension settling during low flow periods.

The deep middle reaches of the river-mouth are typified by muddy sediment with a high organic content. The very well sorted sand fraction of this sediment, coupled with its very fine sand grainsize suggests deposition from suspension following increased river flows upstream and rapid deceleration in the deep part of the channel. There is a tendency for a slight upstream increase in sand grainsize in the deep channel and this, together with the factors outlined above, suggests that the deposits in this area represent a type of laterally-restricted, pro-delta environment, confined within the river-mouth channel because sedimentation has not proceeded to such an extent that the deltaic sediments are deposited in the sea. Gould (1960) described a similarly confined deltaic deposit in the Hoover Dam on the Colorado River, in which delta bottom sets and foresets comprise clay and silt respectively. As no bedforms were noted in the Mtamvuna channel upstream it appears that turbulent flow may entrain the fine fraction of the bedload, taking it into suspension as it flows through the upper reaches. The sediment in the middle reaches then represents the fine material eroded from the coarsely skewed sands in the upper reaches of the river-mouth.

A marked change in skewness along the north bank in the middle reaches may be attributed to gravity fall of coarser particles from the sandstone cliffs which define the river-mouth's north bank.

The lower reaches adjacent to the barrier are typified by shallower water and sandy sediment whose medium grainsize, very good sorting and near symmetrical distribution suggest reworking under high energy conditions, as expected in a wave-dominated barrier and inlet environment. The fact that the area upstream is considerably deeper than the mouth area and is bottomed by muddy sediments rules out the river as a sediment source under present conditions. No other sediment-transporting river discharges into the ocean in the vicinity of the Mtamvuna river-mouth and the barrier sediment must therefore be considered to be transgressive marine sand, which may ultimately have been derived from the Mtamvuna River during a lower sea level stand. A transgressive marine origin is further indicated by the presence of up to 11 % skeletal carbonate in the sediment.

4.6. SEDIMENTARY FACIES OF THE MTAMVUNA RIVER-MOUTH

Textural variations discussed in the previous section, together with variations in the primary and biogenic sedimentary structures, permit recognition of several characteristic sedimentary facies within the river-mouth area. These are discussed below. Their spatial arrangement in terms of the facies architecture of the river-mouth is assessed in section 4.10, where a facies model is presented. As in the case of most Natal river-mouths a distinction can be made into barrier-associated and back-barrier facies (Cooper, 1988a).

4.6.1. River-mouth facies

4.6.1.1. Upper river-mouth channel.. Sediment in the upper reaches of the Mtamvuna river-mouth is dominated by medium- to coarse-grained sand which is characteristically unbedded. Neither bedforms nor bioturbation of the channel floor were observed. The lack of current-generated bedforms suggests that much of this sediment is derived from adjacent rockfalls rather than from upstream. The deposit resulting from such an environment may resemble a typical scree deposit but will lack the fine fraction: this is characteristically removed by river currents in the same way that fines are winnowed from alluvial fans by wind action (Friedman & Sanders, 1978).

4.6.1.2 Middle reaches . The middle reaches of the Mtamvuna river-mouth are the deepest (up to 13 m). Bottom sediment in these areas is dominated by mud (up to 96%) and a minor component of very fine to fine sand. Sedimentation in these areas is therefore dominated by suspension settling, and rates of sedimentation caused by this process must be sufficiently low to have enabled the preservation of the great depths observed in the river-mouth. Sedimentary structures and bioturbation are rare. The lack of bioturbation may be attributed to frequent anoxic and even sulphidic water conditions which are unsuitable for benthic life. The deep channel is dominated by anoxia conditions and the lack of living organisms is demonstrated by the pristine nature of the very fine sediment.

4.6.1.3. Vegetated channel margins. The shallow channel margins are commonly vegetated. This is generally specialised aquatic vegetation tolerant of the salinity and water-level variations experienced at each location at which it occurs. In the middle to upper reaches marginal vegetation comprises *Phragmites* reeds which are intolerant of high salinities (Benfield, 1984). These act to stabilise sandy banks and provide a quiet water habitat for aquatic fauna. In the lower reaches, mangroves of the genera *Bruguiera* and *Avicennia* are present in small areas. They support dense comunities of burrowing crabs and gobioid fish (Berjak *et al.*, 1977).

4.6.1.4. Overbank levees. Limited overbank deposits occur in the upper reaches where they form levees whose lateral extent is restricted by the narrow river valley. They are up to 4 m thick and are either muddy or sandy. Overbank sandy deposits tend to occupy more elevated positions than muddy ones. This may reflect the higher flows and water levels required to transport sand in suspension. The muddy deposits are typically located close to the present water level and are generally bioturbated with both invertebrate burrows and root casts as they provide a suitable area for vegetal colonisation.

Variation from muddy to sandy overbank deposits depends on the velocity and turbulence of the flows which entrained and deposited them. Both of them overlie screes at the valley sides which probably provided the base upon which deposition could occur.

The sandy overbank deposits are generally thinly parallel-bedded and bioturbation structures are limited to surface trails of arthropods and small vertebrates. Vegetation cover on most levees causes destruction of bedding by rootlet bioturbation.

4.6.2. Barrier-associated facies

4.6.2.1. River-mouth barrier. The barrier of the Mtamvuna river-mouth is located in the lower reaches of the river valley and is bounded to north and south by rocky coastlines. This limits longshore drift of material to and from the barrier. The barrier comprises medium grained sand, and the dominant sedimentary motif is a graded, planar-bedded washover deposit which dips landward at low angles. The forebeach is much steeper and characterised by graded beds dipping seaward at between 3 and 8 degrees.

One or more extensive washover fans frequently extend into the river-mouth. These are generated by storm waves and transport material from the forebeach into the back-barrier area. This material may be recycled back into the nearshore through ebb-tidal currents or remain in the back-barrier area until a large flood erodes it.

4.6.2.2. Inlet channel. The inlet migrates within the constraints imposed by the steep, confining valley sides. These variations in position may be related to changes in discharge, wave approach and barrier width. Limited lateral inlet movement occasionally takes place by marginal swash bar migration which produces large-scale bedding dipping gently to the north or south (ie parallel to the length of the barrier). Alternatively the inlet may change position by filling up with overwash-deposited sand and subsequently cutting a new course across the next lowest part of the sandbar.

4.6.2.3. Tidal deltas. A noteable feature of the Mtamvuna river-mouth is its flood-tidal delta, which may be elongated into the river-mouth for distances of up to 400 m landward of the inlet. Variation in flood-tidal delta morphology is shown in Figure 4.8A-J. The flood-tidal delta and shallow washover fan surfaces in the river-mouth are sparsely inhabited by burrowing crabs of the genus *Ocypode* and a burrowing sandprawns of the genus *Callianassa* .

The relative strength and separation of ebb and flood-tidal flows permits the simultaneous existence of ebb and flood-tidal deltas. Because ebb-tidal deltas are subjected to direct wave influences their internal structure and morphology is different from flood-tidal deltas. In the Mtamvuna case ebb-tidal deltas are limited in size by high wave energy. Their internal structure has not been studied

Sand in flood-tidal deltas may be reworked by swash action in the lower reaches of the river-mouth and driven landward to the channel margins where it forms marginal bars or beaches. The potential for reworking is enhanced by changes in spatial hydrodynamics caused by the closure of the inlet or inlet channel movement. These marginal bars are commonly inhabited by burrowing *Ocypode* crabs.

4.7. FLOOD IMPACTS AND POST-FLOOD RECOVERY

During the study period a major flood occurred in the Mtamvuna (September, 1987). Lack of access to the southern Natal coast due to damage to the road infrastructure prevented extensive observations of the flood impacts on the ground but aerial photography was used to determine the major morphological changes. Flood impacts were mainly restricted to the mouth area where the barrier was eroded and a plume of fine suspended sediment extended into the Indian Ocean. Overbank deposits accumulated in the margins of the channel between the bank and the cliff sides. The reduction of surface velocities with depth probably reduced any scouring action the flood may have had in the middle reaches, while cross-sections surveyed after the flood revealed no major downstream progression of the shallow, upper channel facies.

Following the flood the barrier was rapidly reconstructed, and then began a to retreat via barrier rollover. Growth of flood-tidal delta and washover deposition proceeded as the barrier was transported landward to assume its normal equilibrium morphology at the point where bedrock outcrop at the rear of the beach prevented further migration. No longshore transport or loss of sediment from the embayment and no particular gain of sediment was evident as a result of the flood. A similar conclusion is reached below for severe floods in 1984.

4.8. HISTORICAL CHANGES IN MORPHOLOGY

Morphological changes in the Mtamvuna during historical times may be gauged by comparison of available aerial photographs and river-mouth channel cross-sections. Such changes are discussed in this section.

4.8.1. Changes in channel morphology

The original bedrock channel size may be estimated by extending the slope of the flanking margins downward to a point where the two sides intersect. This occurs at a depth of approximately 40 m near the barrier. This is consistent with borehole investigations which failed to reach bedrock at -32 m at the mouth of the river-mouth (Orme, 1974; Fig 4.9).

The position of the palaeochannel base at the upper limit of the present river-mouth is indicated by a narrow rock-confined channel and the presence of numerous boulders in the river channel. The palaeochannel was not much deeper than the estimate of 10 m which was used to calculate the bedrock palaeovalley dimensions. When computed this gave an estimated volume for the original bedrock valley of 8.9 x 10^6 m^3. The current water volume below low tide is 1 x 10^6 m^3 which indicates that the river-mouth is presently about 89 % full of sediment.

Using an estimate of 10 m depth to bedrock at the head of the river-mouth produces a bedrock channel gradient of 6 m per km (0.006) over its lower 5 km, substantially steeper than the modern river gradient (0.0016) over the lower 16 km of its course. Continuing the extrapolation to the edge of the continental shelf at 100 m (assuming the river flowed directly to it without significant deviation) yields a bedrock channel gradient from the head of the present river-mouth (0 to 100 m depth) over the 5 km of the river-mouth and 10 km-wide continental shelf of 0.15 or 6 m /km. This may be taken as verification of the assumed bedrock channel depth.

Therefore, approximately 7.9 x 10^6 m^3 of sediment has been retained in the river-mouth since it began to fill. Most of this is fluvially derived, but the modern barrier sediments comprise almost 1.3 x 10^6 m^3. The remaining 6.6 x 10^6 m^3 represents net deposition in the river-mouth since drowning of the bedrock channel during and since the Postglacial Marine Transgression.

4.8.2. Changes in barrier morphology

NRIO (1981a) and Perry (1985c) assessed morphological changes in the Mtamvuna river-mouth based on aerial photography. One of the major findings was that while the channel migration was limited by the steep rocky banks, a significant increase in side-bar areas occurred between 1937 and 1943. This was attributed by Perry (1985c) to an increase in fine-grained sediment yield from upstream but a closer examination of the areas in which the reduction occurred, coupled with the coarse-grained nature of the deposited sediment, rather suggests that landslides and rockfalls were responsible for this increased sedimentation

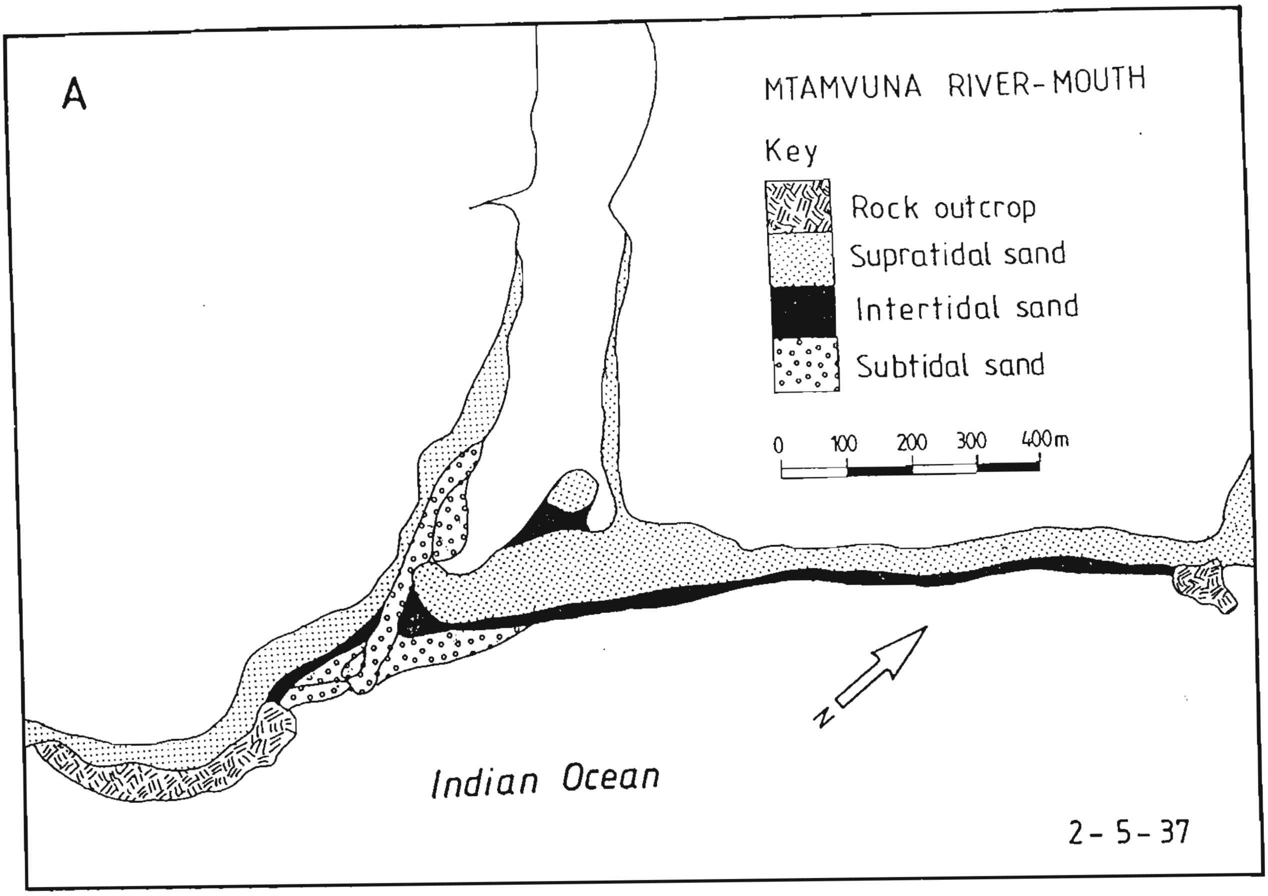
Most of the changes which have occurred in the Mtamvuna river-mouth are restricted to the lower reaches in the vicinity of the barrier. Barrier morphology at various times was scaled to 1: 10 000 for comparison of morphology at different periods. The results are shown in Figures 4.8A-J. The major morphological characteristics are summarised in this section.

2nd May 1937. Fig. 4.8A. Analysis of aerial photography of the river-mouth in 1937 reveals that an inlet was present in the southern end of the barrier and that a small flood-tidal delta was present in the river-mouth. A large ebb-tidal delta was present at the inlet. Two swash bars on its seaward margin indicated landward movement of the ebb-delta. Marginal sand bodies extended up the flanks of the river-mouth channel to the position of the present bridge. A large sand body landward of the barrier may be a washover fan or part of an old flood-tidal delta.

18th April 1973. Fig. 4.8B. Photography from this date shows the inlet channel situated at the extreme south of the embayment against the rock outcrop there. No flood-tidal delta was present and only a small ebb-tidal delta occurred. The beach was particularly wide opposite the northern margin of the river channel and erosion was evident in a concavity immediately north of this sand accumulation. The wide beach section may represent ebb-tidal delta deposits from a slightly earlier inlet position which caused updrift erosion of the adjacent beach section. Upstream marginal sand bodies occur on the southern bank and what appears to be a relict flood-tidal delta deposit is present. No flood-tidal deposition is evident at the active inlet, a fact which might be ascribed to the rock across which the channel flowed, preventing upstream sand transport.

11th July 1975. Fig. 4.8C. At this time the inlet assumed a position across the southern part of the barrier. Both ebb and flood-tidal deltas were present. A large washover fan was deposited in the southern part of the barrier and this coincided with a period of shoreface erosion and reduction of beach gradient due to a storm and associated high wave energy (Fromme, 1975). Channel marginal sandbars occurred on the south bank of the river-mouth. The barrier was thinner at its northern end than in April 1973.

23rd June 1976. Fig. 4.8D. The 1976 orthophoto shows an unusually large volume of sand on the marginal bars of the south bank of the river-mouth and a small volume of sand in a marginal bar on the north bank. The inlet channel was in a southerly position and the morphology indicated that it was



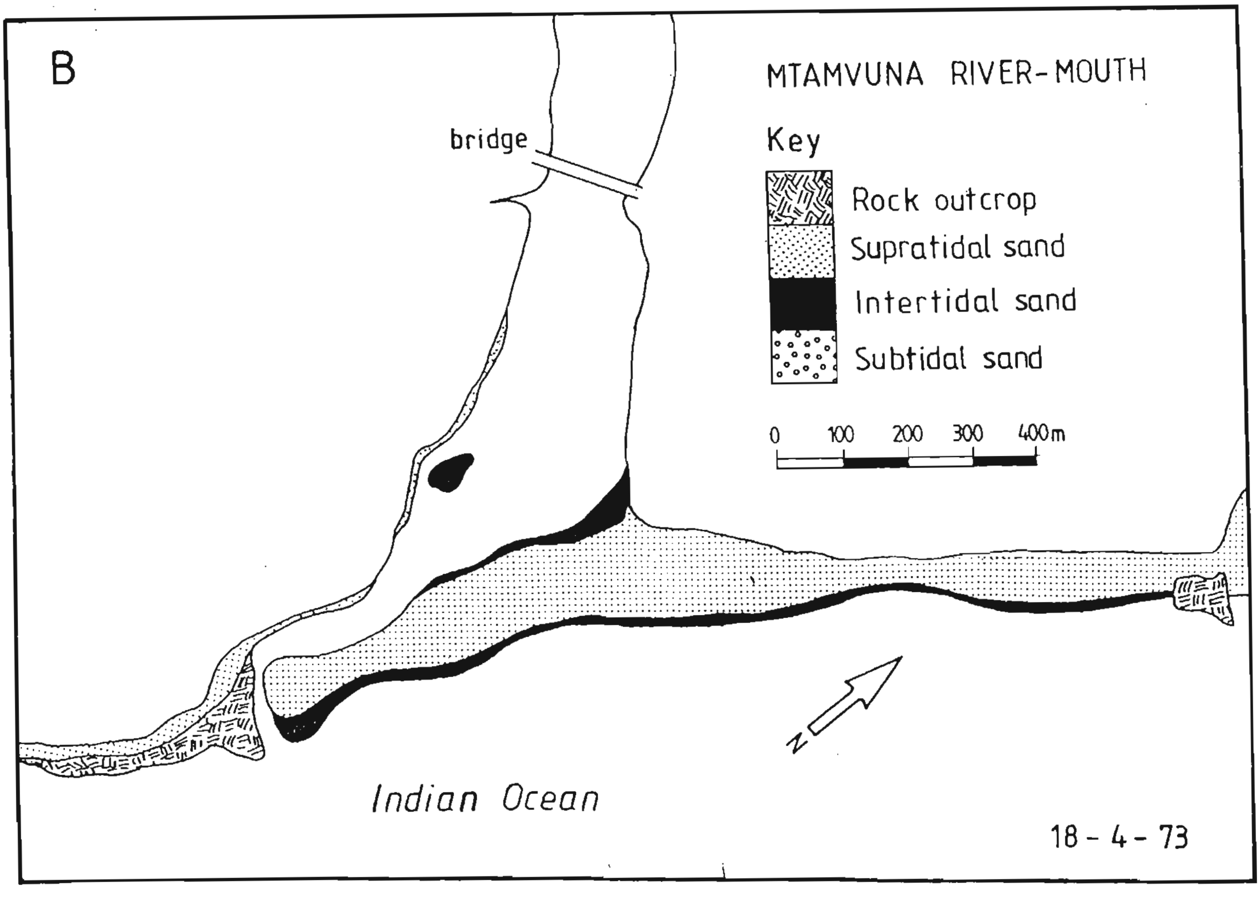


Figure 4.8A-J. Historical changes in morphology of Mtamvuna river-mouth based on aerial photography 1937-1989 (continued overleaf).

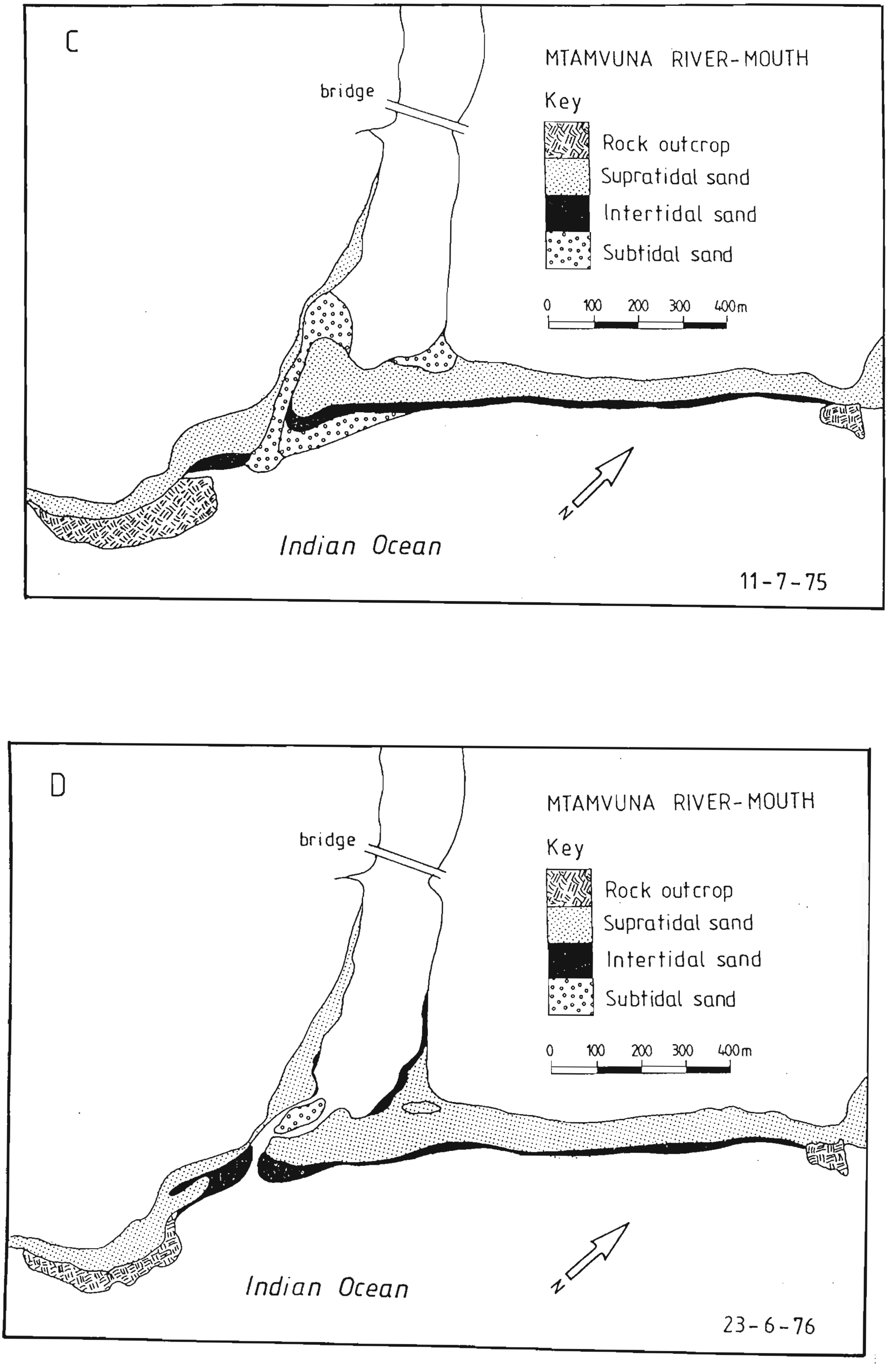
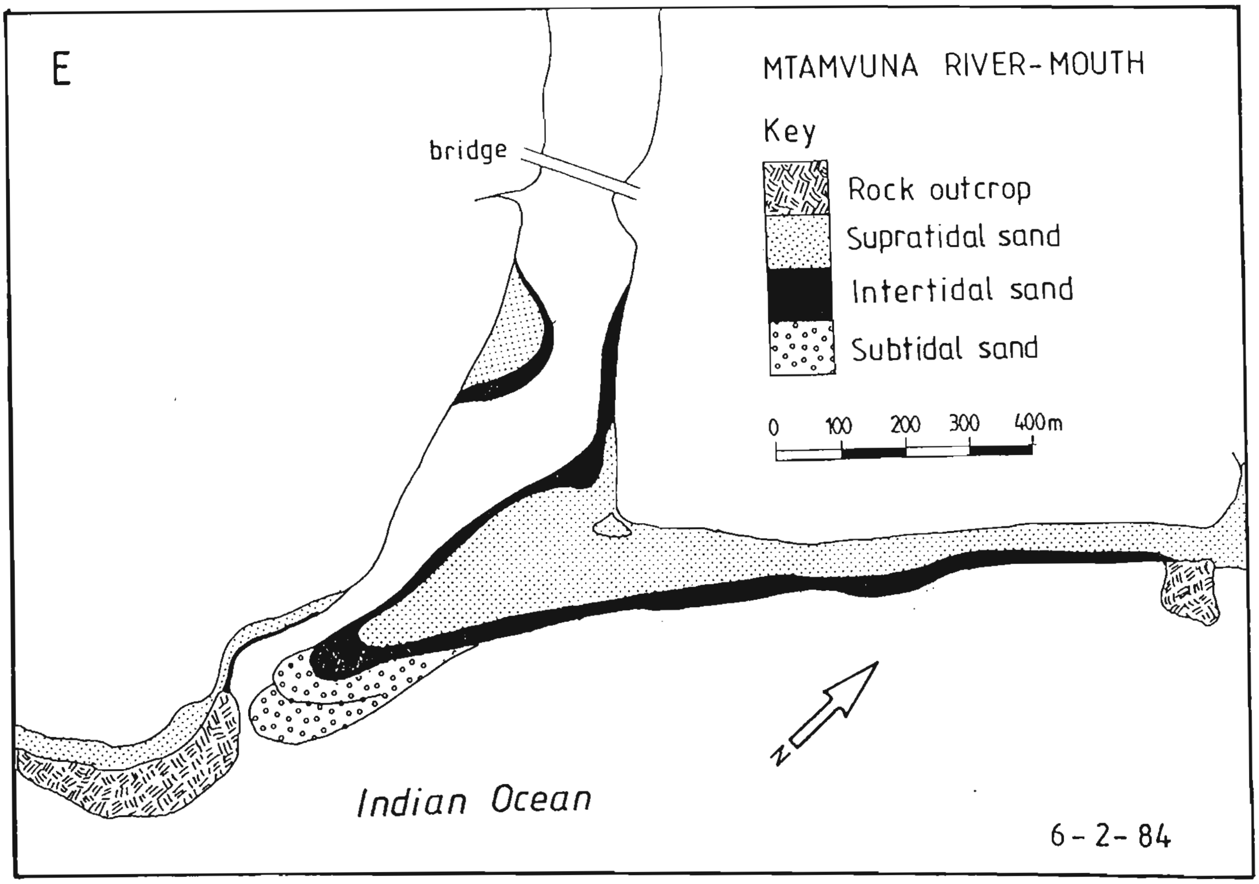


Figure 4.8A-J. Historical changes in morphology of Mtamvuna river-mouth based on aerial photography 1937-1989 (continued overleaf).



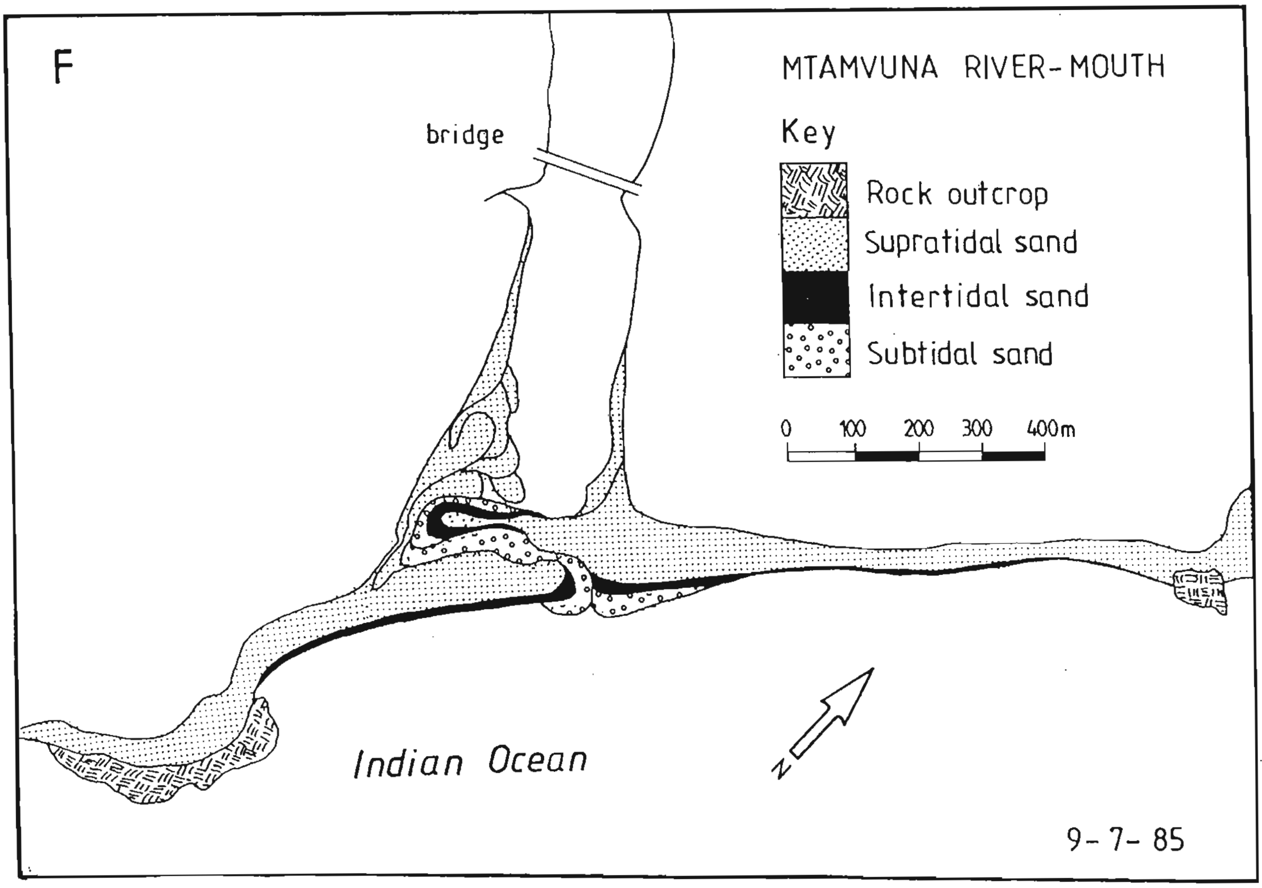
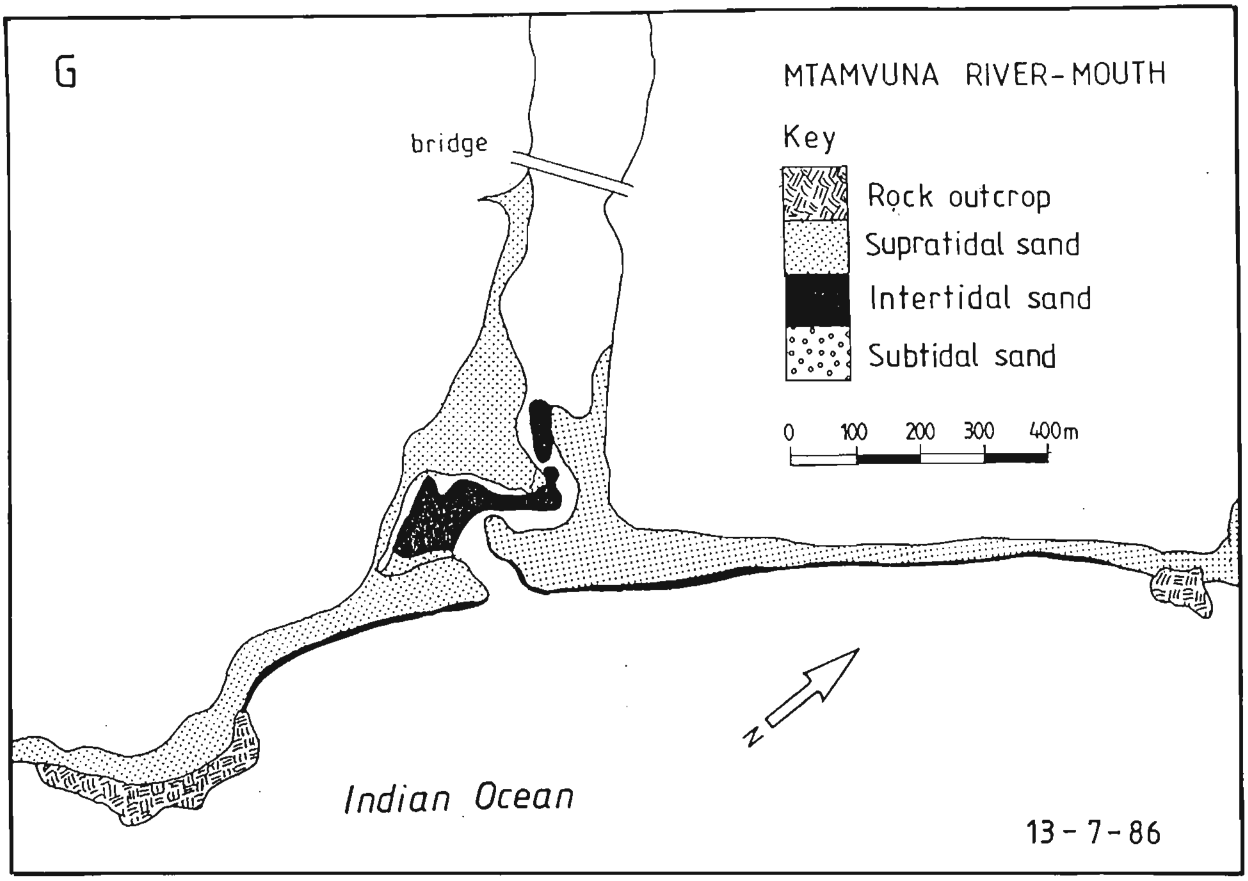


Figure 4.8A-J. Historical changes in morphology of Mtamvuna river-mouth based on aerial photography 1937-1989 (continued overleaf).



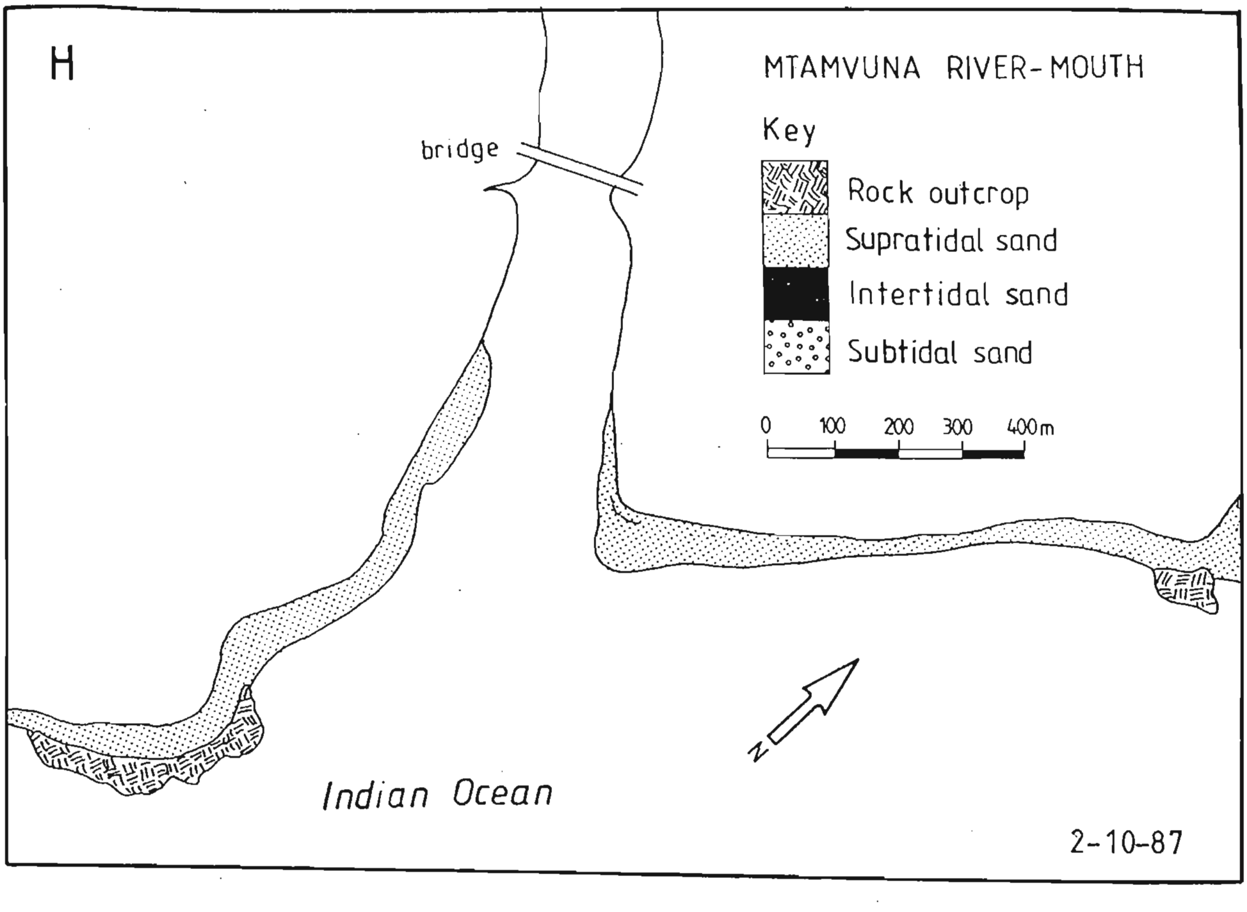
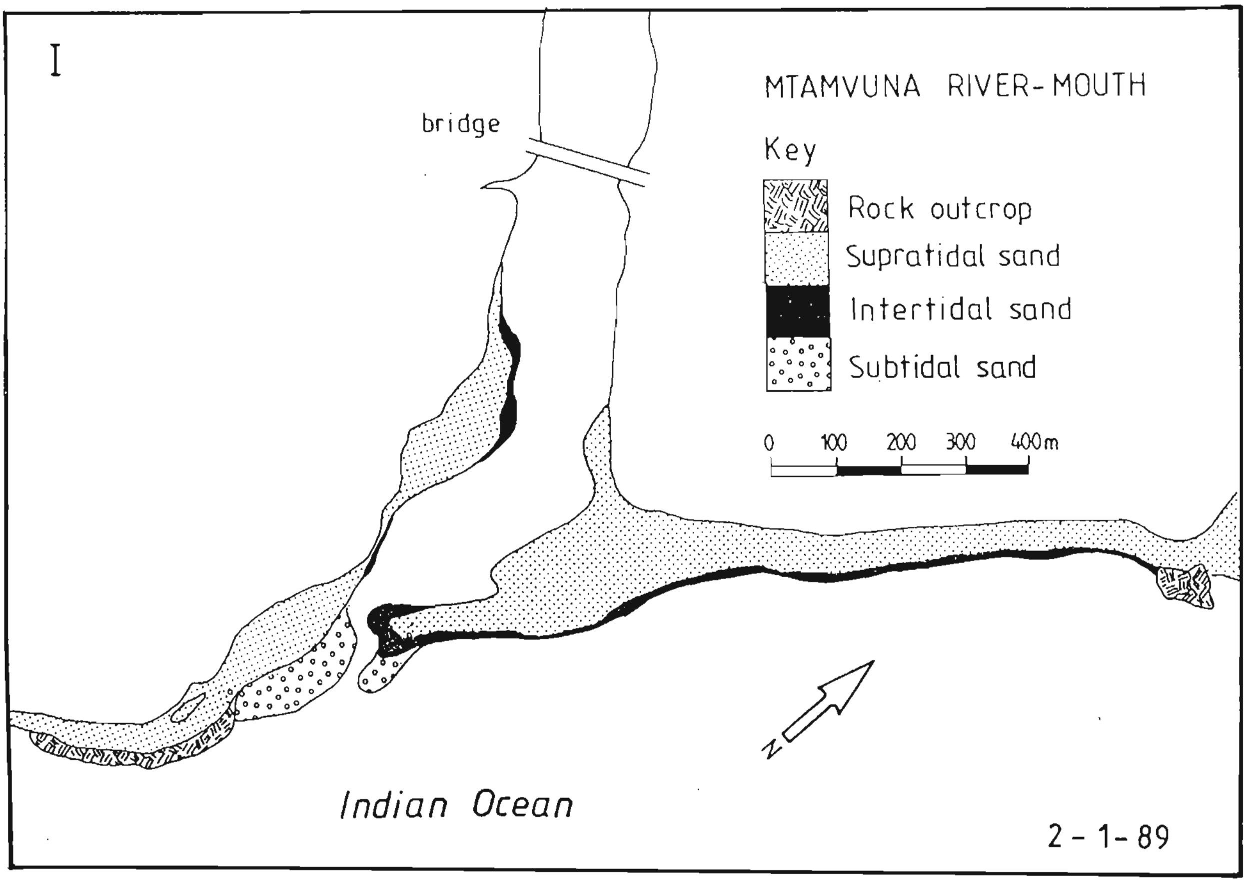


Figure 4.8A-J. Historical changes in morphology of Mtamvuna river-mouth based on aerial photography 1937-1989 (continued overleaf).



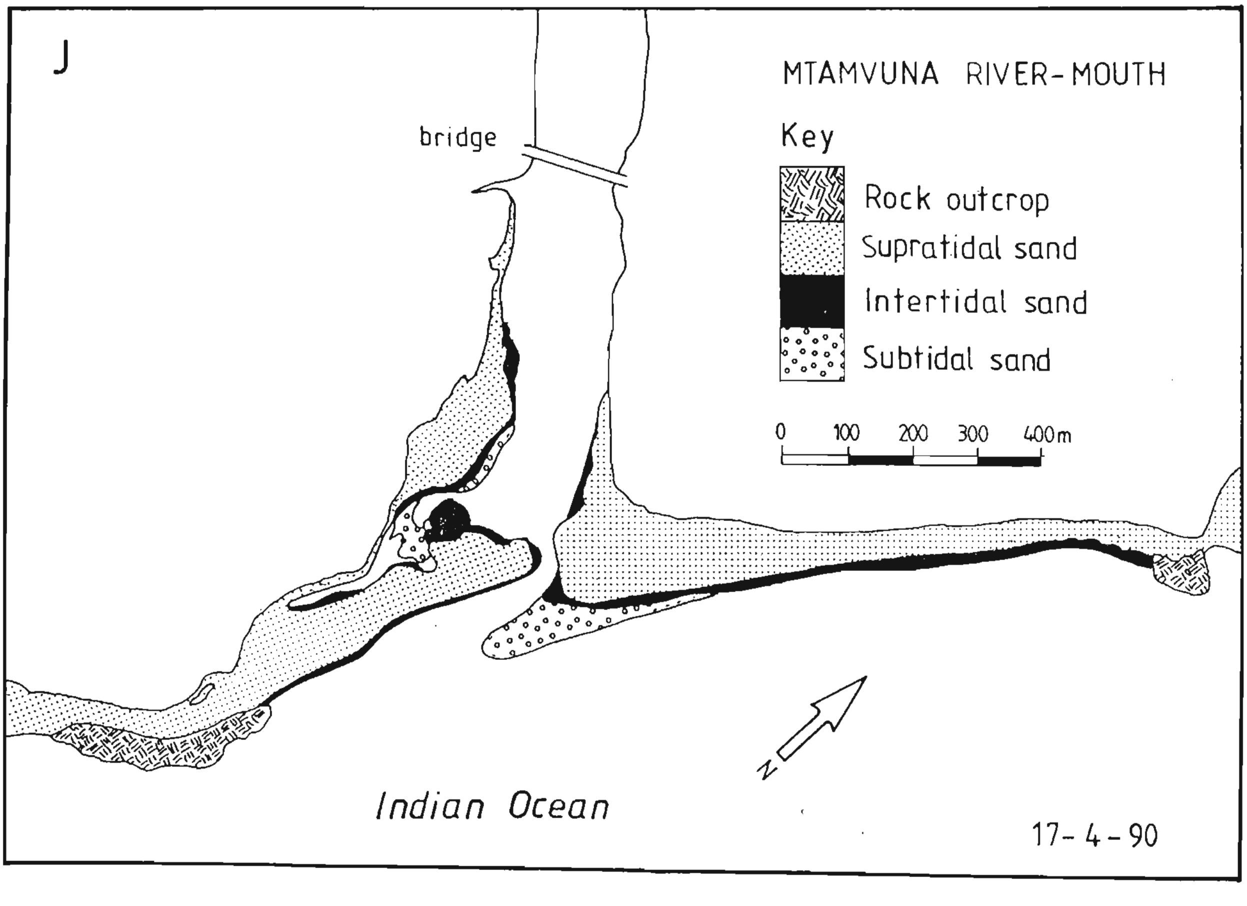


Figure 4.8A-J. Historical changes in morphology of Mtamvuna river-mouth based on aerial photography 1937-1989

migrating northward. A previous, recent inlet channel had taken the course against the rocks in the south of the embayment but this had been abandoned and a swash bar had partially enclosed the former channel position. A small flood-tidal delta was present and an ebb-tidal delta was formed on the northern part of the inlet.

6th February 1984. Fig. 4.8E. At this time the river-mouth had recently experienced the effects of tropical cyclone Demoina which struck Natal in January 1984. The inlet channel was located in the extreme south of the embayment and a large ebb-tidal delta was present. The orientation of the ebb-tidal delta suggested that it had prograded south (and would ultimately close the inlet there, causing it to reform back in its normal position). No flood-tidal delta was present. A thin channel-marginal sand bar extended up the north bank of the river-mouth and a prominent marginal bar was present some 250 m upstream on the southern bank. These marginal bodies may have been deposited following the Demoina flood before the barrier was back in place. That the barrier was reconstructed in approximately its normal position after complete erosion in the Demoina flood, is evidence of rapid wave reworking of sediment in the nearshore.

9th July 1985. Fig.4.8F. In 1986 the inlet channel followed a sinuous path, running obliquely across the barrier. A small ebb-tidal delta was present in the same position as the wide beach of April 1973, suggesting that the 1973 position resulted from a similar mouth configuration shortly before the time of photography. The sinuous channel was shallow and contains several sand bodies which terminated inside the river-mouth in a flood-tidal delta. The flood-tidal delta displayed a number of sand bodies prograding into the river-mouth and had coalesced with the prominent marginal bar which had been present since February 1984. A small marginal bar occurred on the north bank with similar dimensions to that of 1984. The net effect of sedimentary processes since 1984 was to drive the barrier landward and transport the former ebb-delta material landward into the river-mouth, enlarging the flood-tidal delta

13th July 1986. (Fig 4.8G) Photographic coverage of the barrier at this time indicates a similarly large accumulation of sand on the inside of the inlet as was present in July 1985. The flood-tidal deltas had evidently coalesced with the marginal bar to produce a very large marginal bar on the south bank. The inlet channel had assumed a position further to the south on the seaward margin of the barrier and a position further to the north on the landward side. A flood-tidal delta was deposited adjacent to the northern bank and had begun to weld onto the marginal bar there. The seaward end of the inlet channel was not visible in the photographs.

2nd October 1987. Fig.4.8H. This photograph was taken 7 days after the peak of devastating floods of September 1987 during which the Mtamvuna peak discharge was calculated at 2680 m^3s^{-1} (Perry 1989). The turbidity of the water makes identification of any subaqueous sand bodies impossible but the complete erosion of the subaerial portion of the barrier is evident. The depth of scour could not be determined. River flow appears to have been concentrated against the northern bank and the marginal bar on the south was partly preserved. All flood-tidal deltas and the bulk of the marginal bars were eroded. A large suspended sediment plume extended northwards in the nearshore zone.

On 2nd January 1989 (Fig. 4.8I) the river-mouth barrier was reformed since the September 1987 flood and the outlet channel trended obliquely southeast across the barrier. A large ebb-tidal delta was present at the outlet. The beach to the north had accreted since the flood and limited flood-tidal deposition had occurred inside the river-mouth.

On 17th April 1990 (Fig. 4.8J.) the southern face of the barrier had retreated landward and the outlet channel was positioned in the centre of the barrier. Sediment buildup in the river-mouth was in the form of larger flood-tidal deltas and subtidal sand bodies.

4.8.3. Discussion

The results given above indicate that the Mtamvuna river-mouth barrier shows wide variation in morphology. This arises mainly from the position in which sediment is stored and changes appear to be caused by variation in mouth position, which responds to fluvial discharge variations. The outlet takes a sinuous route during low discharge and a more direct route when discharge is high. Under extremely low discharge the mouth may close, while with extremely high discharge the entire barrier may be eroded. Such changes result in the erosion and redeposition of barrier and adjacent beach sediment (Plate 4.3A,B). However, comparison of barrier morphology at different times suggests that no long-term erosion or accretion is evident. A qualitative comparison of the various morphologies also suggests that the sand volume in the embayment remains constant.

The location of the Mtamvuna river-mouth in an embayment with an equilibrium planform coupled with a lack of sand in the littoral zone south and north of the embayment precludes losses or additions of sediment from those sources. The deep river channel upstream, and sediment distribution patterns within the river-mouth, also indicate that no bedload sediment is supplied from that source. This is in accordance with conditions prevailing in the small neighbouring Zolwane river-mouth the bed of which is almost entirely rocky (Begg 1984a). Thus the combined volume of sediment in the barrier and the embayment as a whole is essentially fixed. The low onshore loss of sand to aeolian dunes is attested to by the lack of morphological change in the coastal dune. Offshore losses cannot be assessed accurately but in view of the rapid reconstruction of the barrier and beaches following major fluvial floods and storms, it appears that offshore areas act only as temporary storage areas for eroded beach sediment which is reworked landward after the extreme event.

The low variation in planform morphology of the barrier face and adjacent beaches within the small embayment may reflect equilibrium with the dominant incident wave regime, and deviation from this situation (for example following ebb-tidal delta deposition) causes erosion of the new feature once wave energy exceeds the hydrodynamic forces which deposited the delta. Thus the distance over which the face of the barrier may migrate landward is limited by wave refraction patterns. The adjacent beaches in the embayment are protected from progressive erosion or landward translation by the presence of

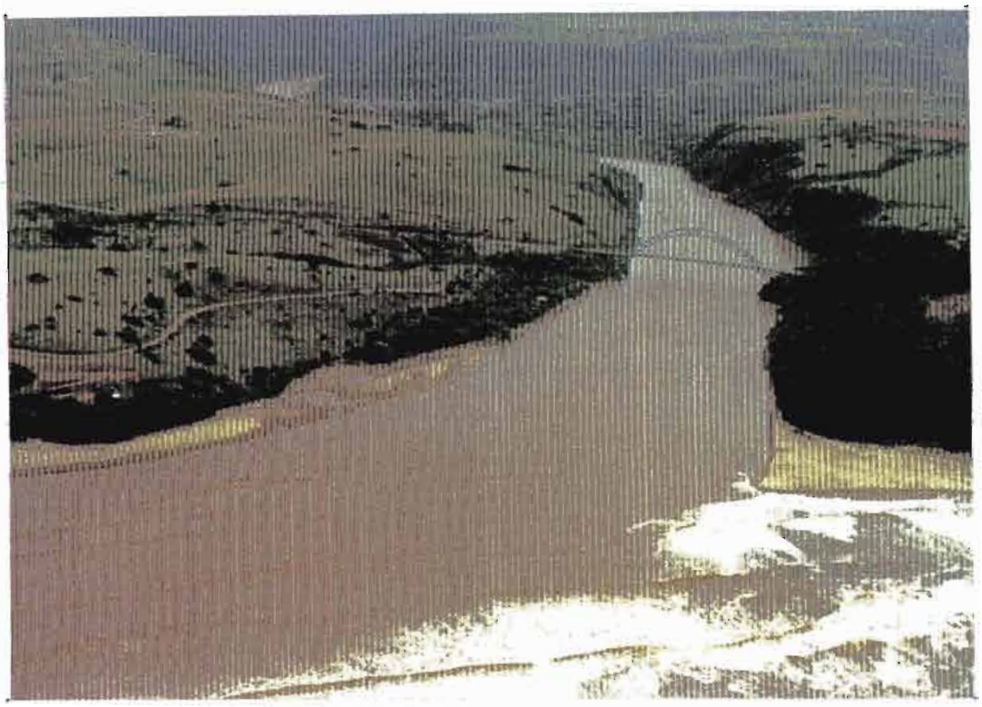


Plate 4.3A. The Mtamvuna river-mouth on 30th September 1987 looking west from the coast. The barrier is completely eroded opposite the river-mouth. sheltered portions of former flood-tidal deposits are preserved on the southern bank of the river.

Plate 4.3B. The Mtamvuna river-mouth on 15th April 1990 from a similar angle to that shown above. The barrier has reformed and the outlet runs obliquely across the centre of the barrier. Note the flood-tidal deltas in the lower reaches of the river-mouth. These act as storage for sediment excess to equilibrium planform requirements.

Plate 4.3A,B. Photographs showing the river-mouth in flood and after the barrier has reformed.

bedrock at shallow depths and consequently the planform shape of the barrier and embayment beach is adjusted to this factor. Sediment in the shallow embayment in excess of hydrodynamic equilibrium requirements is stored in the barrier which consequently shows a much greater cross-sectional area than the adjacent areas (Fig. 4.5). The barrier's location across the mouth of the incised river valley render it the only part of the embayment with a storage capacity for excess littoral sediment. This sediment is driven landward into the river valley to a point where landward-directed flood-tidal currents are insufficient to transport sediment further upstream.

In a review of coastal barrier morphology in southeast Australia, Thom (1983) identified several types of prograded Holocene embayment barriers in a setting where fluvial sediment supply to the coast is negligible and alongshore inputs limited by embayment development. A Late Holocene progradation was attributed to localised excesses of transgressive sand. Adjustment to an equilibrium morphology took place by sediment transfer from the nearshore to the beachface, causing steepening of the nearshore profile and beachridge genesis. The situation at the Mtamvuna river-mouth does not exhibit beachridge progradation of this type as excess sediment is driven into the lower reaches of the river-mouth.

Ebb-tidal deltas and flood-tidal deltas contain only reworked barrier sediment and are not augmented by fluvially derived sediment. Thus their sizes are linked not only to opposing current velocities but also to one another. The trend in the long term is for growth of the flood-tidal delta at the expense of the ebb-tidal delta, in a similar manner to many of the deep estuaries of the Eastern Cape (Reddering & Esterhuysen 1981) and the larger estuaries of Zululand (Wright, 1990; Mason & Wright, 1990) which have low fluvial sediment supply compared to other rivers in Natal.

The major finding is that the volume of sediment in the embayment appears to have remained constant for the period under review. Temporal changes in the lower reaches of the Mtamvuna are limited to erosion of the barrier during fluvial floods and its rapid reconstruction by wave action. Under wave attack in the ensuing months the barrier is driven landward by barrier overwash and material is transported into the river-mouth to form a flood-tidal delta, however, the shoreline position within the embayment changes little.

4.9. SYNOPSIS: SEDIMENTARY PROCESSES IN THE MTAMVUNA RIVER-MOUTH

The upper reaches of the Mtamvuna river-mouth are characterised by periodic sediment inputs caused by gravity fall from the valley sides and by overland flow which winnows sediment from adjacent screes and transports it into the river-mouth. A lack of bedforms in the upper reaches suggests little bedload transport in that area. The presence of low volumes of muddy sediment indicate suspension settling of sediments under low flow conditions and suggest erosion of this material under increased fluvial discharge. Coarse-grained fluvial sediment input is very low.

The middle reaches of the river-mouth remain deep due to low sediment inputs from gravity fall. This may reflect the increased valley width and different geology in the valley sides. Sedimentation in this area is confined to suspension settling of mud and very fine-grained sand in the deep channel sections. Through its location this environment may be regarded as a prodelta environment.

The channel margins are typically colonised by aquatic vegetation in the form of *Phragmites* reeds or mangroves. The trapping of fine sediment by mangroves has been documented from Australia (Bird, 1986) and the muddy sediment surrounding their roots in the Mtamvuna suggests that they fulfil the same sedimentological function there. The burrowing infauna associated with the mangroves produces a distinctive suite of biogenic structures (Cooper, 1986a, 1988a; MacNae & Kalk, 1969).

Flood conditions promote deposition of fine-grained sediments (fine sand or mud) in overbank areas, forming levees along the valley margins. The same flows cause little scour in the river-mouth channel, except at the mouth where the barrier may be completely eroded.

In its lower reaches the Mtamvuna river-mouth is dominated by tidal currents associated with the tidal inlet. Variations in their relative magnitude and spatial arrangement cause deposition of flood and ebb-tidal deltas of varying size. These are composed of transgressive marine sediment which has a distribution confined to the lower reaches by barrier stabilisation in the prevailing wave field and a limited volume. Thus while the barrier has essentially a typical transgressive stratigraphy (Kraft & John, 1979; Thom, 1983), apparently similar in size to small transgressive barriers in sediment-starved embayments (Roy *et al.*, 1980) of southeast Australia (Thom, 1983), its continued landward recession is prevented by bedrock outcrop and the narrow river channel which prevents pivoting around the fixed outcrops on either side of the river-mouth barrier as envisaged for coarse-grained barriers by Carter *et al.* (1987).

The barrier is situated close to the shore between two distinct headlands where its destruction by northward transport of sand in longshore drift is prevented. This may be a common factor for river-mouth barriers in sand-starved areas compared with areas of abundant sand where barriers may exist in a more seaward position enabling longshore extension of the river-mouth.

The sand of the Mtamvuna barrier can only have been derived from landward reworking of shelf sands during the Holocene Transgression. As such, the barrier conforms well to the rollover transgressive barrier island model of Swift (1975) whereby a barrier maintains its integrity as sea level rises, through semi-continuous barrier overwash. The Mtamvuna barrier may therefore differ in origin from the other examples discussed subsequently.

The lack of longshore drift in the area, coupled with a lack of coarse-grained sediment supply from the river catchment through the unfilled river-mouth results in a closed (possibly leaky) sedimentary system in the barrier in which the volume of sand combined in the barrier and flood-tidal delta remains almost constant. Losses may occur: (a) offshore during storms or during severe fluvial floods if material is deposited below wave base; (b) onshore by aeolian transport. In the long term the volume of sand has remained reasonably constant.

The Mtamvuna river-mouth remains in an immature stage of development and retains a large sediment storage capacity. The low sediment supply is reflected not only in the large residual volume of the river-mouth but also in the nature of the coast. The predominantly rocky coastline in southern Natal and neighbouring Transkei may be attributed largely to low sediment input from its rivers. This has resulted in most river-mouth barriers being located in small embayments and littoral sediment along the coast being otherwise confined to pocket beaches. Part of the reason for a rocky coastline rather than a linear barrier island coastline must also be due to an unsuitable coastal morphology for barrier stabilisation in a position seaward of the mainland. Evans *et al.*, (1985) cited a change in bedrock gradient as a reason for stabilisation of transgressive barriers seaward of the mainland on the west Florida coast. Although wave energy on the Natal coast is much greater than that in west Florida and would hinder barrier stabilisation in such a position without adequate sediment supply, the nearshore bedrock gradient is steep and the continental shelf narrow, so that no opportunity has existed for deposition of a coastal depositional plain since the Early Tertiary. The coastline has probably remained largely rocky since that time, in contrast to Zululand where adequate sediment supply combined with a gentle bedrock gradient deposited an extensive sandy coastal plain (King, 1972).

A schematic diagram of upstream variation in sedimentary facies in the Mtamvuna river-mouth is shown in Figure 4.10. A transgressive sandy barrier overlies back-barrier silts and fine sands deposited in relatively deep water. The upper reaches of the river-mouth are characterised by a lag deposit of talus from the adjacent cliffs, from which fine sediment has been eroded by river flows. By comparison with other Natal river-mouths (Orme, 1974), the base of the bedrock valley is probably overlain by a coarse fluvial gravel.

4.10. HOLOCENE EVOLUTION OF THE MTAMVUNA RIVER-MOUTH

In common with all other Natal rivers, the Mtamvuna river-mouth was incised during periods of lowered sea-level. The latest of these occurred during the Würm Glaciation when the sea dropped to 130 m below its present level on the South African coast (Chapter 1). The fact that the river channel is laterally restricted has resulted in all sediment from previous depositional episodes being eroded during the last incision. During the Holocene transgression a barrier formed on the shelf from sand deposited there by the incised rivers. The barrier at the Mtamvuna may have moved onshore as a discrete entity during the transgression, before stabilising in its present position where further landward migration was prevented by bedrock outcrop. It probably diminished in size during that transgression due to a lack of further sediment supply from unfilled river valleys further to the south. During transgression sedimentation rates in the river-mouth could not keep pace with the rate of sea-level rise and consequently a deep back-barrier river-mouth was formed behind the trangressive barrier. Since the barrier stabilised the river-mouth channel has been filling at very low rates, principally by suspension settling and from landslides in the deep gorge. The morphology of the river-mouth has, due to its constricted valley,

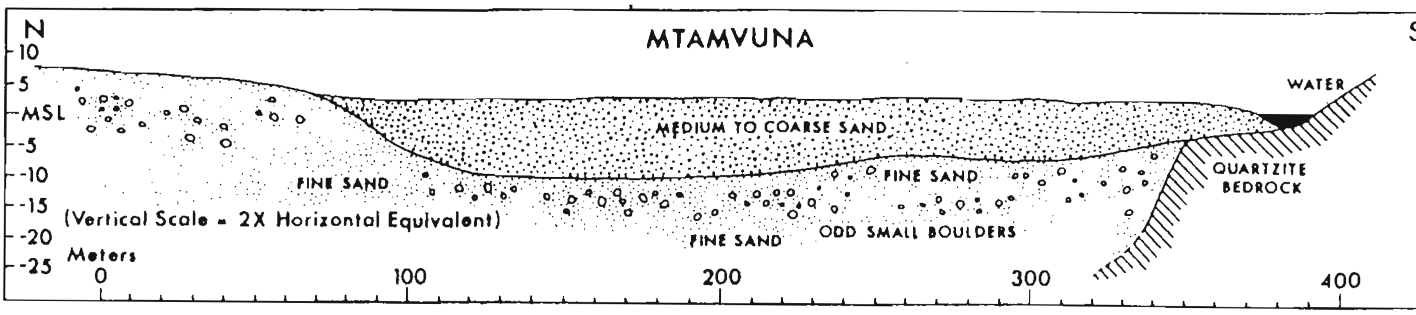


Figure 4.9. Cross-section of sediments underlying the Mtamvuna river-mouth barrier (after Orme, 1974). The transgressive barrier sands rest on fine-grained back-barrier sediments.

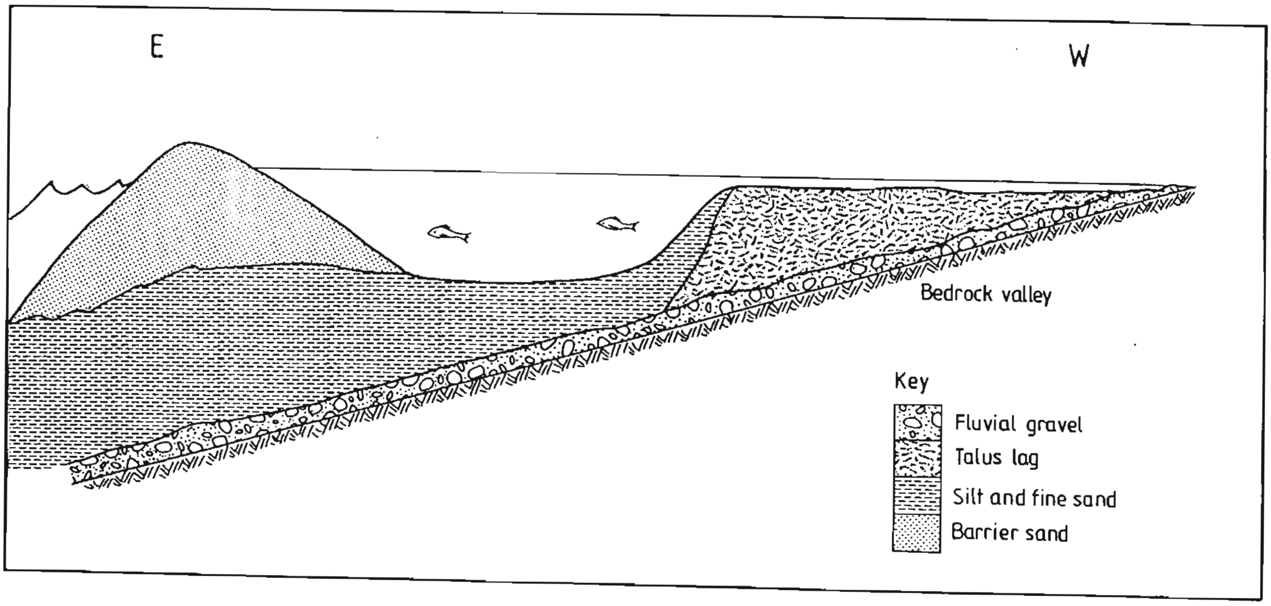


Figure 4.10. Conceptual diagram of sedimentary facies in the Mtamvuna river-mouth showing down-channel changes.

changed very little since stabilisation of sea-level in the late Holocene. No evidence was found of high Holocene sea-levels. The sedimentary succession in the river-mouth consists of a basal boulder deposit associated with scour during incision, overlain by a mixture of landfall, landslide and suspension settling deposits. The morphology of the mouth area may have been different during the early stages of the transgression as the early formation of a barrier off shore could have enabled a long shore-parallel barrier system to form on what is now the shelf. During lowered Pleistocene sea-levels the presence of aeolianite ridges preserved on the continental shelf suggests that a barrier island system was present. This would have produced a different coastal morphology from the present, as during such periods, sediment supply from incised rivers would have been greater, and the lower bedrock gradient may have permitted stabilisation of a barrier-island system. This would have occurred some distance from the mainland coast, thus enabling the formation of extensive lagoons into which several of the small rivers (which now have individual mouths), once flowed.

Whether or not this occurred during the Holocene Transgression requires further seismic and vibracoring investigations. The rapid response time of the sandy barriers of the Natal coast has permitted rollover of barriers in certain settings in Natal. For example, the succession recorded in the Late or Middle Pleistocene Port Durnford Formation in Zululand (Hobday & Orme, 1974; Hobday & Jackson, 1979) has been cited by Carter (1988) as a prime example of barrier rollover during transgression. This occurred in conditions of similar wave energy and littoral sediment grainsize as those in southern Natal.

At high sea levels the coastal zone occupies an area of steep bedrock topography and hence littoral sediments are driven landward to form mainland-attached pocket beaches and river-mouth barriers rather than barrier islands backed by extensive lagoons.

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CHAPTER 5.

MHLANGA RIVER-MOUTH

5.1. INTRODUCTION

This chapter is concerned with sedimentation in the lower reaches of the Mhlanga River, commonly referred to as Mhlanga Lagoon (Begg 1978, 1984a). Although Day (1981) is critical of the term 'lagoon" and prefers use of the term "blind estuary", Begg justifies his terminology on the basis of the river having only an ephemeral connection with the ocean and having a quiet back-barrier environment in which the fauna is not typically estuarine. "River-mouth" is used here but the problem of terminology for transitional coastal environments is discussed at length in Chapter 8. Previous studies (Cooper, 1987; 1989) compared sedimentation in the Mhlanga river-mouth under fairweather and flood conditions and suggested environmental management guidelines. This chapter includes some material from those studies together with previously unpublished data.

Mhlanga river-mouth (29°42'S; 31°05'E) is 20 km north of Durban, near the town of Umhlanga Rocks (Fig.5.1) and forms part of the Mhlanga Lagoon Nature Reserve. It has a small catchment area and lacks a connection with the sea as a beach barrier is in place for long periods. When the barrier is breached, rapid draining takes place, followed by a period of infilling. River-mouths characterised by such sedimentary processes are poorly known in the literature. Previous studies of such river-mouths in South Africa are those of Grobbler (1987) and Grobbler *et al.* (1987, 1988) in Natal and van Heerden (1985) in the Cape Province. Sedimentological processes in Mhlanga river-mouth might be is similar to those in the numerous small river-mouths on the Natal south coast. Elsewhere, small lagoons mediated by cycles of barrier breaching and closure have been reported from Ireland (Carter *et al.*, 1984) and Maine, USA (Duffy *et al*, 1989). Clifton *et al.* (1973) described the outlet characteristics of small coastal streams in Oregon, USA.

5.2. CATCHMENT CHARACTERISTICS

5.2.1. Catchment topography

The Mhlanga River has a catchment area of 118 km^2 (Fig 5.2.) and is one of the smaller rivers on the Natal coast. It rises at an altitude of 324 m above sea level and is 28 km long. Mean annual runoff amounts to 26 x 10^6 m^3. Flow has been measured between 0.02 and 1.75 m^{3}s^{-1} and averages 0.28 m^{3}s^{-1} (Brand *et al.*, 1967). Its overall gradient is 1:86 or 0.012 but in the lower 10 km this decreases to 1:444 or 0.0022 (Fig.5.2.). No dams are present in the catchment.

5.2.2. Catchment geology

The geology of the Mhlanga River catchment (Fig.5.3.) consists of Natal Group Sandstone in the upper reaches, but is dominated in the lower reaches by various, typically fine-grained, sedimentary units of the Ecca Group. Karoo dolerite is uncommon in the catchment and only a small area of the uppermost catchment is underlain by rocks of the Natal Structural and Metamorphic Province. The lower

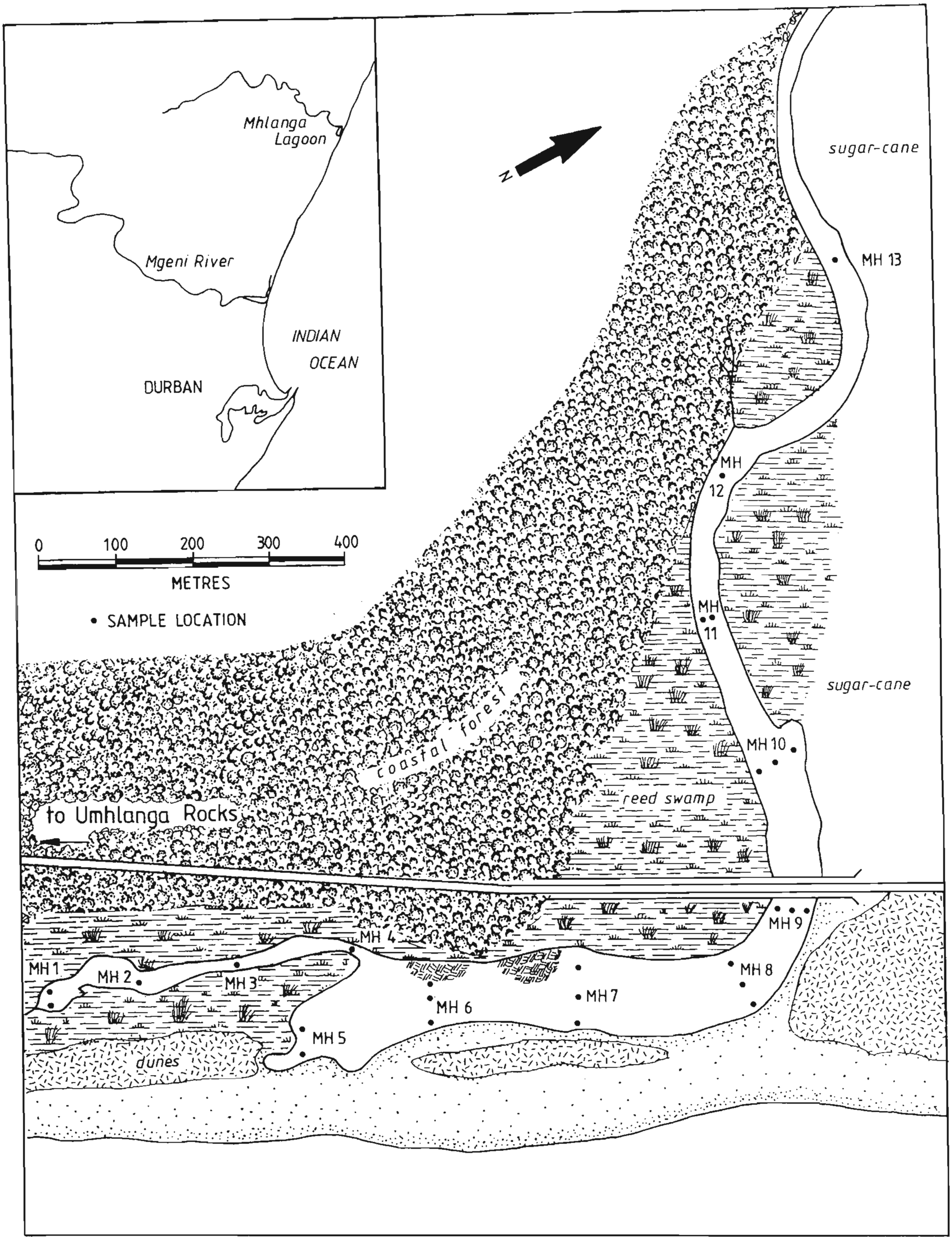
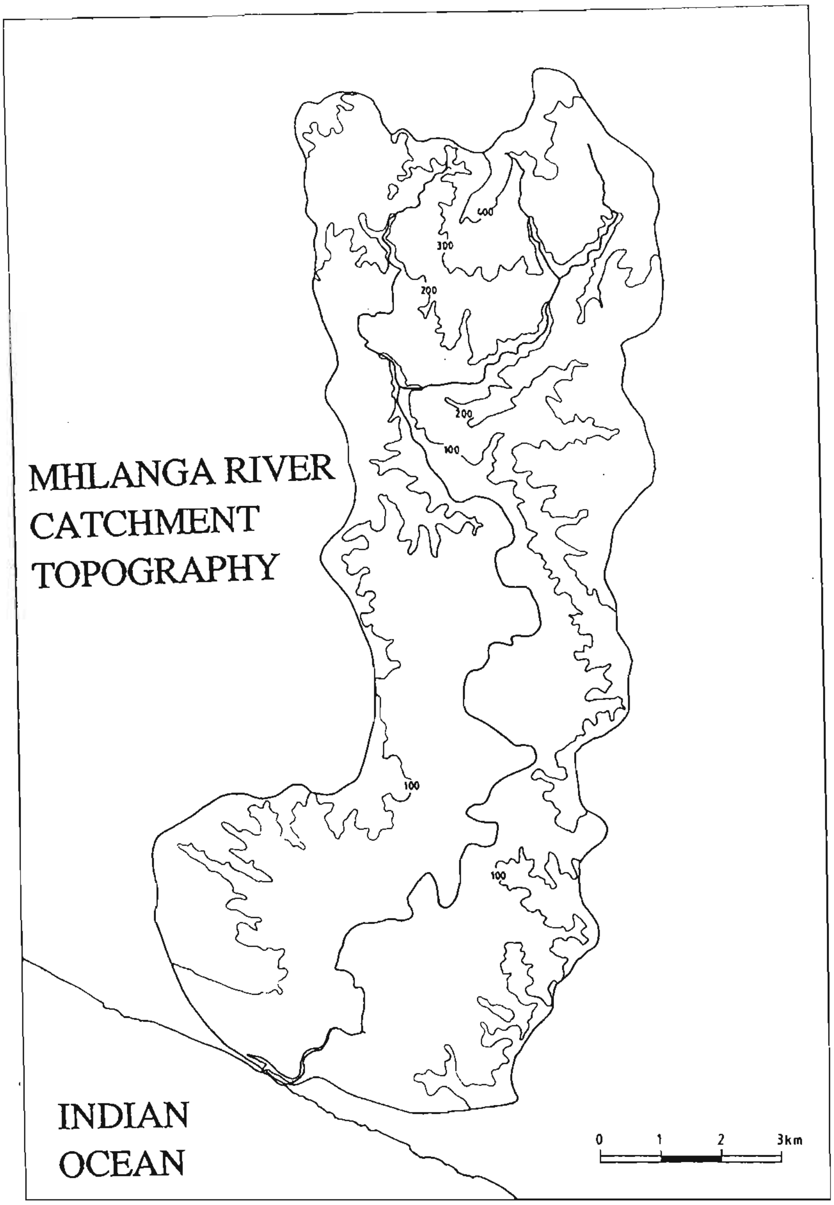


Fig. 5.1. Locality Map of Mhlanga river-mouth showing surrounding vegetation types and sediment sampling transects. Samples collected on each transect were numbered from right to left looking downstream. Rock outcrops in the landward margin of the river-mouth are indicated by cross-hatching.



Mhlanga River Downstream Profile

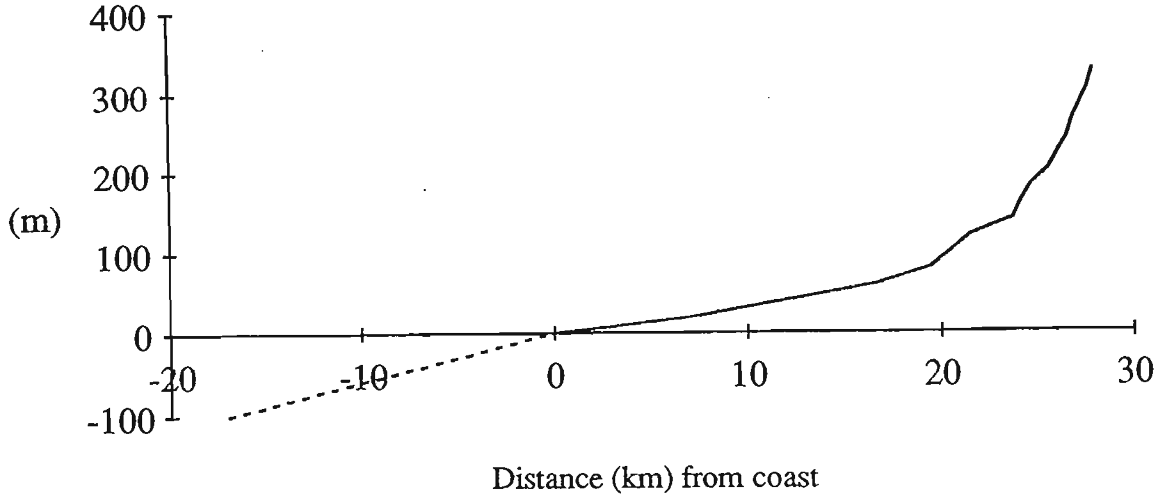


Fig.5.2. The 118 km^2 Mhlanga River drainage basin (contours at 50 m intervals) is shown in the upper diagram. The lower diagram depicts downstream changes in river channel gradient. Note the reduction in gradient at the coast. The dotted line represents a linear extension of the river course to the shelf break during the Würm glacial maximum, 17 000 years BP.

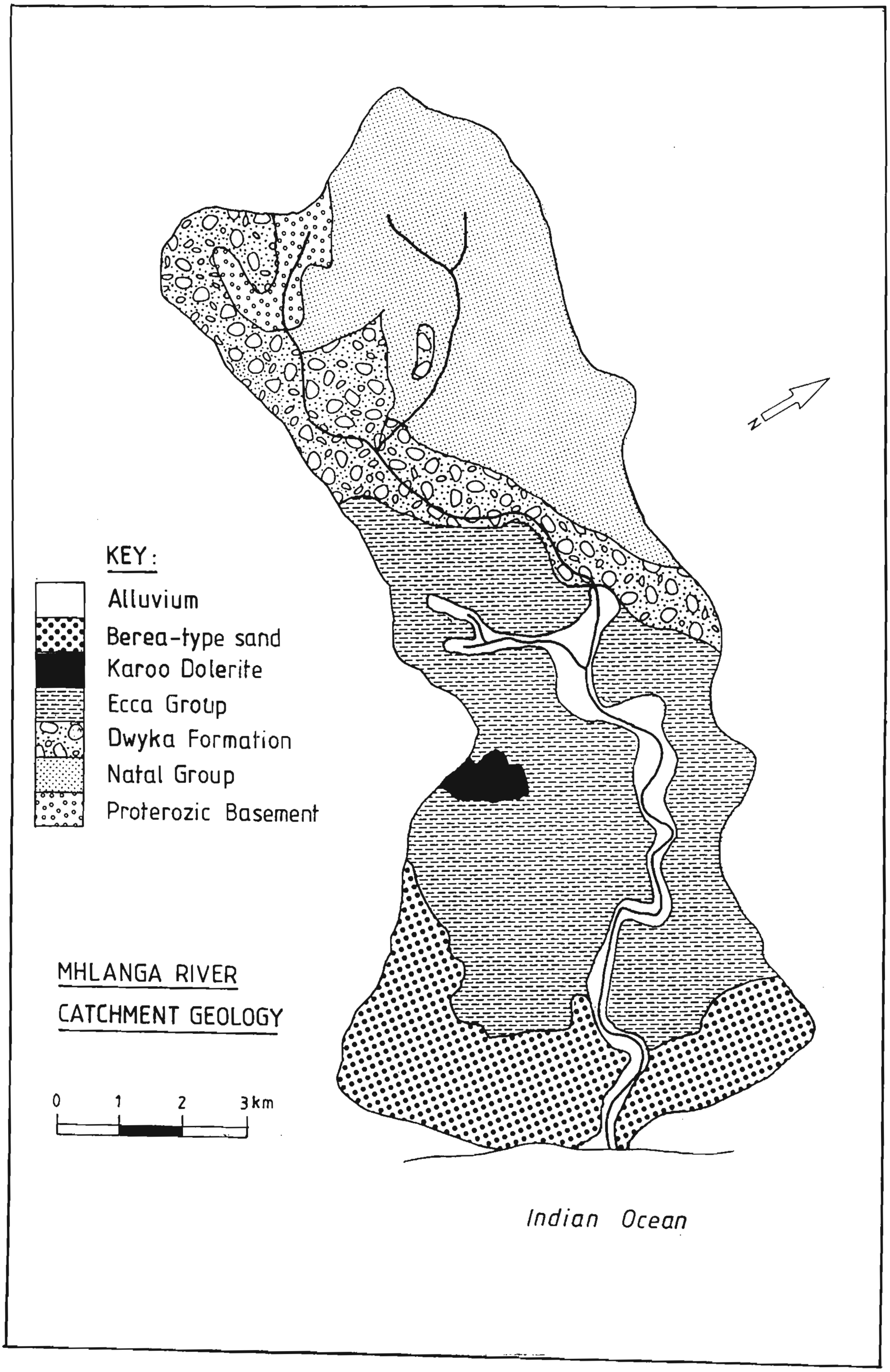


Fig.5.3. Geology of the Mhlanga River catchment. Most of the lithologies are shales and mudrocks which yield only fine-grained sediments.

catchment is largely covered by ancient, probably Pleistocene, coastal dunes of Berea-type Red Sand. Vryheid Formation (middle Ecca) sandstones and dolerite crop out in the river-mouth and carbonate-cemented beachrock is periodically exposed on the beach (Maud, 1968). Because of the small catchment size, alluvium forms a significant component of the surface geology of the catchment.

The potential sediment yield from the catchment was calculated at 47 200 tonnes per year (NRIO, 1986) based on a sediment yield map (Rooseboom, 1978). This would require a mean sediment concentration in river water of 1.8 x 10^{-3} tons/m^3 or 1.8 kg/m^3 (1800 ppm) if sediment supply was considered to be constant throughout the year. Actual measurements (Begg 1984a) during summer, a dry winter period and in winter after a minor flood gave suspended sediment concentrations of only 362, 417 and 384 ppm respectively. As the river-mouth is characterised by low energy, tranquil conditions for 90% of the year (Begg, 1978; and Section 5.4.) and one of the suspended sediment concentrations was after a minor flood, it appears that current estimates of sediment yield from the catchment are in the region of 5 to 6 times too high. This is especially true as floods in the catchment are very short-lived.

5.3. MORPHOLOGY OF MHLANGA RIVER-MOUTH

5.3.1. River-mouth morphology

Mhlanga river-mouth is located in a broad valley cut into Vryheid Formation shales and sandstones. The channel is incised into a 500 m-wide alluvial floodplain (Fig. 5.4.). Upstream of the road bridge the channel follows a sinuous course (sinuousity = 1.4) across the floodplain but where it approaches the coast it is diverted southward into an elongate coast-parallel back-barrier area, approximately 1 km long and 150 m wide. (Sinuousity must be 1.5 for formal classification of a channel as meandering, Gregory & Walling, 1973).

The southern end of the river-mouth consists of a narrow (5-6 m wide) backwater channel draining a *Phragmites* reed swamp and is protected from the Indian Ocean by a high, vegetated, Holocene dune barrier up to 30 m high. The partially vegetated barrier is composed of marine sand. Freshwater runoff is normally insufficient to maintain an outlet against littoral drift and wave action, and therefore no connection exists between the river-mouth and the ocean for about 90% of the year (Begg, 1984a). Salinity in the river-mouth varies from totally fresh to hyposaline, but averages less than 10 ‰ (Whitfield, 1980a,b). Begg (1984a) concluded that average salinities were actually much lower than 10% as the river-mouth water is frequently totally fresh. Seawater enters the river-mouth by barrier overwash and stratification is commonly developed in the water column (Begg, 1984a, Ramm *et al.*, 1986). When the barrier is continuous a near-constant water depth averaging 1.5 m is maintained by the balance between freshwater inflow and seepage through the porous barrier. When the barrier is breached (naturally or artificially) the river-mouth drains, subaerially exposing most of the bed, as it is above mean sea level. The outlet normally closes within about 10 days (Whitfield, 1980a,b), except when located against beachrock outcrops (Cooper, 1987) when increased scour may enable it to remain open for up to three weeks. Rapid closure through wave action prevents the outlet from migrating significantly.

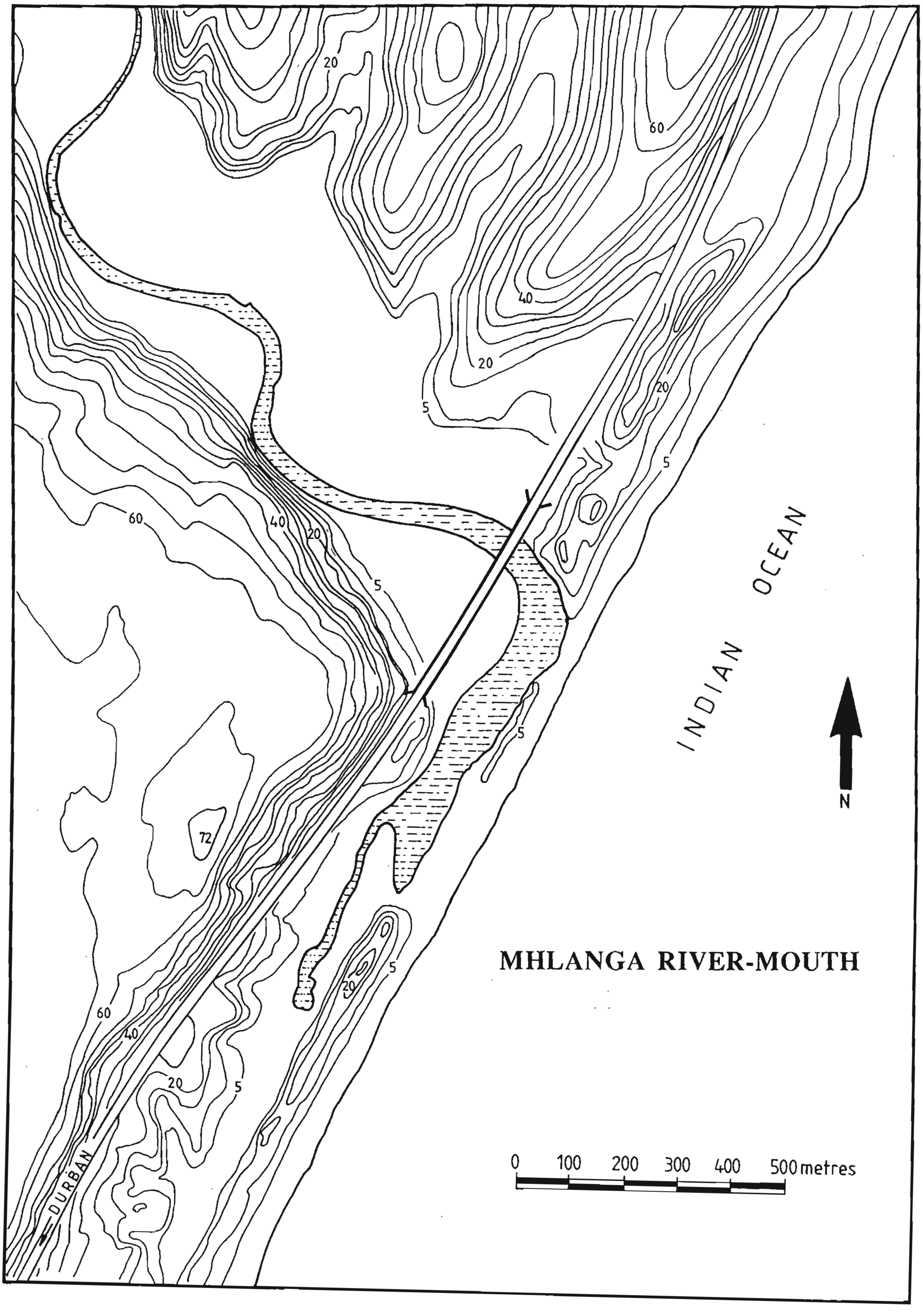


Fig.5.4. Topography of the area surrounding Mhlanga river-mouth. Note the well-defined alluvial plain and small, incised, sinuous channel (based on 1: 10 000 scale orthophoto). Contour interval 5 m.

5.3.2. Barrier morphology

The river-mouth barrier is composed of transgressive, littoral marine sand which forms part of a linear clastic shoreline (Plate.5.1; Cooper, 1991b). Suitable wave refraction patterns coupled with a gentle bedrock gradient stabilised the transgressive barrier at a short distance seaward of the rocky mainland, hence facilitating the coast-parallel extension of the rivermouth behind the barrier. The southern part of the barrier, where it diverges from the mainland shore, is topped by a densely vegetated 30 m high dune (Plate.5.1). The dune flora includes mature trees which form a climax dune forest community in which the Red Milkwood (*Mimusops caffra*) is considered important (Begg, 1978). On the seaward side are small dunes with a dune pioneer plant community dominated by *Scaevola*.

The northernmost 1 km of the barrier (Plate.5.1) consists of a low sandbar on which dune development is limited to a small central area. On either side of this the barrier is sufficiently low for overwash to be a common occurrence. The dune in the central part of this barrier is only sparsely vegetated with a pioneering dune flora which indicates that it is younger than the adjacent coastal dunes both to the north and south. The low barrier averages 80 m wide.

The Mhlanga river-mouth barrier is underlain by a semi-continuous strip of beachrock (Plate.5.2A,B) of probable Holocene age. This reduces barrier porosity but enhances its stability. It is located in two distinct levels: one in the modern intertidal zone and the other at an elevation some 2 m higher. This is discussed further in the context of the Holocene evolution of the river-mouth (Section 5.8).

The sand of the Holocene dune comprises mainly quartz with subordinate feldspar, skeletal carbonate grains and heavy minerals. It thus differs from the Pleistocene dunes on the landward side of the river-mouth which are composed of Berea-type Red Sand. The latter contain abundant clay minerals produced by prolonged tropical weathering (McCarthy, 1967; Maud, 1968) and are devoid of carbonate grains.

5.3.3. Aquatic Flora & Fauna

The flora and fauna of river-mouths and estuaries often exert considerable control on sediment texture and sedimentary processes. Important in this regard are filter-feeding organisms which aid in the agglomeration of fine suspended particles causing more rapid settling, and infaunal and epifaunal faunal animals which modify and mix sediment as a result of their activities. The fresh to brackish water in the river-mouth is only suitable for habitation by specialised benthic organisms and is relatively impoverished (Whitfield, 1980a,b). The burrowing sandprawn *Callianassa kraussi* is present in the lower river-mouth in association with sandy sediment (Whitfield, 1980a,b) whereas upstream the benthos is dominated by chironomid larvae (Begg, 1978). Small bivalves of the genus *Musculus* attach to the *Phragmites* reeds. Aperiodic breaching of the normally continuous barrier ensures that the benthic infauna remains sparse. The shells of an estuarine molluscan fauna found in the sediment suggest that in the recent past, the river-mouth was open to the sea more frequently: these molluscs cannot survive in the freshwater conditions which currently prevail for long periods in the river-mouth. This may relate

Plate.5.1. Photograph of the Mhlanga river-mouth barrier looking north. The near-linear sandy barrier rests on bedrock outcrop. Note the lightly vegetated dune in the centre of the barrier and the forested (?late Holocene) dunes to the north. The low barrier segments are sites of overwash and outlet formation.

Plate.5.2A. Photograph of beachrock underlying the modern barrier, exposed in a breached outlet. The beachrock is dominated by trough cross-bedding, indicating an original intertidal facies. Beachrock outcrops help maintain the outlet by causing turbulence.

Plate 5.2B. Beachrock exposed in the intertidal zone on the seaward margin of Mhlanga river-mouth barrier.

to a post glacial high sea-level stand which is discussed later in relation to the Holocene evolution of Mhlanga river-mouth (Section 5.10).

The *Phragmites* reeds which dominate marginal vegetation in Mhlanga river-mouth (Fig.5.1.), trap a portion of the suspended sediment, which would otherwise be too fine to settle to the bottom, in a similar manner to the pneumatophores of mangroves in more saline estuaries (Bird, 1986). The presence of reeds also dampens the effect of wind-generated waves and protects the river-mouth margins from erosion. Mangroves are absent from the river-mouth due to low salinities, lack of tidal exchange and large variations in water level following breaching.

5.4. SEDIMENT DISTRIBUTION PATTERNS

5.4.1. Introduction

Sediment samples were collected under fairweather conditions in February 1987 at locations shown in Figure 5.1. For the purposes of this discussion "fairweather conditions" are defined as those conditions prevailing when the river-mouth is closed, and excludes those events which cause breaching of the river-mouth. The results of a sediment distribution survey are summarised graphically in Figure 5.5. The areal distribution of mud, sand, carbonate and organic carbon at that time are discussed below. The amount of gravel (>2 mm (1ø) grain size) was insignificant.

5.4.2. Distribution of mud (< 63 um; < 4ø)

Mud (silt and clay) was recorded as a dry weight percentage and may thus give a lower mud content than that suggested by visual or tactile examination. It is derived both from the catchment and from organic detritus produced in the river-mouth. It is carried in suspension and deposited at low current velocities. In general, the amount of mud in the surface sediments increases upstream and in the southern backwater of the river-mouth (Fig. 5.6A). In those areas it forms over 20% of the sediment. A small area of exclusively mud-size sediment occurred in a 3 m deep section in the centre of the river-mouth. At 50 cm depth (Fig 5.6B) mud was generally less abundant (commonly < 5%). Maximum mud concentrations occurred in mid channel, upstream of the bridge and in the extreme southern end of the river-mouth.

5.4.3. Distribution of sand (2mm to 0.063 mm; -1ø to 4ø)

Sand is the dominant grain size fraction in the river-mouth (commonly > 90% of the total sediment). Quartz is the dominant constituent but feldspar and heavy minerals are also present. Because sand comprises a large volume of the bottom sediment its distribution alone is a poor reflector of sedimentary processes. For this reason the hydraulic grain size distribution of the sand fraction in each sample was determined by settling tube.

In most cases the dominant grain size fraction was medium- to fine-grained sand (Fig.5.7). The general absence of very fine sand in the sediment and its close correlation with high mud concentrations is noteable. Willis (1985) noted a similar lack of very fine sand in the Bot Estuary in the southern Cape

FIGURE 5.5. (A) PRE-FLOOD GRAINSIZE DATA

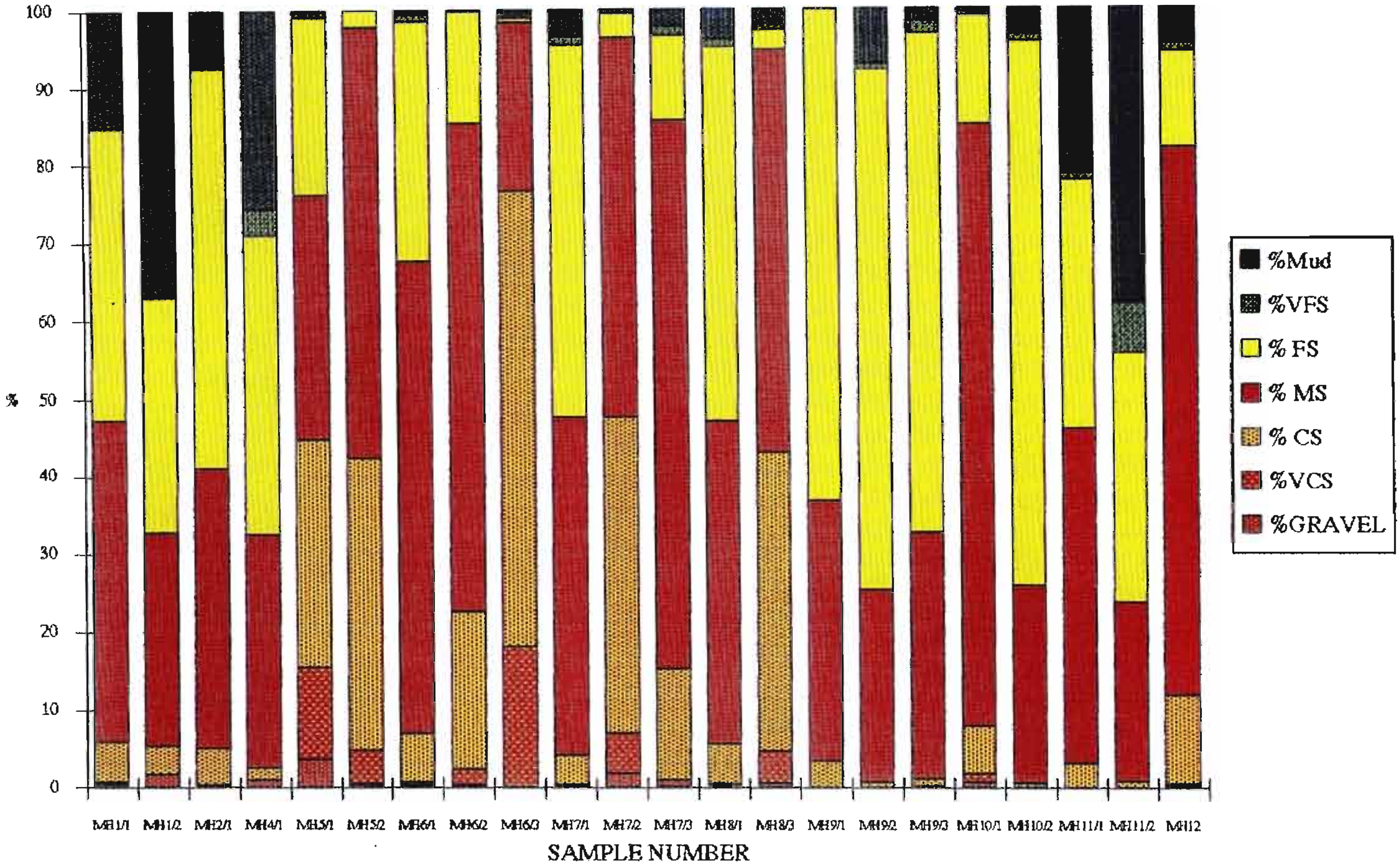


FIGURE 5.5. (B) POST-FLOOD GRAINSIZE DATA

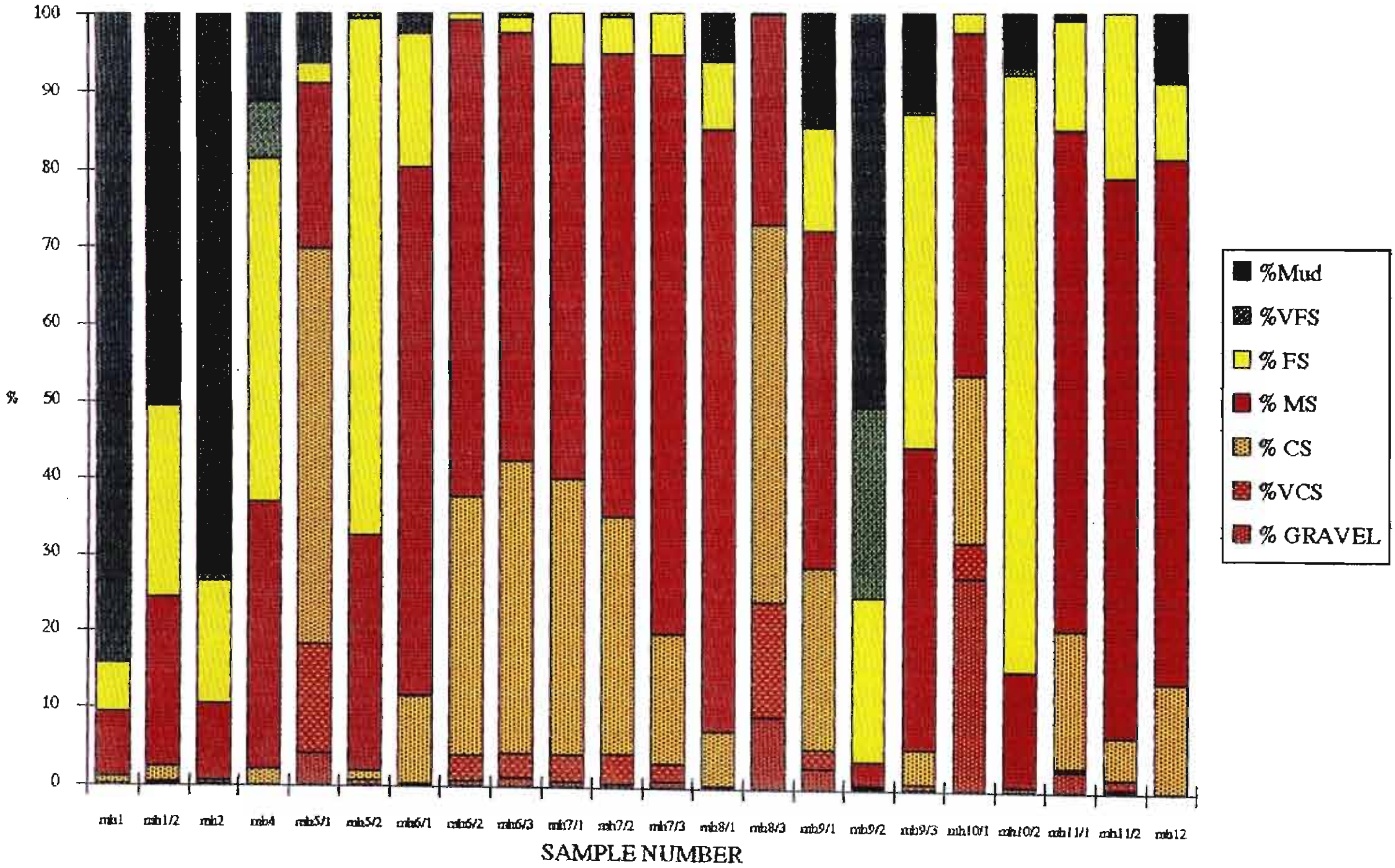


Fig.5.5. Graphic representation of sediment grainsizes at the same sampling stations (A) before and (B) after the September 1987 flood. Note the change from fine-sand (yellow shading) to medium-grained sand (red shading) in the middle reaches and the increase in amount of mud (green shading) in the backwaters represented by the columns at left.

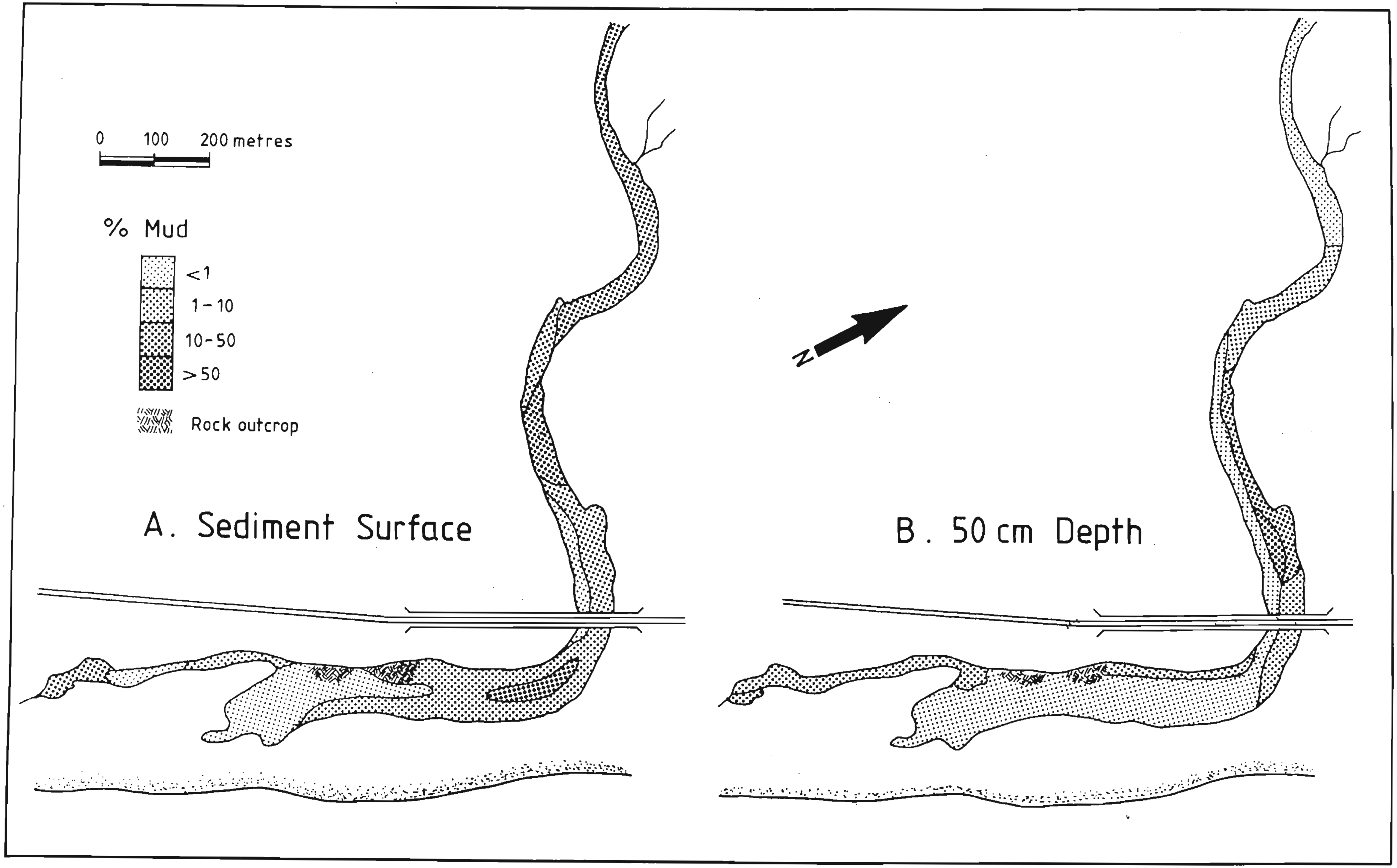


Fig.5.6. Distribution of mud in Mhlanga river-mouth sediments (A) at the surface and (B) 0.5 m below the sediment surface.

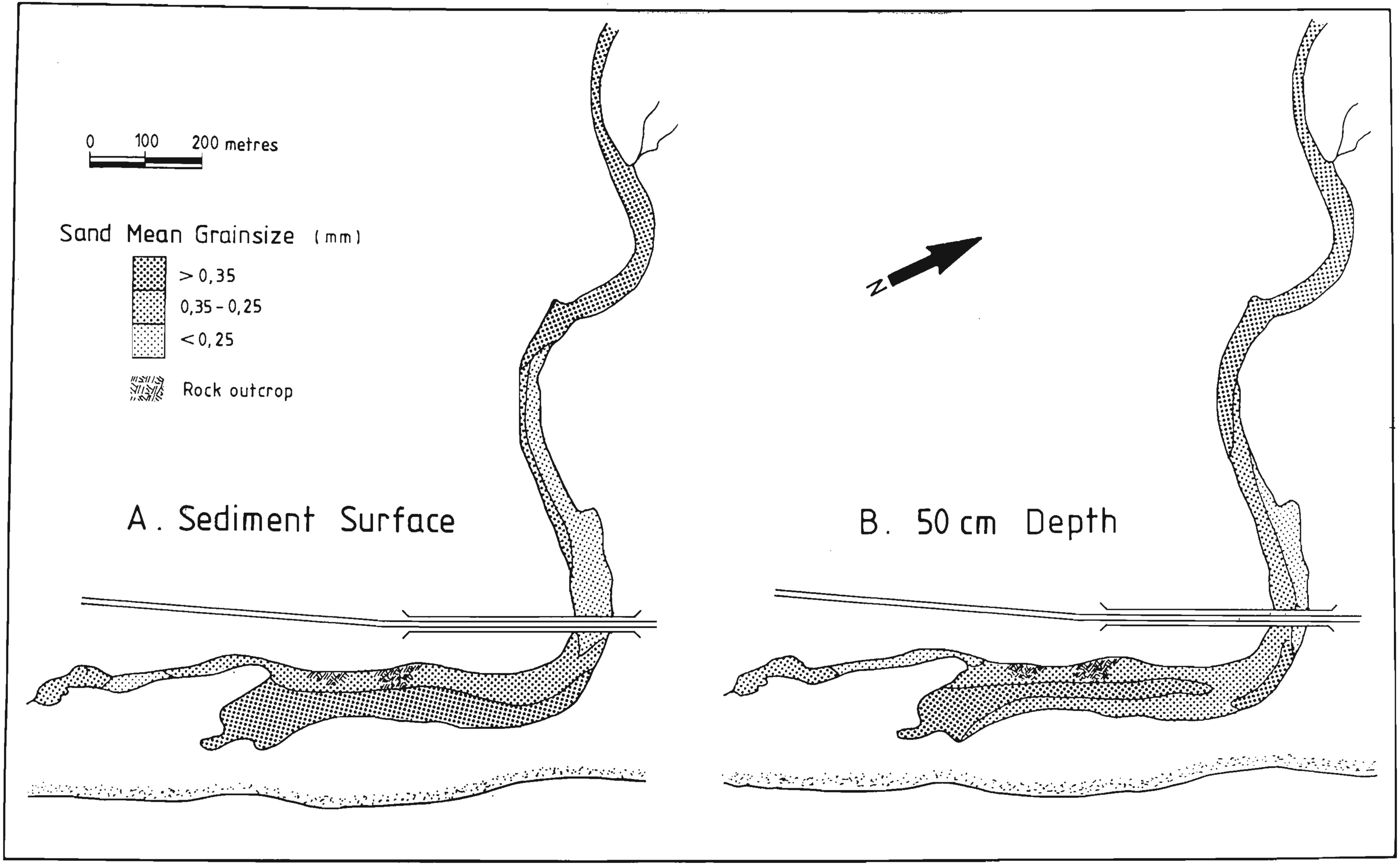


Fig.5.7. Sand mean grainsize in Mhlanga river-mouth (A) at sediment surface and (B) 0.5 m below the sediment surface.

Province. Sand had near-symmetrical grainsize distributions. The mean grain size of the sand fraction (Fig. 5.7) close to the barrier is 0.45 mm (1.15 ø), which is similar to sand on the adjacent beach which had a mean grain size of 0.49 mm (1.02 ø). In the upper reaches of the river-mouth the mean sand grain size was 0.36 mm. This is somewhat coarser than sand in the adjacent palaeo-dunes of the Berea Red Sand Formation (mean grain size 0.23 mm; 2.12 ø) which are being eroded in that area. Between these areas finer-grained sand predominated (Fig.5.7A).

Maximum mean grain sizes of samples from 0.5 m below the sediment surface occurred in a well-defined strip in the centre of the river-mouth which converged on the south end of the barrier (Fig.5.7). This coincided with the deepest areas of the river-mouth.

5.4.4. Carbonate content

Carbonate in the river-mouth sediments was almost wholly of skeletal origin. The cement of eroded beachrock particles formed only a minor constituent. Molluscan, echinoderm, bryozoan and foraminiferal skeletal remains indicate a marine origin for this fraction which is concentrated next to the barrier (Fig. 5.8). Fragments of relict infaunal and epifaunal mollusc shells were noted in the southern end of the river-mouth but they contribute only a minor amount of carbonate. Traces of carbonate elsewhere in the river-mouth reflect the presence of brackish-water, benthic foraminifera. (The red sands of the Berea Formation adjacent to the river-mouth contained no carbonate so this must be ruled out as a possible source of carbonate in the river-mouth). Carbonate content of the barrier averages 7% for both beach and dune environments. In the river-mouth, carbonate-bearing, marine-derived sediment is progressively mixed with non-calcareous river-mouth sediments and is therefore reduced in concentration with distance from the barrier. An anomalous carbonate concentration (90% at the north end of the river-mouth) was caused by the collapse of a shell midden in the eroded dune. At 50 cm depth carbonate distributions followed a similar pattern to the surface..

5.4.5. Organic content

Organic content determination by ignition also removes bound water from clay minerals so values obtained may be slightly higher than those obtained by other methods. Measured organic matter ranged from 0 to 42% of the total sediment and averaged only about 2%. No significant difference was noted between surface and subsurface samples. Higher concentrations were associated with high mud contents indicating that a proportion of the mud fraction is derived from the breakdown of organic matter but no clear linear relationship was apparent. The distribution of organic matter in the river-mouth is shown in Figure 5.9.

5.4.6 Discussion: sediment distribution patterns

Sediment distribution patterns result from the interplay between sediment provenance and spatial variations in the nature and intensity of sedimentary processes. The distribution of sediments under fairweather conditions are assessed below. Such conditions occur for approximately 90% of the year and therefore represent the average sedimentary conditions in the river-mouth.

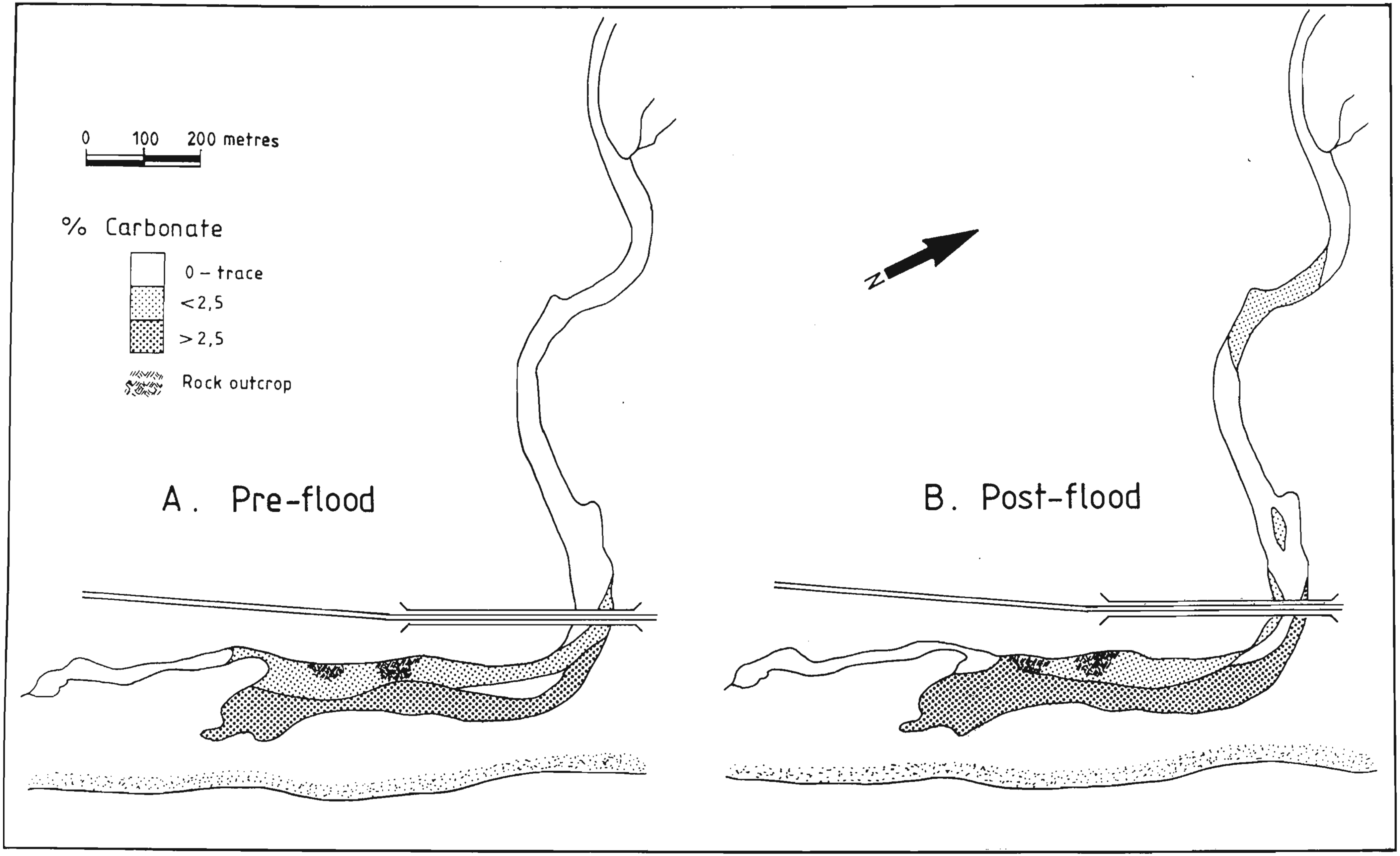


Fig.5.8. Distribution of carbonate in bottom sediments in Mhlanga river-mouth (A) under pre-flood conditions and (B) after the September 1987 flood.

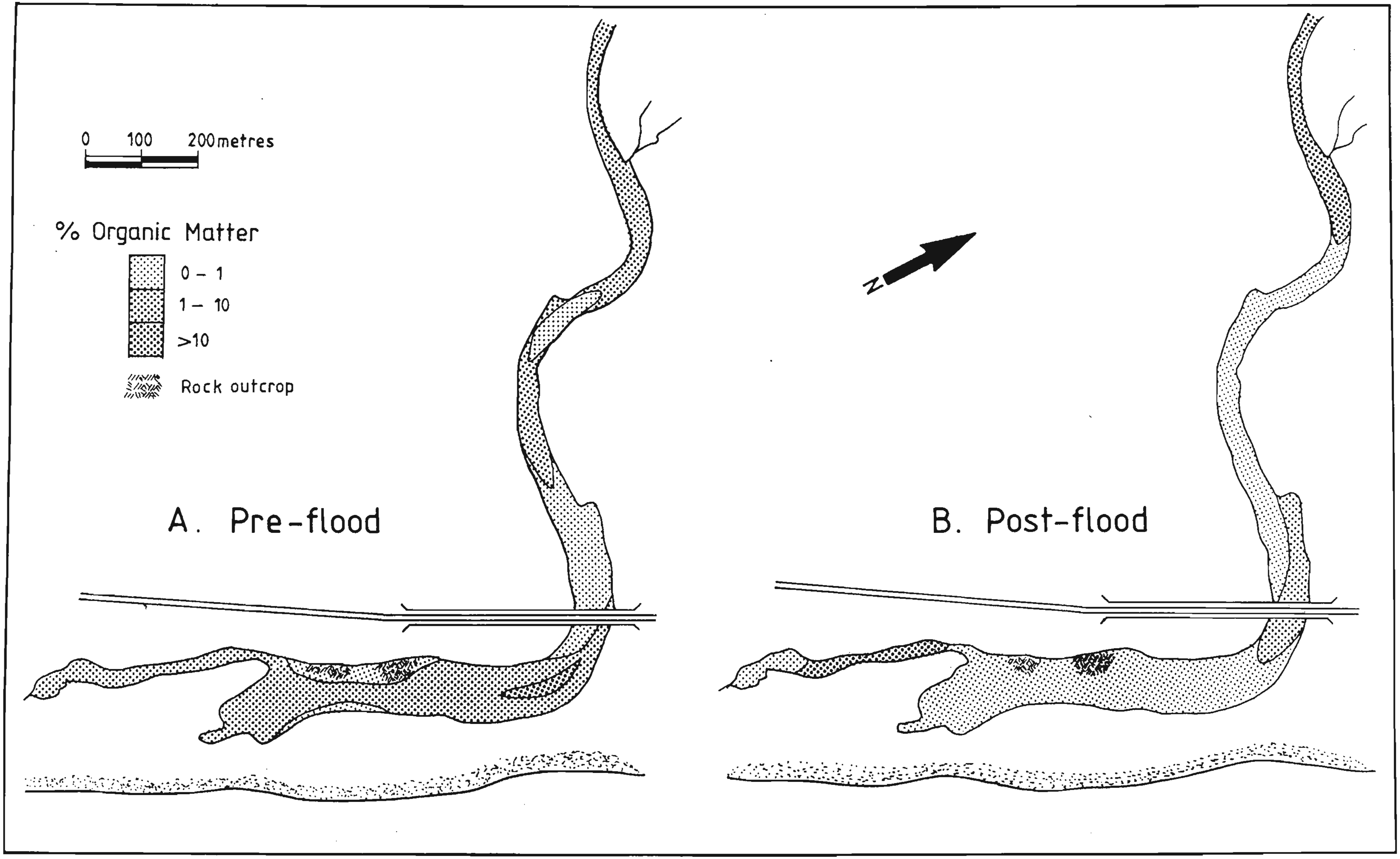


Fig.5.9. Distribution of organic matter in bottom sediments in Mhlanga river-mouth (A) under pre-flood conditions and (B) after the September 1987 flood.

The range of sediment grain sizes in Mhlanga river-mouth is restricted because of the limited size range of grains available in the catchment and beaches adjacent to the river-mouth: its catchment does not contain lithologies capable of yielding much gravel sized sediment for example. Furthermore, during fairweather conditions, water currents in Mhlanga river-mouth have low velocities which are ineffective in transporting coarse-grained sediments. Under such conditions river discharge is between 0.02 and 1.75 m^3s^{-1} (Brand *et al.*, 1967). Given an estimated cross-sectional area of 90 m^2 (based on a channel width of 60 m and a mean depth of 1.5 m) the calculated mean current velocities lie in the range 0.02 to 1.9 cms^{-1} which, according to the Hjulström diagram (Middleton & Southard, 1977 in: Blatt *et al.*, 1980) are barely capable of transporting fine-grained sediment (silt and clay) in suspension. Frictional retardation of currents at the channel base would further reduce the current velocities at the bed. Thus under fairweather conditions the sedimentary regime is one of low energy and sediment supply from the catchment is minimal. As a result the only sediment entering the river-mouth from the catchment comprises fine-grained particles carried in suspension. This is deposited in quiet-water areas where settling is facilitated; however, this process may be disrupted by wave-induced turbulence in the water column.

Wave action is greatest in the coast-parallel section of the river-mouth whose long axis is parallel to the prevailing winds and provides the greatest fetch. The concentration of mud in sheltered backwater areas in the southern end of the river-mouth and in its upper reaches reflects the strong control exerted on mud deposition by the wave regime. Mud deposition also occurs in deep sections of the river-mouth below effective wave base. The paucity of the very fine sand fraction may be attributed to either the lack of a suitable source material in the catchment or to its preferential erosion from the river-mouth. Willis (1985) noted a similar paucity of very fine sand in the Bot River Estuary and suggested that as the critical erosion velocity of this fraction was well below that generated by wave action in the estuary this would have resulted in that fraction being preferentially removed from that estuary during periods when it was open to the sea. Mud is less easily eroded because of increased cohesion. It is likely that this is also the case in Mhlanga river-mouth but further studies are necessary to firmly rule out a lack of a suitable source of very fine sand in the catchment.

The close relationship between the very fine sand and mud fractions suggests that the break between suspended load and bedload occurs in the very fine sand fraction.

Given the prevailing low current velocities in the river-mouth, sand may be derived only from the sea and/or bank erosion. The similarity in grain size between beach sand and that in the lower reaches, coupled with the latter's high carbonate content, indicates the introduction of marine sand via barrier overwash and wind action. The process of barrier overwash has been shown to be important in introducing marine sand into Natal river-mouths due to the high-energy wave regime (Cooper & Mason, 1986). This process periodically deposits marine sand in Mhlanga river-mouth adjacent to the barrier where it remains in the absence of any flood-tidal currents. Wind action forms dunes on the sandbar which may become vegetated. Some of this sand is also blown into the lagoon. The small fetch means that wind-generated waves are of small amplitude and are unable to transport sandy sediment, although swash action on the sandy margins of the river-mouth may concentrate heavy minerals by selective winnowing of quartz and feldspar.

The fine-grained sand which dominates the river-mouth's middle reaches is fluvially-derived and reflects the inability of river flow and wave action to transport coarser particles. Coarse-grained sand in the upper reaches may be derived either from the catchment during high river flows or from bank erosion. The presence of eroded faces on the Berea Red sand on the banks indicates introduction of sediment from that source, however the greater mean grain size in the channel sediments indicates the presence of a coarser-grained fraction which must be catchment-derived. Given the low energy conditions the sediment yield from the catchment is low.

Subsurface sampling indicates the coarsest mean grain sizes to be concentrated in midstream areas of the river-mouth where they coincide with deep water areas. They are thus considered to represent a lag deposit formed by winnowing of finer-grained sediment during fluvial floods. The presence of this lag at depth in the sediment indicates that fine-grained sediment accumulates during inter-flood periods, a contention supported by higher mud concentrations at the surface than at depth. The coarser-grained fraction of this sediment would probably have been deposited under the waning energy regime following directly after a flood peak and the sediments would thus be expected to show a fining-upward trend.

The organic content of river-mouth sediments is generally high as a result of production of organic detritus in adjacent swamps, however, the wide range of organic contents recorded in Mhlanga river-mouth suggests that deposition of organic-rich material is highly localised.

5.5. SEDIMENTOLOGICAL EFFECTS OF BREACHING

5.5.1. Introduction

The previous section assessed sedimentation within the river-mouth during fairweather conditions (90% of the year). In this section the impact of episodic events, which cut ephemeral outlets in the barrier, are assessed.

Under certain conditions seepage through the barrier is insufficient to cope with the discharge and a mouth forms when the rising water level overtops the lowest point on the barrier. The overflowing water erodes the non-cohesive sand of the barrier and forms a constricted outlet. The elevation of the river-mouth bed above high tide level means that when an outlet is formed water drains rapidly into the ocean, exposing most of the bed. No landward flow of sea water occurs through the barrier as reported in other areas (Carter *et al.*, 1984), because the bed elevation is too high. Outlets form in two positions in Mhlanga river-mouth: directly opposite the 90^0 bend at the coast and at the southern end of the broad coastwise extension adjacent to the southern forested dune (Fig.5.1) but only one outlet is present at any particular time.

Outlet formation may arise under three sets of natural circumstances (artificial breaching is illegal). The three circumstances are:

a) following fluvial floods associated with heavy rainfall in the catchment;
b) after continuous rainfall over a prolonged period, which causes the river-mouth water level to rise slowly, ultimately overspilling and breaching the barrier; and
c) after the formation of marine overwash channels which intersect the river-mouth water level.

The net effect of all three circumstances is similar. The river-mouth drains rapidly (within a few hours), generating high current velocities and entraining sediment. During draining, the current velocity of the outflowing water is maximised at the breach as the depth of flow is reduced across the barrier, but upstream the greater channel cross-sections reduce the mean velocity. Flow at the outlet is commonly in the form of antidunes which indicate current velocities in excess of 1 ms^{-1} which are capable of entraining and eroding the sand of the barrier. The fact that the river-mouth is not receiving additional water from upstream at the rate at which it is being lost through the mouth reduces bottom turbulence and hence the sediment-entraining ability of the river-mouth waters. In the case of a river flood, the high current velocities may extend upstream of the mouth and outflowing velocities may be sustained for a longer period as flow from the catchment augments the outflowing water and prolongs the draining period.

5.5.2. Flood-associated breaches

Flooding during September 1987 provided a rare opportunity to study the effects of a particularly severe flood on Mhlanga river-mouth (Cooper, 1989). In a five day period most of the Mhlanga catchment experienced between 200 and 400 mm of rain (based on data from Kovacs, 1988). The 1987 floods are among the most severe conditions likely to occur in the river-mouth. (A flood in 1953 was probably of similar total magnitude but was shorter -lived, as an equivalent amount of rain to the 1987 flood fell but in a single night rather than over five days. The peak discharge was therefore greater in 1953 than the 1987 event. Increased scouring at the northern end of the sandbar associated with these higher current velocities in 1953 was probably responsible for formation of the mouth in a northerly position at that time.)

During the 1987 flood an outlet channel was eroded across the southern end of the barrier. A small mouth bar or delta was deposited in the sea and a plume of turbid river water entered the Indian Ocean and was carried southward by the ocean current. Erosion of the banks occurred on the outside of channel bends and at the point where the river-mouth was diverted south behind the coastal barrier (Fig.5.10A, Section 5.7.). Sand from Berea-type red dunes in the upper section of the estuary slumped into the channel when the sediment-stabilising vegetation was undermined.

No gauging weir is present on the Mhlanga River and consequently the magnitude of the flood was not recorded; however, because of the small catchment the flood peak was small and short-lived, lasting for only a few hours. Current velocities may be gauged roughly by the size of bedforms produced

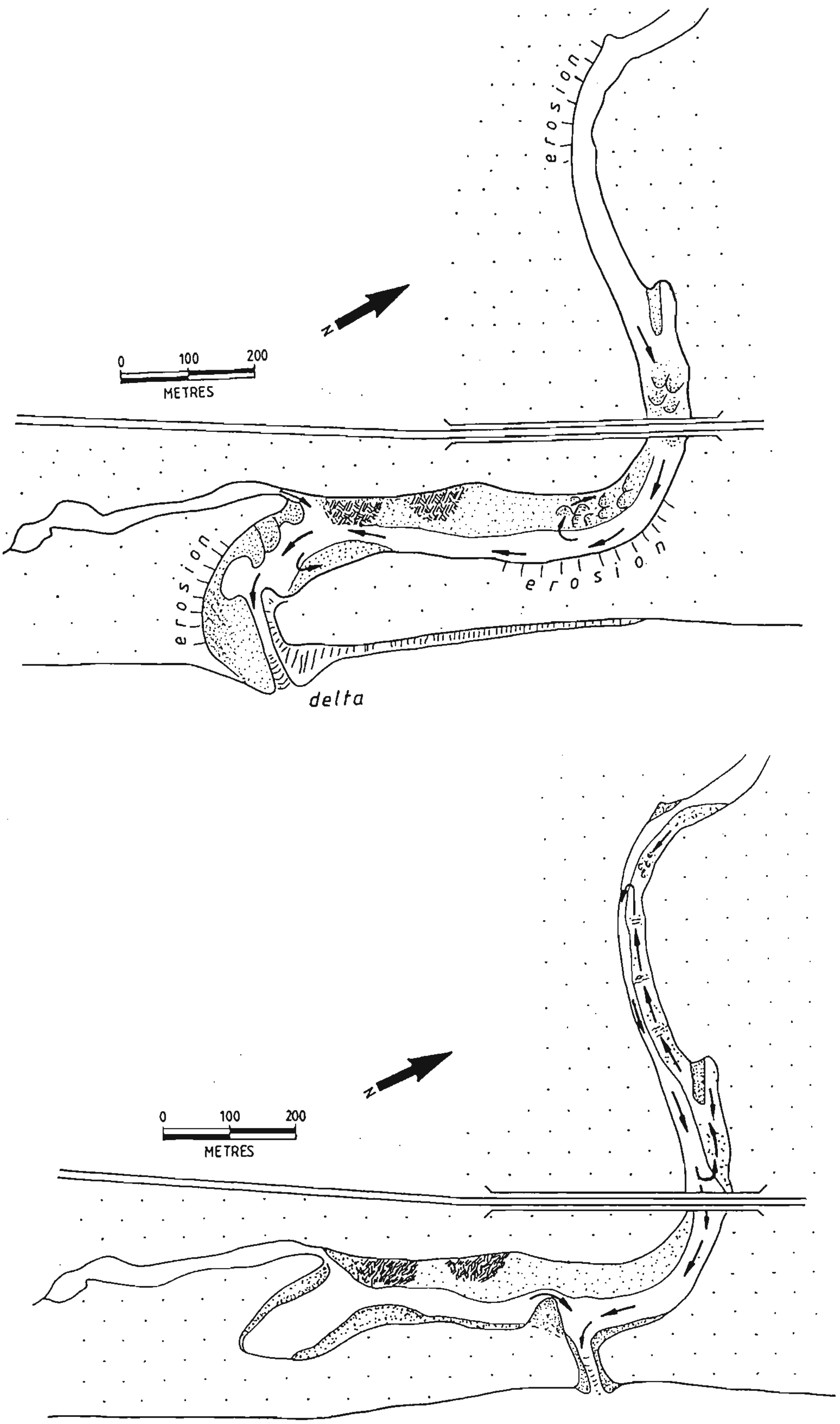


Figure 5.10.Directional data for outflowing currents deduced from bedforms preserved on the lagoon bed after draining through breaches (A) at the south and (B) at the north end of the barrier. Flood-generated structures revealed after the river-mouth drained in September 1987 (A) indicated the presence of an eddy current ay the river bend at the coast. Current directions indicated by bedforms are shown by arrows. Structures revealed on the bed after breaching in a northern location (B) also indicate the presence of eddy currents in the coast-normal channel. Different water levels account for the differences in amount of bed exposure in the two diagrams.

although it is impossible to determine whether they were produced during the rising or waning flood stage. Linguoid megaripples of 1-2 m wavelength were produced on the inside of channel bends while in the area upstream of the road bridge sandwaves (wavelength 10 m; amplitude 0.5 m) were exposed when the river-mouth drained. These features suggest a current velocity in the range of 0.5-0.60 ms^{-1} according to established bedform/current velocity relationships (Middleton & Southard, 1977; in Blatt *et al.*, 1980). Some bedforms indicated an upstream current movement (Fig.5.10A) and the presence of eddy currents during flooding. Similar development of eddy currents was recorded during floods in eastern Cape estuaries (Reddering & Esterhuysen, 1987b)

Bottom sediments were sampled 6 days after the flood peak, at the same locations as the pre-flood samples. At the time of sampling the river-mouth had drained and much of the bed was exposed. Grain size characteristics of post-flood surficial sediments are illustrated graphically in Figure 5.5B.

In the sheltered, southern backwater of the river-mouth the proportion of mud increased to 80% following the flood, indicating deposition in that area (Fig.5.5B). In the coast-parallel river-mouth sector a marked increase in the proportion of medium-grained sand at the expense of fine sand was noted after the flood. The relative proportions of the other grain sizes remained relatively constant. At the roadbridge an increase in mud and fine-grained sand occurred compared to the pre-flood situation. This suggested deposition of fines in that area while upstream a slight increase in the coarser grain sizes indicated minor erosion of fine-grained sediments from the bed. The slight post-flood increase in carbonate content of sediments in the lower reaches of the river-mouth (Fig.5.8B) suggests relative enrichment in skeletal material due to erosion of fine-grained, non-calcareous fluvial sand. The organic content of surface sediments (Fig.5.9B) was reduced from 1% to 0.5 % throughout most of the lower reaches but showed a marked increase in the southern extremity of the river-mouth indicating erosion and deposition in the respective areas.

A small stream-mouth bar was deposited seaward of the barrier outlet (Cooper, 1988b,1990d). It consisted of simple lobate sand bodies 20-30 m wide and 10-15 m normal to the coast. A 5 to 10 m-wide ebb channel, in a median position, was flanked by broad swash platforms lacking swash bars. The terminal lobe was submerged at all tidal stages. The mouth bar was too small to cause appreciable wave refraction, and was rapidly reworked under southeasterly wave action. The associated outlet channel was diverted northward through a distance of a few metres or tens of metres, lengthening its course and progressively losing competence and closing. Ultimately, the mouth bar was incorporated into the barrier through swash and overwash action, within two weeks of its formation.

5.5.3. Non-flood-associated breaching

During the study period the river-mouth breached several times due to slowly rising water levels or formation of barrier overwash channels. Both processes were also observed by Begg (1984a). Under both circumstances initial formation of the outlet leads to rapid outflow of the river-mouth water. This erodes the sandy barrier and enlarges the outlet channel, and the entire river-mouth drains within a few hours. Because the inflow from upstream is less than the outflowing volume, high current velocities are not sustained for long and their effects do not extend far from the outlet. Turbulence and sediment entrainment is minimised as the surface layers of the river-mouth water drain first and shear is probably accommodated within the water column. Observations of channel bedforms indicate the presence of large scale eddy currents after the river-mouth breaches and drains (Fig.5.10B). The deeper part, in which water is retained, is bottomed by fine sand in which small current ripples indicate downstream transport. The exposed portion, however, preserves small scale ripples (Plate.5.3) which indicate upstream transport and the presence of a large-scale eddy current. The formation of this eddy may be due to a greater frictional resistance on the shallower part and hence reduced current velocities. The complex ripple crests found at the first bend upstream (Plate.5.4) suggests that area to be the centre of the eddy.

Slight mud enrichment in bottom sediments may occur in localised areas but no mud accumulation occurs in the backwater channel: it drains and is not backed up with muddy flood waters. The short period in which the river-mouth drains minimises bedload transport but may be sufficient to remove accumulated fine sediment if not consolidated.

Ephemeral mouth bars deposited opposite breaches are rapidly reworked in the same way as those deposited after floods.

5.5.4. Sedimentary impacts of breaching

The sedimentological impacts of outlet formation through the three mechanisms described above must be assessed in terms of their contribution to the overall sedimentology of the river-mouth and preservation potential in the sedimentary record.

Changes in sediment distribution patterns following floods reflect conditions during both the flood peak and the waning flood stages. Care must therefore be exercised in interpretation of the data. One of the most marked changes brought about by the flood was the deposition of mud in the blind southern arm of the river-mouth. This was due to bypassing of that area by the main flood and the entrapment of turbid water from which deposition took place. When the flood waned the channel drained and the outflowing currents were insufficient to erode the deposited mud. The decrease in fine-grained sand in the main section of the river-mouth may be attributed to erosion of that grain size. Inman (1949) demonstrated that loose, fine-grained sand is the most easily eroded grain size because of the relationships exhibited by Shields' and Hjulström's diagrams. The calculated current velocity for erosion of fine sand is 0.4-0.5 ms^{-1} (Miller *et al.*, 1977) which is in general agreement with the current velocities indicated by the sedimentary bedforms. Long-term, selective erosion of fine grain sizes is suggested by the generally coarser grain sizes at 50 cm depth in the sediment during the pre-flood survey. Increased mud content near the roadbridge may be due to scouring around the bridge piers during the flood peak. The resulting scour hole would act as a focus for deposition from suspension during and after the waning flood stage. Upstream of the bridge slightly increased proportions of coarse grain sizes suggests that no waning stage deposition had occurred at the time of sampling. This is borne out by the preservation of large bedforms (sand waves) in mid channel.

Plate.5.3. Upstream-directed current ripples exposed on river-mouth bed after breaching. Sea is to left of photograph. (Lens cap for scale).

Plate.5.4. Complex arrangement of ripple crests at the first bend upstream of the barrier. This suggests it to be the location of the centre of an eddy current generated during breaching. (Lens Cap for scale).

The major differences between fluvial floods and overwash- or slowly-rising water-level-associated breaching, are the lack of mud deposition in backwater areas, less turbulent flow and lower net sediment transport under the latter two conditions. Flood-induced breaching is followed by a limited period of increased inflow from upstream which accomplishes greater sediment transport than the other mechanisms. Overwashing may form a channel irrespective of the river-mouth water-level and thus the magnitude of the discharge through the mouth may vary considerably when the river-mouth breaches through this mechanism.

Conditions during breaching are much more energetic than the low energy conditions in the river-mouth when isolated from the sea (Section 5.4.). It is only after breaching that bedforms are produced and bedload is transported. However, the short duration of high flows minimises potential sediment transport and the mouth bar deposited in the ocean mainly comprises material eroded from the barrier breach. Breach-generated bedforms are unlikely to be reworked when the river-mouth fills with water and thus bedforms produced by breaching are likely to be preferentially preserved in the sedimentary record, although such conditions prevail for less than 10% of the year.

5.6. SEDIMENTARY FACIES OF MHLANGA RIVER-MOUTH

5.6.1. Introduction

The nature and distribution of sedimentary facies are controlled by a combination of (i) hydrodynamic factors which determine sediment grainsize and sedimentary structures and (ii) physico-chemical characteristics which affect the distribution and abundance of organisms which bioturbate the substrate. In this section the modern sedimentary facies are described and assessed in relation to these factors.

The low water visibility due to suspended sediment makes observations of sedimentary structures difficult when the river-mouth is full of water. However, breaching and subsequent draining reveals the channel floor and the sedimentary structures preserved there. In the previous section it was demonstrated that except during floods and following breaching of the barrier, the river-mouth has a very low energy regime in which suspension settling dominates sedimentation and bedforms are not destroyed under the low energy conditions prevailing when the outlet is closed. The density of infauna is low and so internal bioturbation of the sediment is minimal. Thus the bedforms generated during breaching are likely to be preferentially preserved in the sedimentary record.

Observations on several occasions when the river-mouth had breached the barrier and drained, revealed the same general size and type of bedforms. The spatial arrangement, but not the size or type, of bedforms does, however, differ when the barrier breaches in the north or south.

Sedimentary facies of the river-mouth are divided into back-barrier and barrier-associated facies, both of which are discussed below.

5.6.2. Back-barrier environments

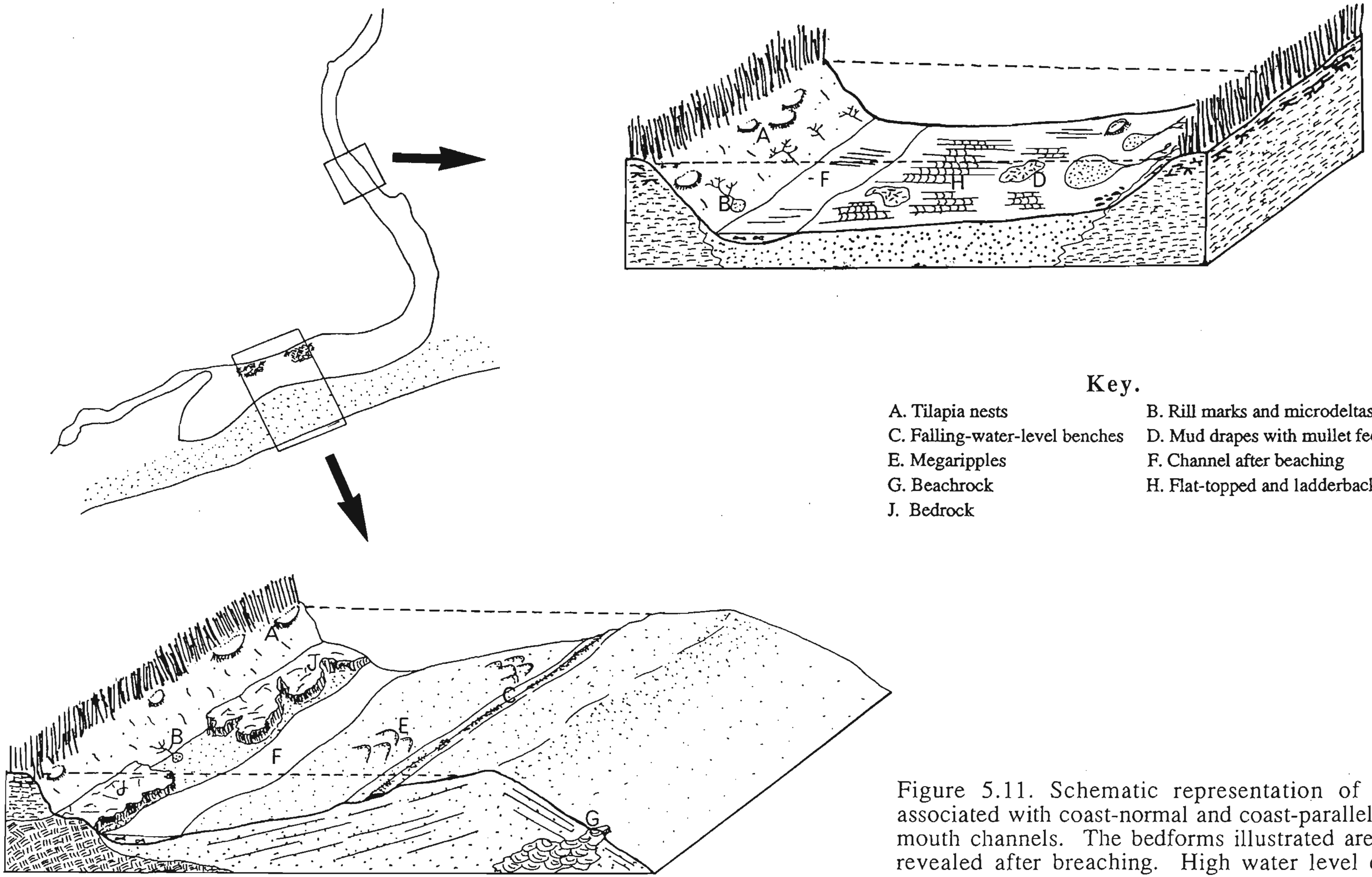
5.6.2.1. Coast-normal channel When the river-mouth breaches and drains this area is subaerially exposed except for a 10 m-wide channel adjacent to the right bank (Fig.5.11). The channel is less than 20 cm deep after breaching occurs and this cross-sectional area is sufficient to accommodate all runoff from the catchment. The channel is composed of fine sand which contains small, straight-crested current ripples, (wavelength 5-10 cm; amplitude 1-2 cm) facing downstream. Mud is absent from the channel and no biogenic sedimentary structures were observed.

The subaerially exposed former river-mouth bed is composed of medium- to fine-grained sand, covered in places with a few millimetres of wet, unconsolidated mud, which occasionally forms drapes over ripples or demarcates ripple troughs. These asymmetrical current ripples are typically straight-crested with amplitudes of 1-2 cm and wavelengths of 5-10 cm. They indicate upstream currents along the exposed section. In a few places these ripples are superimposed on larger straight-crested ripples, 1.5 m in wavelength and 15 cm in amplitude, also facing upstream. The exposed surface reveals many of the features of late stage emergence runoff typically associated with intertidal flats (Klein, 1977). Dendritic rill marks occur near the channel margins and these frequently feed small emergence runoff channels which terminate in microdeltas up to 1.5 m in radius (Plate 5.5A). Flat-topped ripples are common and many exhibit falling water level marks. Ladderback ripples (Plate.5.5B) are produced by emergence runoff concentrated in the ripple troughs. Mud drapes in some ripple troughs indicate suspension settling from muddy water trapped in the troughs and inability of late stage runoff to erode it. Numerous drag marks, up to 8 m long, are produced by pieces of vegetation being dragged across the sediment surface, and frequently the debris which produced them (small branches and reeds) is left stranded on the exposed surface (Plate.5.5C).

Mud lumps eroded from the channel margins occur on the surface, both as relatively unabraded, irregular lumps and as rounded and transported mudballs, only occasionally showing traces of armouring. Similar formation of mudballs was noted in small estuaries of the Transkei after breaching (Dardis & Plumstead, 1988). Desiccation of algal mats on parts of the exposed bed produces small algal rip-up clasts where the algae cling to the underlying sand. Other desiccation features, however, have little opportunity to form as the river-mouth refills with water relatively quickly after the breach closes.

A number of biogenic structures were preserved on the exposed surface, including the following:

a) Mugilid (mullet) feeding traces. These are locally numerous chisel-like scoops which occur chiefly in poorly consolidated mud and less commonly on fine sand. Each trace consists of a depression less than 1 mm deep, 1.5 cm wide and 4-5 cm long (Plate 5.6A). They have a central ridge which matches the shape of the underside of the mugilid mouth. They are irregularly oriented and suggest a feeding strategy which removes algae and diatoms from the muddy surface with a regular short scraping motion;



Key.

A. Tilapia nests
B. Rill marks and microdeltas
C. Falling-water-level benches
D. Mud drapes with mullet feeding traces
E. Megaripples
F. Channel after beaching
G. Beachrock
H. Flat-topped and ladderback ripple marks
J. Bedrock

Figure 5.11. Schematic representation of facies associated with coast-normal and coast-parallel river-mouth channels. The bedforms illustrated are those revealed after breaching. High water level during closed phases is illustrated by a dashed line.

Plate.5.5A. Microdelta fed by emergence runoff from muddy channel margins.

Plate 5.5B. Ladderback ripples produced during falling water levels associated with breaching. Such features are typical of intertidal flats.

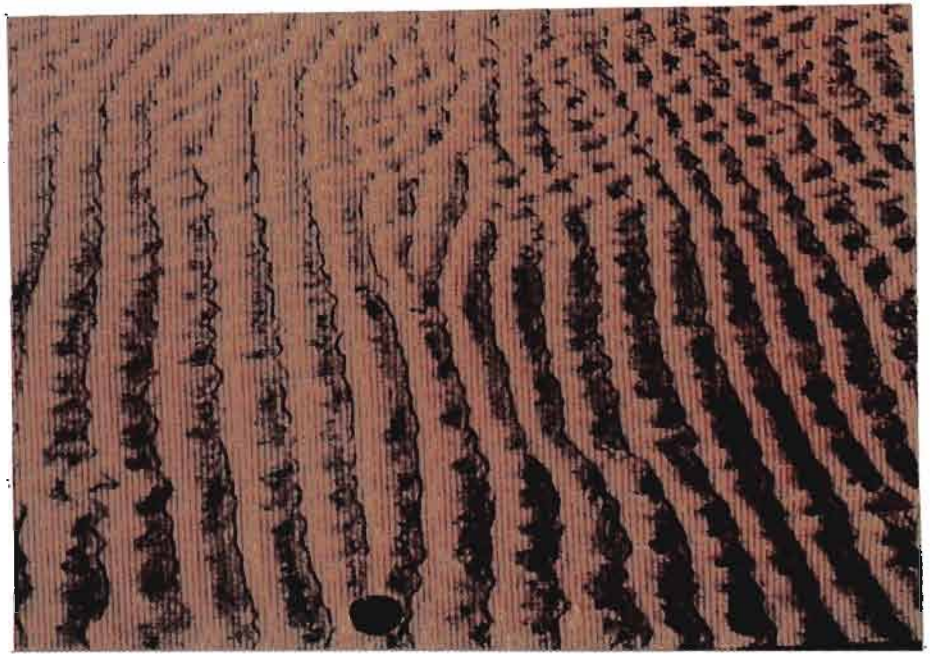


Plate 5.5C. Drag marks produced on the bed of the lagoon by vegetation carried in the outflowing water. The reeds which produced these drag marks are shown in the top left.

Plate 5.5A-C. Photographs of characteristic breach-generated sedimentary structures on the exposed river-mouth bed. Because of low-energy conditions when the outlet closes these have a high preservation potential.

Plate 5.6A. Mullet feeding traces which abound on soft muddy substrates in the breached river-mouth. Their chiselled shape suggests a scooping movement as the fish scrapes algae and diatoms from the bed. (Lens cap for scale)

Plate 5.6B. Tilapia nests on the exposed sandy bed. These large circular rims with a central depression frequently contain mud drapes deposited as water levels fell.

Plate 5.6C. Tilapia nests in the shallow marginal areas of the breached river-mouth channel. Measuring board has a total length of 0.75 metres.

Plate 5.6A-C. Photographs of biogenic sedimentary structures on exposed sediment surface.

b)Sesarmid crab trails. These are uncommon surface trails made by the chelipeds of these small crabs as they traverse both sand and mud. They are better preserved on mud. They consist of a series of small indentations arranged in a longitudinal band roughly equivalent to the width of the crab carapace (typically 1-2 cm across). Trails up to 5 m long have been noted;

c)Tilapia "nests". The large "nest" structures of the fish, *Oreochromis mossambicus*, (Tilapia) are excavated in both the consolidated muddy banks and the sandy bed. They consist of a central depression between 20 cm and 1 m across, but are typically about 50 cm in diameter. They are surrounded by a low rim of excavated material and the central depression is 5-10 cm deep (Plate 5.6B,C). They have been termed nests (Bruton & Boltt, 1975) because they are excavated by the male fish which lures a female to lay her eggs in the nest after which he fertilises them. However, the eggs are then removed from the nest by the female who mouth broods the eggs and the juveniles and the nest is abandoned. The structures themselves are likely to be preserved in such low energy environments if sheltered from high flows. As most are located on the higher parts of the bed they are rapidly elevated above the falling water and may escape erosion by outflowing water. They frequently trap a pool of turbid water which evaporates leaving a muddy drape when water levels fall. Their significance in bank erosion is discussed by Cooper & Harrison (1991);

d)Worm-casts. These small features consist of a tube with a diameter of 1 mm or less, forming small coils 1-2 cm across. They are found only in mud and are uncommon;

e)Sandprawn burrows. A few, widely scattered burrow entrances of the prawn *Callianassa kraussi* occur. The burrow is marked by a mound of excavated sand (Zoutendyk &Bickerton 1988) 4-5 cm across and 1-2 cm high in the centre. A small central orifice is present. Observations elsewhere (Weimer & Hoyt, 1964) have found that *Callianassa* produces an anastomosing burrow system which may be preserved as the trace fossil *Thalassinoides*, *Spongeliomorpha*, or *Ophiomorpha*.

f)Vertebrate footprints. Exposure of the bed enables reptiles, birds and small mammals to traverse it. Footprints observed include those of the monitor lizard, various unidentified birds, small antelope and monkeys. The latter leave a distinctive median trail when the tail drags on the sediment. No bird beak trails were noted at any time, suggesting a lack of infaunal animals for avian consumption in the sediment.

If preserved, the biogenic structures, in particular, yield valuable information for palaeoenvironmental reconstruction. The distinctive Mullet feeding trails may be attributed to the abundance of benthic-feeding mullet in the river-mouth. They dominate the ichthyofauna of small, generally closed Natal river-mouths, despite being marine fish (Harrison, 1990) and enter them as juveniles by swimming through outlet channels against the outflowing current (Harrison & Cooper, 1991). They are tolerant of salinities lower than seawater and are common in estuaries. The abundant nests of Tilapia suggest a freshwater environment. Although *O. mossambicus* is tolerant of salinities as much as five times that of seawater, it is a freshwater fish and is found in abundance in waters which are generally fresh or almost fresh (Whitfield & Blaber, 1979). In studies of the Georgia coast, Howard (1975) concluded that very few unique estuarine indicators occurred among the individual lebenspurren. The coexistence of both mullet and Tilapia biogenic structures in the sedimentary record must, however, be seen as compelling evidence of an enclosed coastal lagoon fed by a river and in intermittent contact with the sea. The presence of Callianassa burrows in the sediment would also indicate a marginal marine environment (Weimer & Hoyt 1964).

A low infaunal density was also noted in Mhlanga river-mouth by Whitfield (1980a,b). This cannot be attributed to frequent erosion or an unstable substrate as in larger Natal river-mouths (Forbes, 1973) but it is likely to be due to the rapid, irregularly spaced changes in water level and salinity brought about by breaching. Creatures requiring regular inundation and exposure could not exist; neither could those which require permanent submersion or exposure.

Because mullet feeding trails were frequently noted on mud drapes between ripples, the bedforms must have been inactive before the water drained from them, to enable the mullet to feed. Thus the conditions which produce the bedforms must only exist for a short period and probably result in very little net bedload transport.

5.6.2.2. Back-barrier channel . In the coast-parallel section of the river-mouth which is floored by medium to coarse-grained sand, principally of washover origin, surface sedimentary structures of any sort are uncommon even after breaching (Fig.5.11). Small (1-2 cm wavelength) sinuous to straight-crested oscillation ripples form in shallow water at the sandy margins as a result of wind-generated waves. A few *Callianassa* burrows occur along the margins. Washover fans are typically elongated into the river-mouth and contain internal structures typical of washover fans on the Natal coast (Cooper & Mason, 1986). On occasion, washovers may extend so far landward into the river-mouth that they partially isolate the southern part. The lack of sedimentary bedforms may be due to the grainsize of the sediment (medium sand) which is not entrained during the flows which form ripples in the fine grained sand upstream. Thus the internal structure of the river-mouth sediment in this area is simply the landward extreme of the washover fan, whose structure is discussed below.

5.6.2.3. Backwater channel . The backwater channel is dominated by suspension-settling of mud when water ponds during floods, however, following breaching it drains almost completely and much of the accumulated muddy sediment is eroded. Outflowing water velocity is insufficient to generate current ripples. The area is densely populated with sesarmid crabs which produce abundant cheliped trails on the exposed surface and Tilapia nests are common along the margins of the adjacent reedswamp.

5.6.2.4. Vegetated channel margins . The channel margins, which are vegetated by *Phragmites* reeds, are typically muddy. The mud is generally compacted and bound extensively by the rhizomes of the reeds. Thus it is high in organics and is erosion-resistant. *Oreochromis* nests occur there and these may undermine the reeds and cause bank collapse. On the surface of these muddy deposits is a laterally persistent organic-rich layer, 10 cm thick, composed of decaying fragments of the *Phragmites* reeds. It has an organic content, determined by loss on ignition, of 13%.

The *Phragmites* beds trap a portion of the suspended sediment during high water levels, however, sustained accretion does not occur as the barrier height and small river catchment limit the level to which the water may rise. This contributes to the long term stability of the river-mouth (Section 5.7.).

5.6.2.5. Sandy channel margins . These areas occur along the landward margin of the barrier and where eroded Holocene and Pleistocene dunes occur adjacent to the river-mouth. Structures of these areas consist of terraces or terracettes which record changes in water level over a vertical range of 2.5 m. The terraces are cut by wave and swash action at stable water levels and hence a series of terraces may record the progressive lowering of water level after breaching. On these terraces, small-scale symmetrical oscillation ripples (wavelength 2 cm; amplitude 1 cm) form in water depths shallower than 10 cm. They are typically shore parallel but may locally form at angles up to 45° to the shore. Concentrations of heavy minerals may also be formed as quartz and feldspars are selectively winnowed by swash action on these margins. Concentrations up to 15 cm thick periodically form elongate, wedge-shaped placers along the river-mouth margin.

5.6.3. Barrier-associated environments

5.6.3.1. Aeolian dune . The largest dunes occur on the Mhlanga barrier at the southern end and are densely forested and therefore expected to be deeply bioturbated by roots. Erosion of the end of parts of the vegetated dune at the north and south ends of the river-mouth do however reveal typical dune internal structures and only the uppermost 1-2 m is structureless. The internal structures are typical of most aeolian dunes (Bigarella *et al.*, 1969; Goldsmith 1984) and are dominated by large scale planar foresets. Old soil horizons are evident at the northern end of the dune (Plate.5.7).

The small dune hummocks in front of these dunes and the dune in the centre of the barrier are covered with pioneering dune vegetation. They show less rootlet bioturbation and lack fossil soils but otherwise their internal structure is similar to the forested dunes when exposed in eroded faces (Plate.5.8). Surface trails are rare on the dune surfaces and only a few insect trails were noted.

5.6.3.2. Barrier beach . Barrier overwash is the dominant process along the Mhlanga river-mouth barrier, but discrete washover fans are deposited only rarely, after single high energy swell events. When deposited, they may extend 50 to 60 m landward of the barrier and are up to 30 m wide. These features partially isolate the southern end of the river-mouth. They have a high preservation potential as they contain medium to coarse sand which is unlikely to be eroded from the river-mouth. Typical structures of washover fans on the Natal coast have been described by Cooper & Mason (1986) and consist of landward-dipping planar bedding, frequently inversely graded, and with interbedded armoured lags. Small scale foresets may occur when a depression is encountered in the underlying surface. In the absence of flood-tidal currents overwash is the only mechanism (other than aeolian) by which marine sand enters the river-mouth.

Plate.5.7. Eroded face of forested Holocene dune showing internal structures. A number of soil horizons (arrowed) are preserved in eroded face of Holocene dune. Large-scale cross-bedding typifies the dune structure.

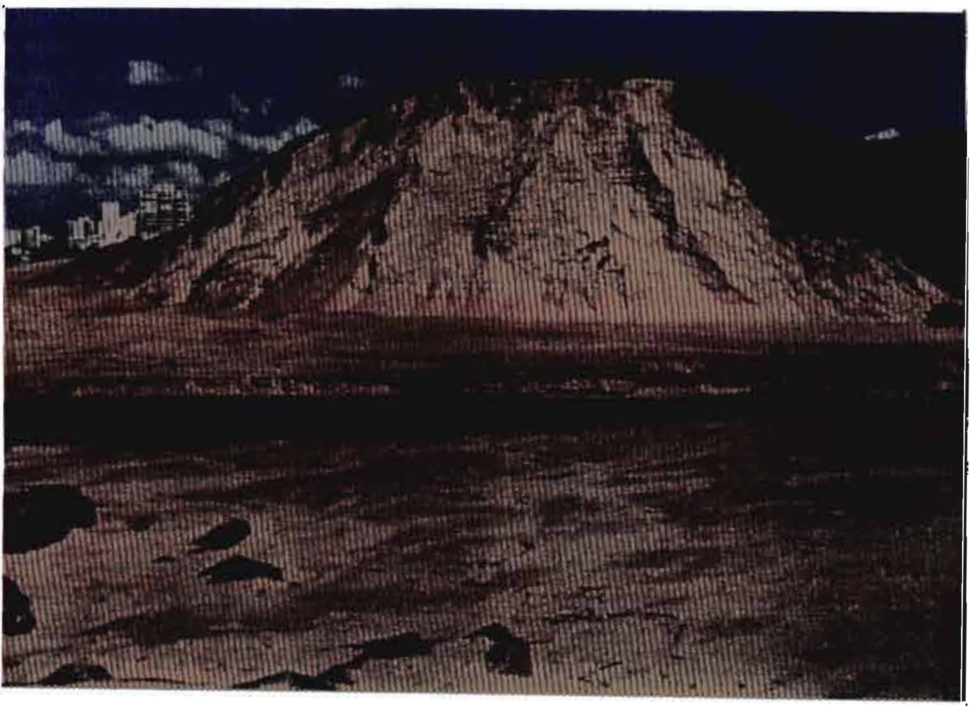


Plate.5.8. Internal structure of the central, sparsely vegetated barrier dune revealed in an eroded face produced by breaching and erosion. Large-scale cross bedding dominates the internal structure but soil horizons are absent.

5.6.3.3. Ephemeral stream-mouth bar . Mouth bars deposited at an ephemeral outlet were described by Cooper (1990d) and in Section 5.7. As the term suggests, their preservation potential is negligible and the material which comprises them is reworked back into the barrier from which it was eroded in the first instance.

5.6.3.4. Ephemeral inlet channel . Ephemeral channels are typified by antidune formation as water discharges but the preservation potential of antidune cross-bedding in this environment is very low. Closure of the channel by washover-deposited sand ensures that no evidence of a channel is left in the sedimentary record. Due to its elevated bed level the river-mouth lacks flood-tidal deltas.

5.7. HISTORICAL CHANGES IN MORPHOLOGY

5.7.1. Introduction

Knowledge of the long-term development of the river-mouth enables an assessment of the relative importance of various physical processes. The historical development of Mhlanga river-mouth was studied using time lapse aerial photographs from 1937 to 1990. The interpretations are illustrated as Figure 5.12 (A-K).

Early accounts of Mhlanga river-mouth documented by Wager (1976) suggest that during the 19th century it had a larger open water area. Reference to mudflats also suggests that the mouth was open at least periodically. Wager (1976, p7) stressed the detrimental effect of draining a large reedswamp in order to plant sugarcane. This apparently caused "extensive reed growth and silting of the deeper areas".

5.7.2. Aerial photograph interpretation

Aerial photographs taken in 1937 show a sinuous channel entering a coast-parallel river-mouth with a similar overall morphology to the present (Fig. 5.12A). The *Phragmites* swamp was already established on point bars except on the seaward-most where, they formed only a 40 m-wide fringe. Forested dunes extended north and south of the river-mouth and a small, partially-vegetated dune was established in the centre of the low, unvegetated sandbar. A washover fan at the south end of the barrier suggested that this was the position of the most recent outlet. Sparsely vegetated sand at each cut bank of the river bends indicated recent erosion, and shallowly submerged sand bars on the downstream ends of point bars reflected their accretion. Recent erosion of the dune at the southern end of the barrier had occurred but was now inactive due to the protection afforded it by a recent washover.

In August 1953 a large washover fan was present at the northern end of the barrier, partially isolating the southern end of the river-mouth (Fig.5.12B). The overwash may be linked to recent outlet formation at this position. Over 17 inches (45 cm) of rain fell, "in a single night" in January 1953 and, "completely washed away all the dunes along the lagoon shore" (Wager 1976, p11). This exaggerated statement, in fact, referred to only the northern end of the sandbar where the mouth formed:

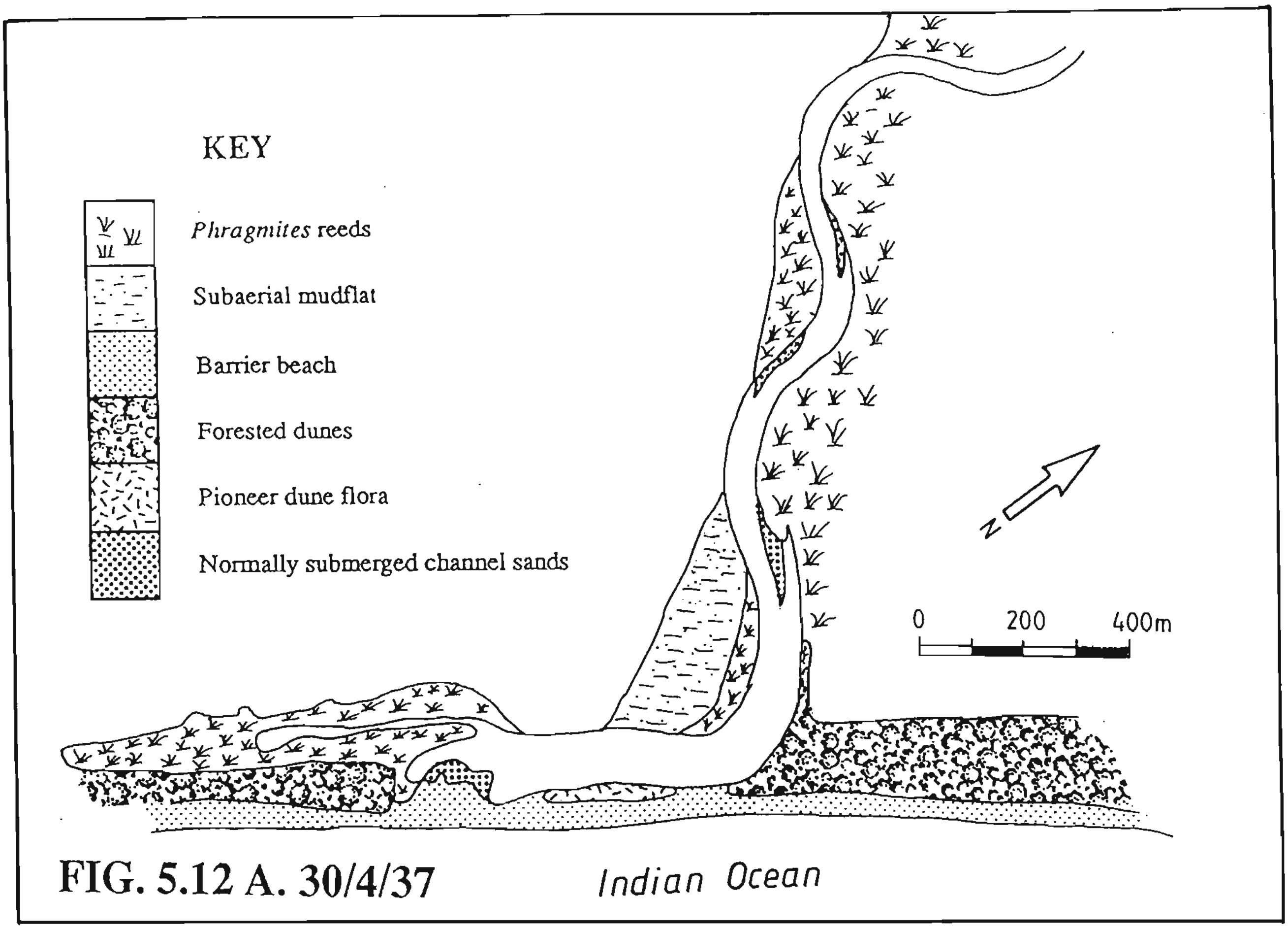


FIG. 5.12 A. 30/4/37

Fig.5.12. A-K. Interpretation of vertical aerial photographs showing sequential changes in morphology of the river-mouth since 1937.

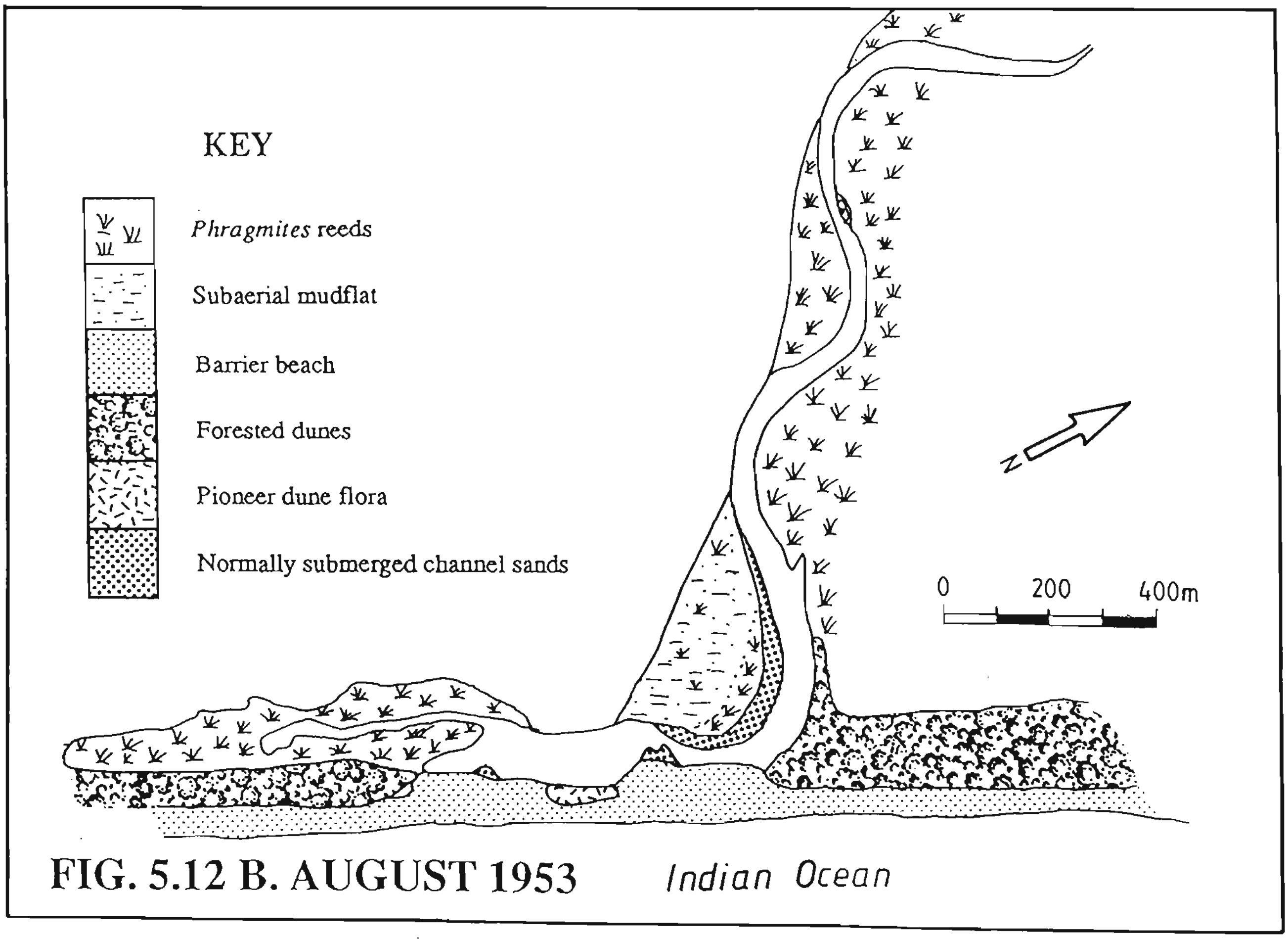


FIG. 5.12 B. AUGUST 1953

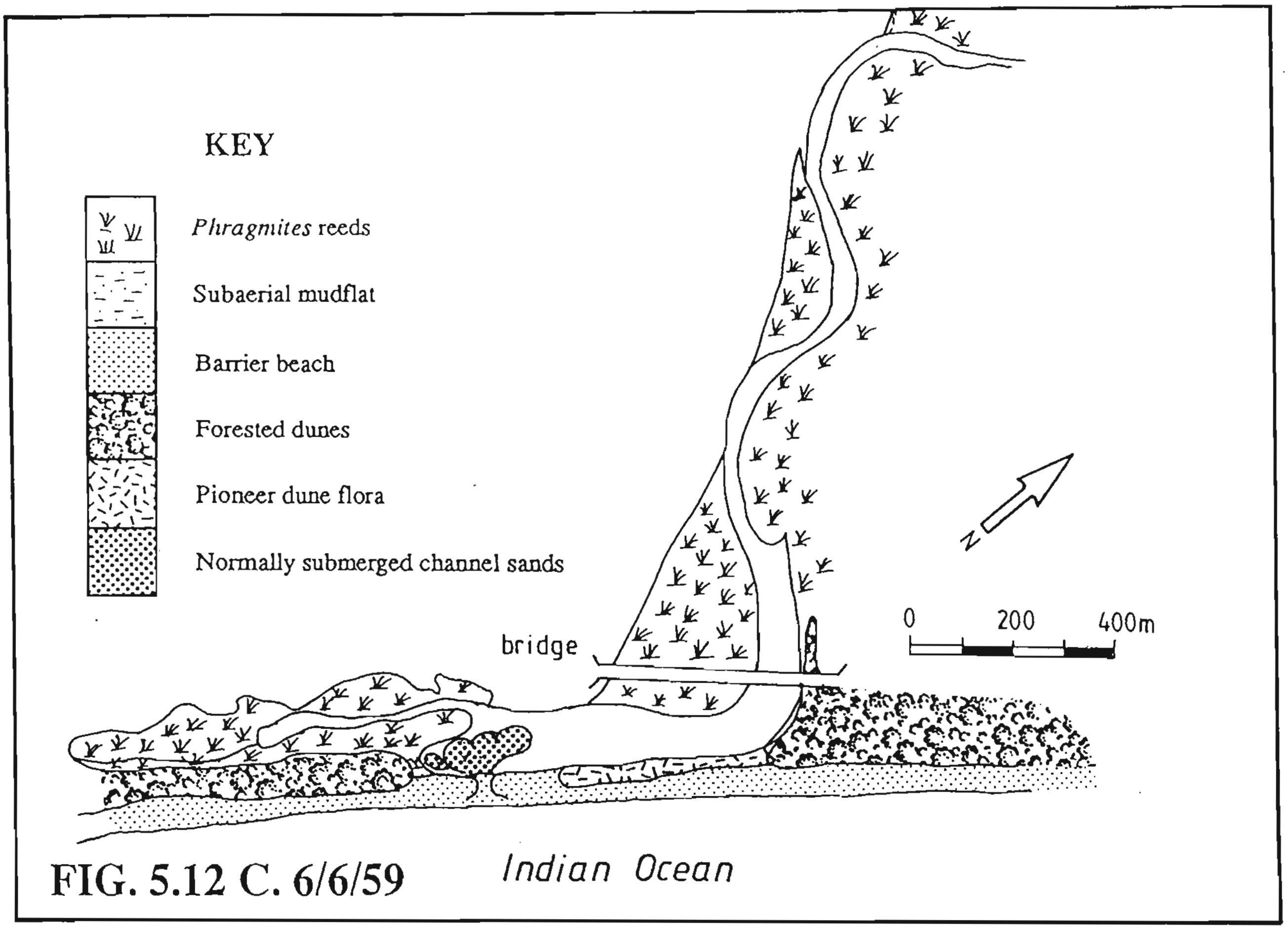


FIG. 5.12 C. 6/6/59

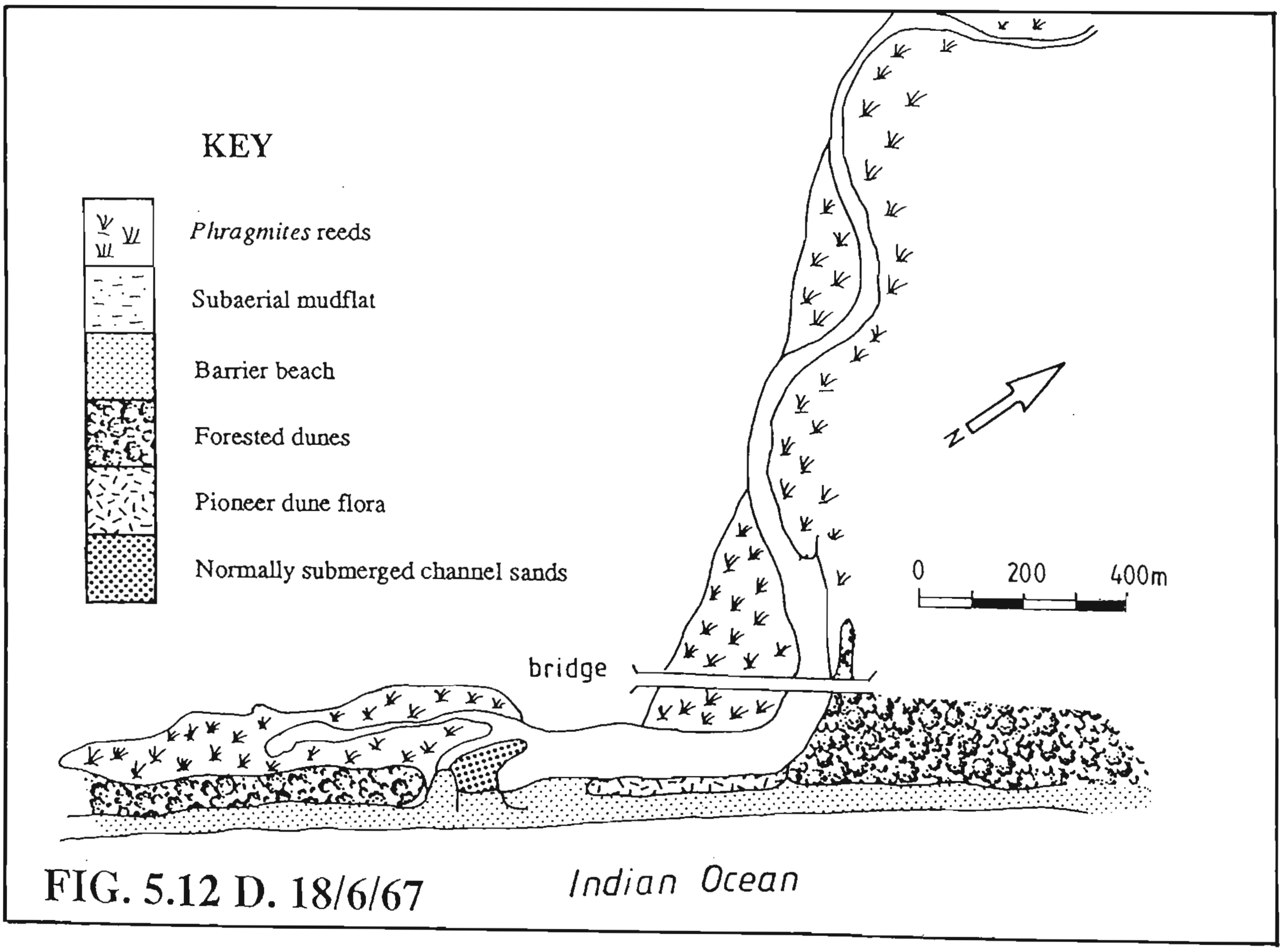


FIG. 5.12 D. 18/6/67

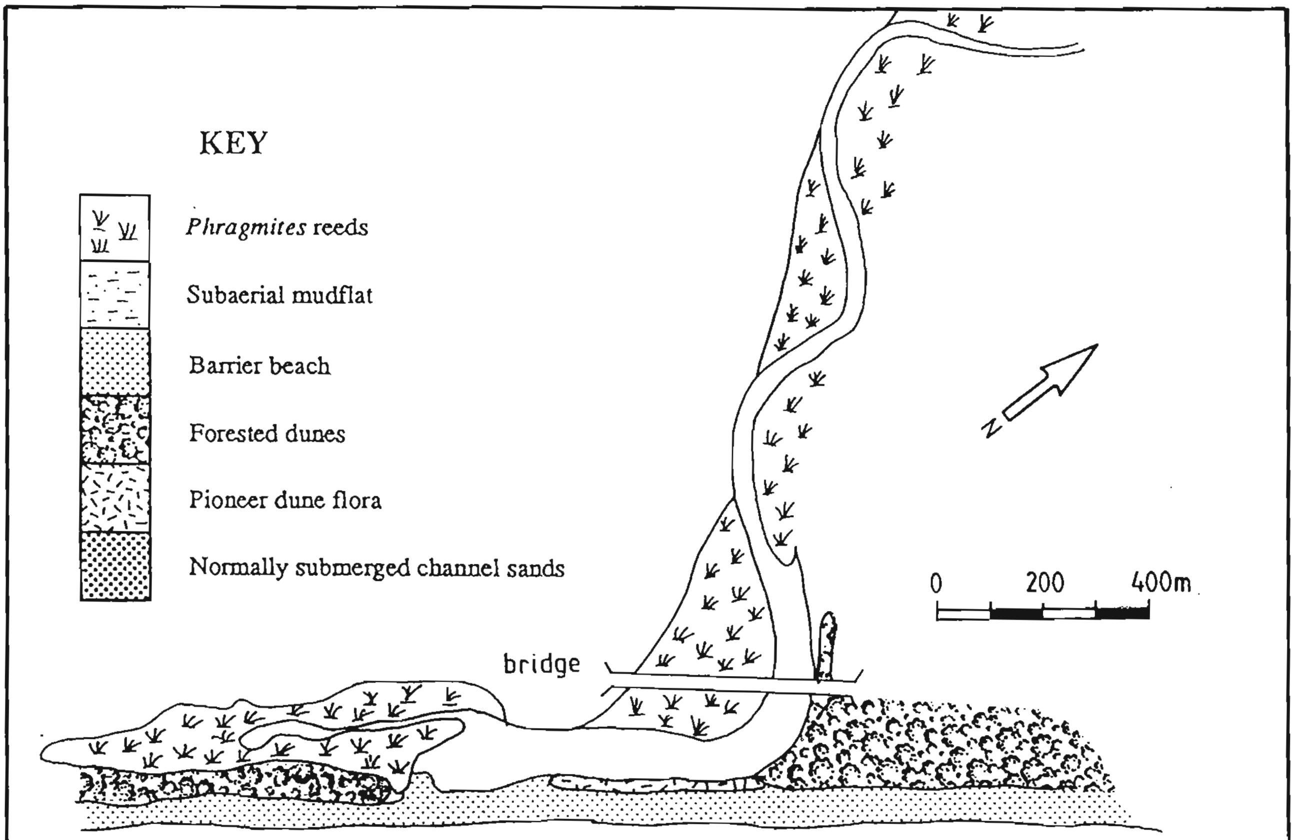


FIG. 5.12 E. 5/9/68

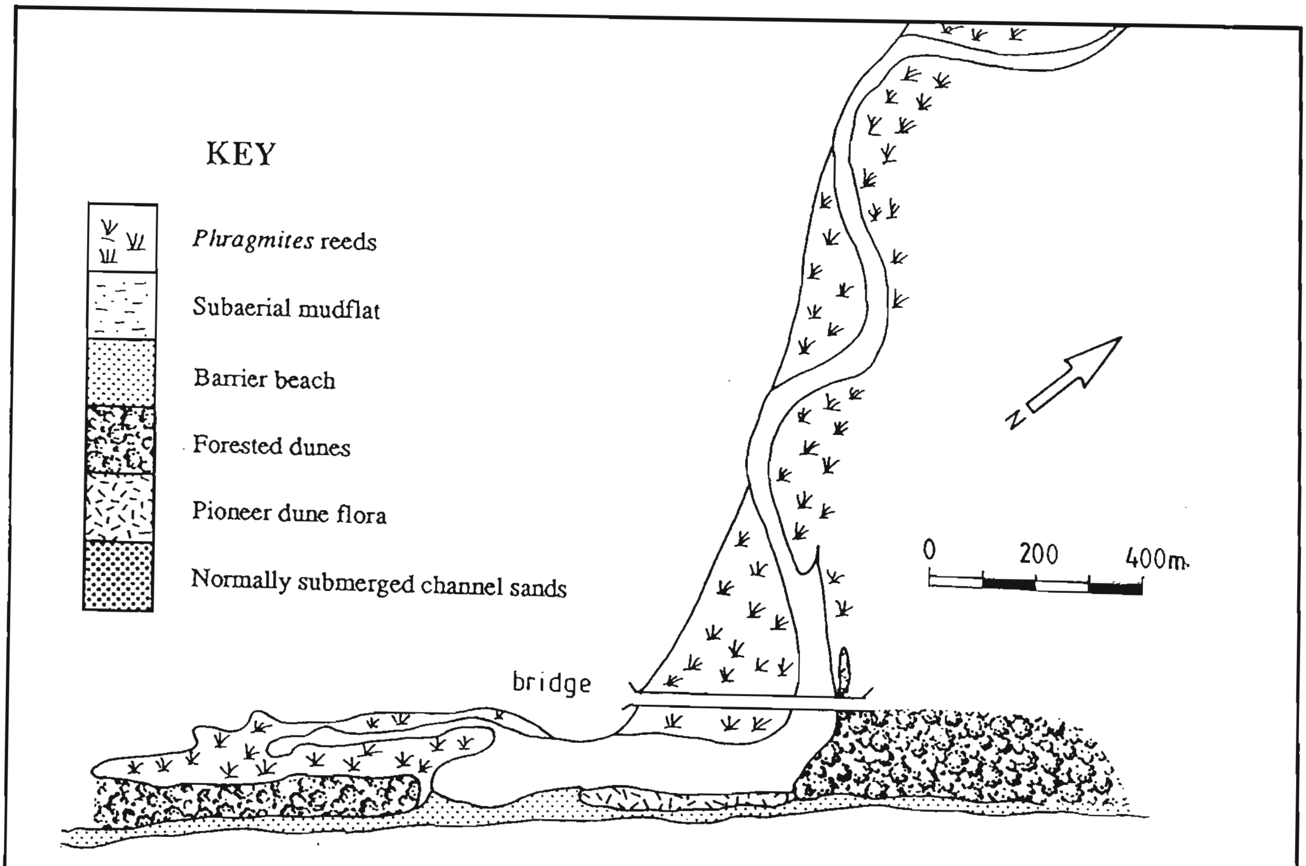


FIG. 5.12 F. 25/4/73

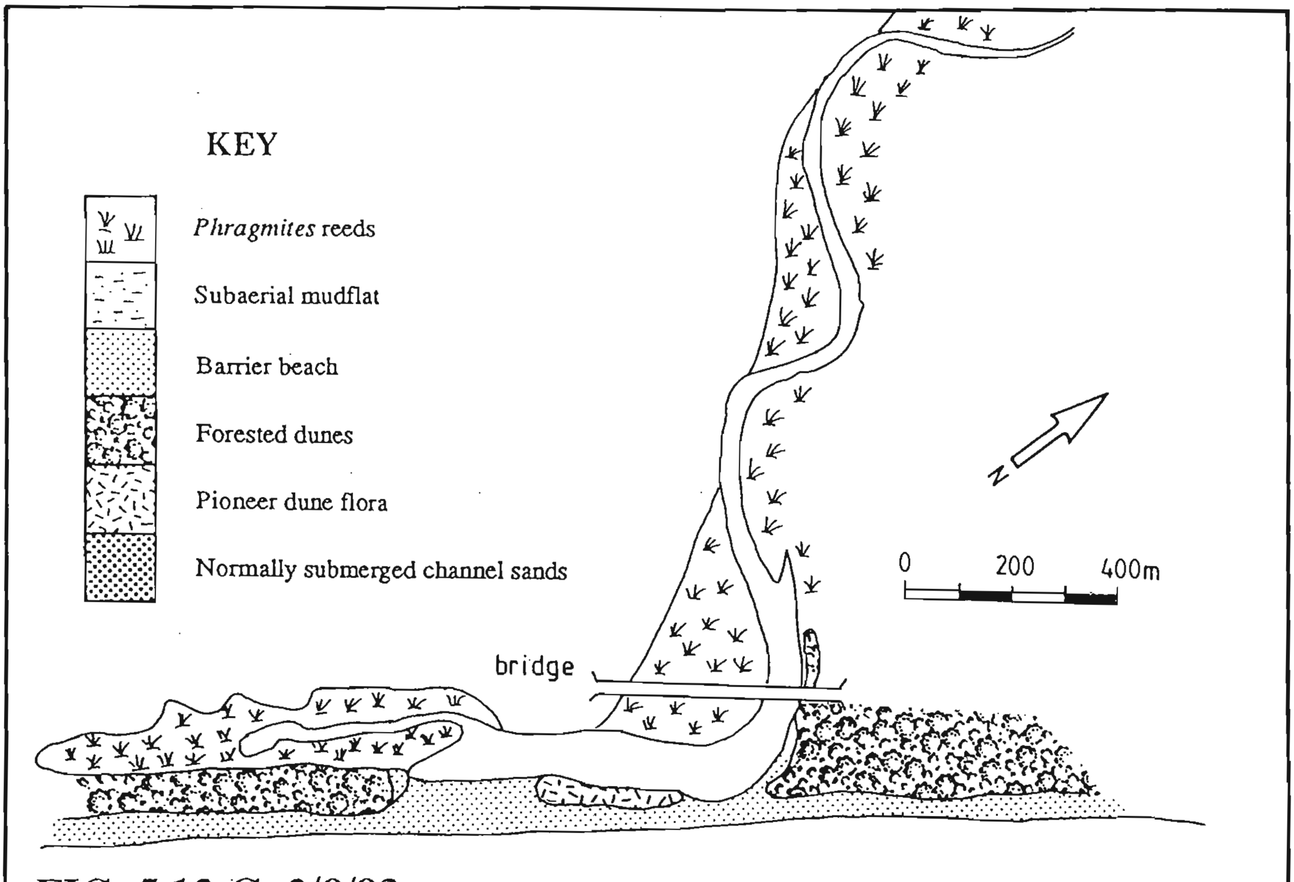


FIG. 5.12 G. 2/8/83

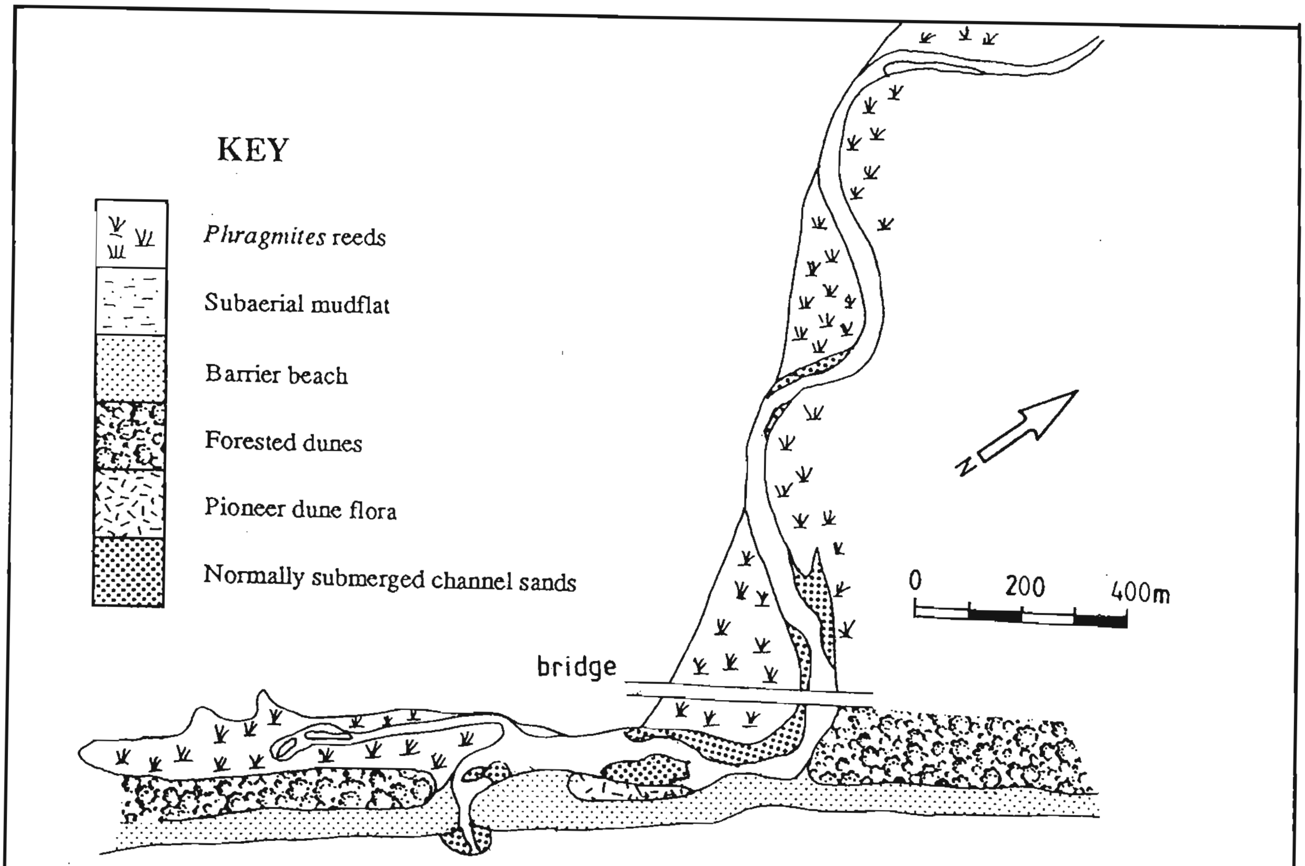


FIG. 5.12 H. 12/2/84

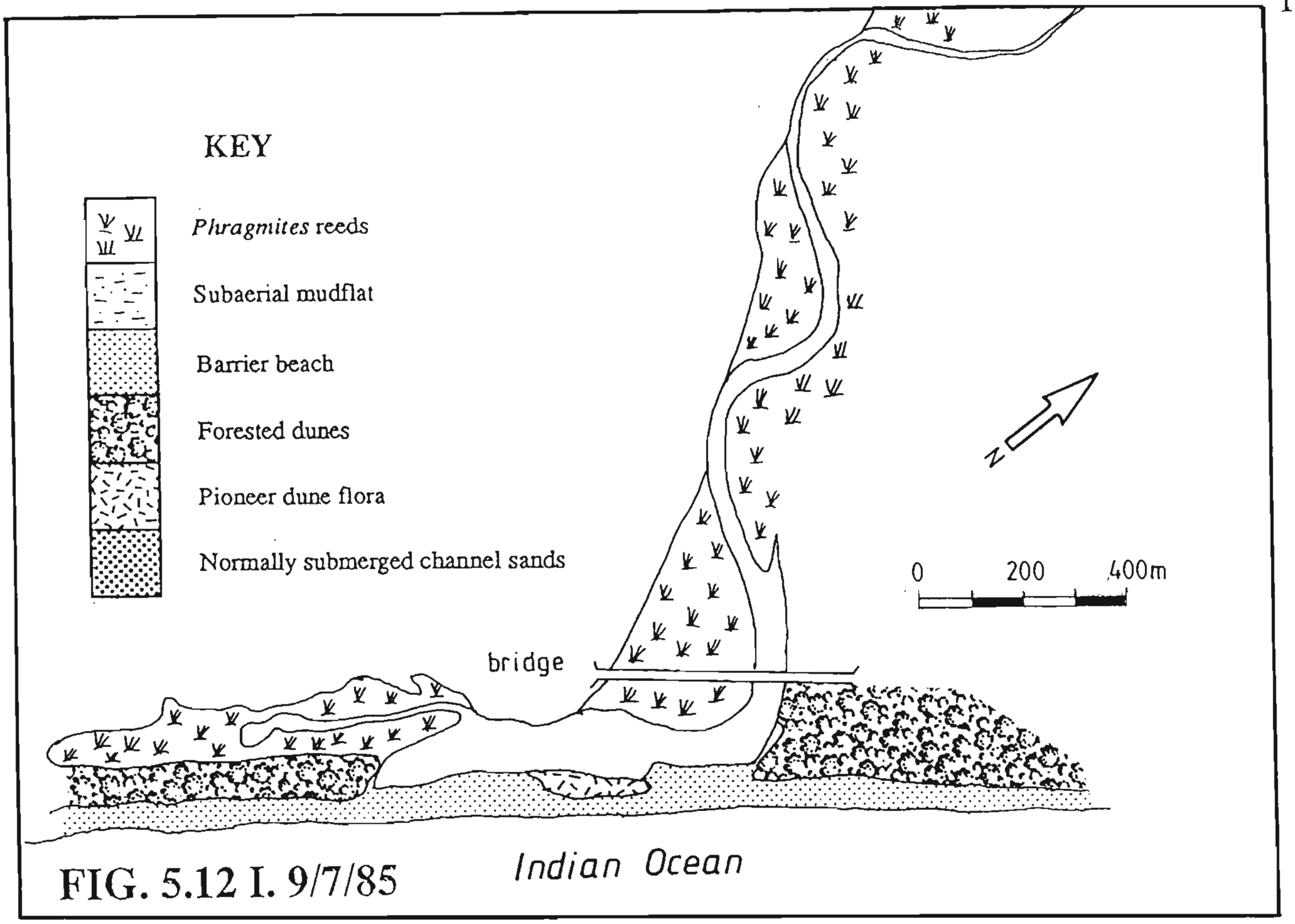


FIG. 5.12 I. 9/7/85

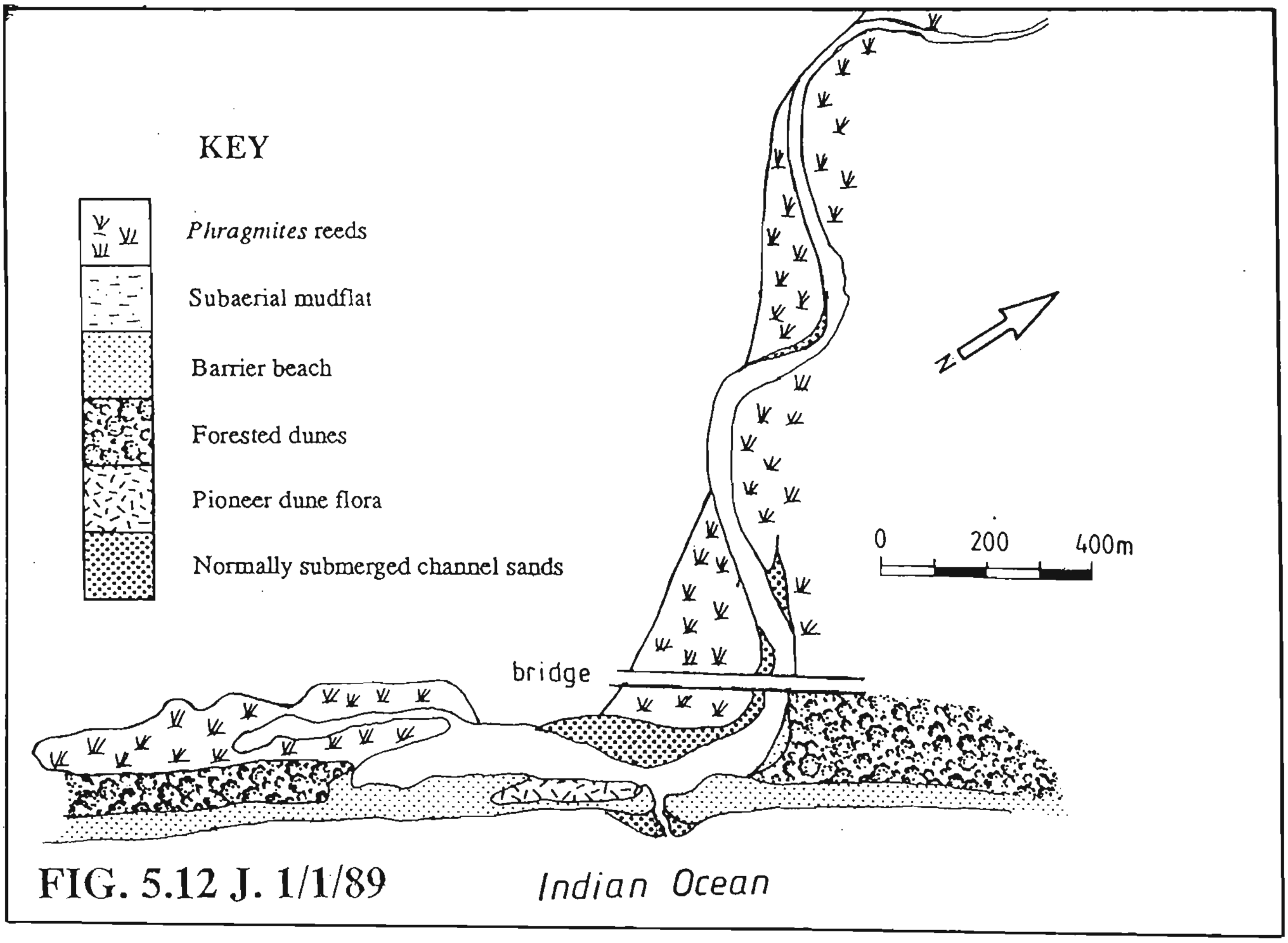


FIG. 5.12 J. 1/1/89

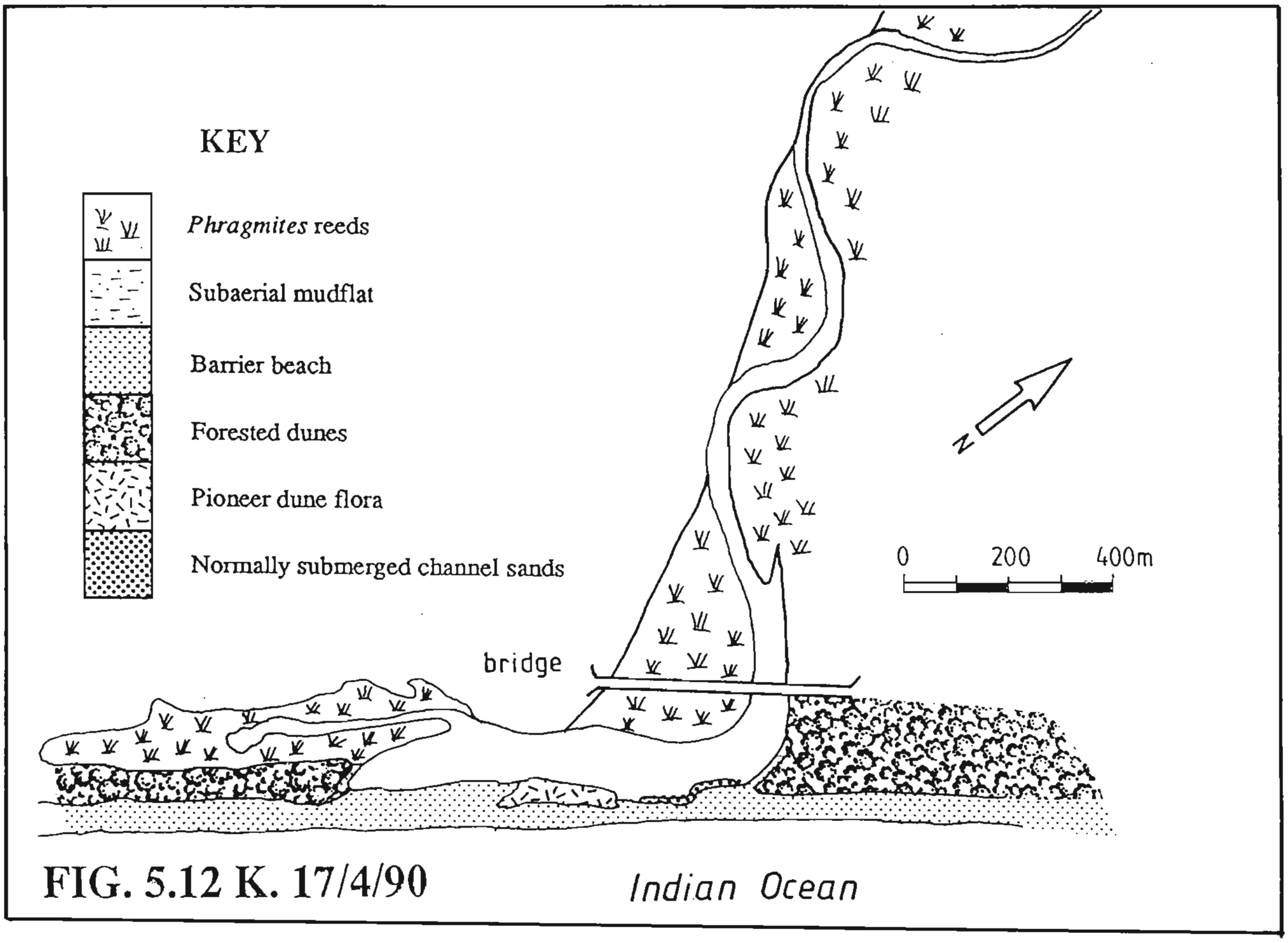


FIG. 5.12 K. 17/4/90

photographic evidence shows that the vegetated dune on the barrier was not eroded. Such discrepancies urge caution in the literal interpretation of written historical records. Sand had accreted above water level on the seaward-most point bar, forming a fringe and the landward parts of the point bar were more densely vegetated with reeds. Upstream, reed encroachment onto sandbars had caused the uppermost section of the river-mouth channel to narrow.

In June 1959 (Fig.5.12C), the roadbridge had recently been completed and the sandbar exposed on the seaward-most point bar had become vegetated with Phragmites, enlarging the point bar. Begg (1978) suggested that construction of the bridge was accompanied by the production of large quantities of silt. If so, this would probably have been readily washed out of the system by subsequent floods. A recent outlet channel was preserved on the southern end of the barrier, 150 m north of the southern dune, and washover sand was present in the river-mouth opposite the outlet. At the northern end of the barrier an aeolian dune stretched along the northern two thirds off the barrier and joined the northern forested dune. This may have been facilitated by aeolian reworking of the large washover fan present in 1953. The forested dune to the south was also extending northwards by sand accretion. The recently deposited dune areas were vegetated with pioneering dune flora. Upstream, formerly eroding banks were fully vegetated and recent erosion was only evident at the 90^{o} bend at the coast.

In June 1967 (Fig.5.12D) aeolian dune growth was continuing and no active erosion was evident within the river-mouth. Recent outlet formation had been in the south and a washover of similar dimensions to that in 1959 was present in the same location. In September 1968 (Fig.5.12E) the situation was similar, with a recent outlet in the south and well-developed pioneer dune flora on the barrier dune.

In 1973 (Fig.5.12F) the barrier beach had narrowed significantly and was clearly in an erosive state as the seaward edge of the pioneer barrier dune was scarped. The barrier was narrowest in the south thus favouring outlet formation there. No bank erosion was evident upstream of the coast-parallel river-mouth sector.

By August 1983 (Fig.5.12G) the northern section of the pioneer dune had been completely eroded and the barrier was only 30 m wide where the dune had been. In the south, however, overwash deposition had widened the barrier, to 80 m, protecting the southern forested dune from erosion.

Oblique air photographs taken in December 1983 record a period during which the outlet reverted to its southern position. At the time of photography the outlet channel trended obliquely northward across the barrier approximately 30 m north of the southern forested dune, suggesting limited outlet migration. A similar outlet position was recorded in January 1984. Lowered water levels revealed the sandy river-mouth bed and a small channel in the central part of the river-mouth. Linguoid megaripples and sandwaves on the exposed parts of the bed indicate relatively high current velocities during draining of the river-mouth.

In February 1984 (Fig.5.12H) the outlet was also open in the south and the river-mouth bed was exposed, revealing normally-submerged sand accumulations on the downstream end of point bars. Erosion of the northern dune was particularly marked.

Breaching during February 1985, to the south of the December 1983 position, caused erosion of the southern forested dune. This undermined the binding roots of the dune forest and large trees fell into the river-mouth. The importance of roots in binding dune sand was stressed by Goldsmith (1984) who pointed out the vital role of vegetation in vertical dune growth. The previous stability of this dune is indicated the period of pioneer dune accretion on the northern end of this dune since 1953, when washover fans protected the dune from river erosion. However, the 1937 photograph suggested that erosion of this dune had also occurred before 1937.

Photographs dating from July 1985 (Fig.5.12I) show the pioneering dune vegetation on the northern end of the river-mouth was eroded and small washover fans were deposited at both the northern and southern ends of the river-mouth. Begg (1984a) noted a period in September 1980 when the mouth opened in its northern position and partially eroded the forested dune at the northern end of the sandbar. Begg (1984a) attributed this erosion to trampling of the pioneer dune vegetation by humans, enabling subsequent overwash to lower the sandbar. Subsequently, high river flow breached the river-mouth in this vicinity. Although Begg (1984a) regarded breaching in the north as entirely due to erosion of dune vegetation it was evident that between 1937 and 1953, there was also no vegetation on this part of the sandbar and yet breaching continued at the southern end of the barrier. It is therefore likely that breaching in 1980 was due to storm-generated barrier overwash, preceded by erosion of the barrier face as shown in the 1973 photograph.

In January 1989 (Fig.5.12J) an outlet was open in the north and the bed was partially exposed. A large, normally-submerged sandbar was present opposite the outlet on the seaward-most point bar. And erosion was marked on the outer banks of the bends upstream. This was probably a result of the September 1987 flood discharge. Erosion of the northern forested dune was continuing and the southern forested dune had retreated by 125 m since 1984, largely as a result of scour on the outer bank of outlets formed in the southern part of the barrier.

In April 1990 (Fig.5.12K) the southern dune had retreated by a further 12 m but was beginning to stabilise through the spread of pioneer dune vegetation. No outlet was evident in the barrier but overwash across the northern barrier and field investigations showed that outlet formation was preferentially located in the northern barrier and was causing erosion of the small pioneer dune in the centre of the barrier. Eroded scarps upstream were being colonised and stabilised by dune vegetation.

5.7.3. Discussion

The above observations illustrate the variation in morphology observed in Mhlanga river-mouth over a 53 year period. This variation may be subdivided into two main areas: barrier morphology and back-barrier channel morphology.

5.7.3.1. ***Barrier morphology*** **.** The main changes in barrier morphology were in the outlet position, episodic overwash, and the growth and demise of an aeolian dune atop the barrier. The seaward margin of the barrier as indicated by the high water mark did not undergo progressive migration but fluctuated through a maximum horizontal distance of 30 m (Fig.5.13). This suggests that the barrier is in equilibrium with dominant wave fronts but minor changes in beach profile may occur due to storm action. Minimal change in this shoreline was also noted by Cooper (1991b) who attributed this to lack of longshore transport of sediment around the rocky headland of Umhlanga Rocks. Maximum erosion in 1973 followed a long period of aeolian deposition on the barrier and may have been in response to progressive depletion of the forebeach sediment by aeolian deflation.

In the period after 1953, aeolian deposition on top of the barrier extended the central dune pioneer, so that by 1959 it covered the northern two thirds of the barrier and became joined to the northern forested dune. This feature maintained its integrity through stabilisation by pioneering dune plants until at least 1973 when a period of erosion was noted. It may even have been present until 1980. Over the same period, aeolian deposition caused the southern forested dune to grow northward. The reasons for this aeolian deposition are unclear but may include decade-scale periodic changes in wind regime, reduced river discharge inhibiting breaching, increased littoral sediment supply, and changes in wave patterns.

Outlet position is closely linked to washover fan deposition. From the aerial photography it is impossible to determine whether breaching encourages overwash or vice versa, although observations in the field suggest that both situations occur. Lowering of a barrier by overwash may promote outlet formation but conversely when overwash raises the barrier height it may inhibit breaching (Carter *et al.*, 1984). Barrier overwash does introduce material into the river-mouth which should promote landward migration of the barrier if the washover sand is not returned to the shoreface and sediment supply from alongshore is at a low rate. Comparison of aerial photography suggests that sand in washover fans is redistributed in part by aeolian action. Dune accretion in 1957 was preceded by deposition of a large, subaerially-exposed washover fan in 1953. This was not visible in 1957 although substantial aeolian accretion had taken place on its landward edge. Outlet formation adjacent to or across a washover fan may carry sediment from the fan to the seaward side of the barrier, thus removing part of it from the back-barrier area. Such a situation is indicated by comparison of the photographs of July 1985 and January 1989. In January 1989 an outlet was formed at the site of a large washover present in July 1985. The part of the washover adjacent to the outlet was eroded and a small ephemeral delta was deposited in the sea.

5.7.3.2. ***Back-barrier morphology.*** To illustrate changes in the back-barrier channel a composite diagram of the channel position at three, roughly equally spaced intervals was prepared (Fig.5.14.) This indicates downstream migration of the channel bends through erosion of the outer bends and deposition on the opposite point bars, followed by colonisation of the point bar by *Phragmites* reeds. The process is, however, episodic rather than continuous as intervening photographs show periodic stabilisation of

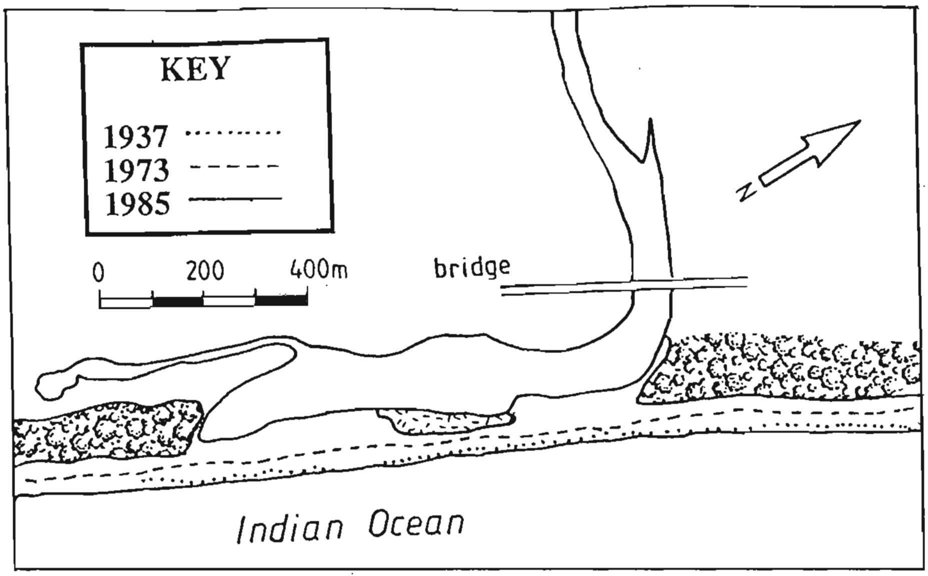


Figure 5.13. Diagram showing shoreline position in 1937, 1973 and 1985. The high water mark shows only minor changes in position within the 1985 and 1973 limits. Maximum erosion occurred in 1973 when the seaward edge of the pioneering dune was eroded. The stability of the shoreline may be attributed to underlying rock outcrop and waves which break parallel to the coast.

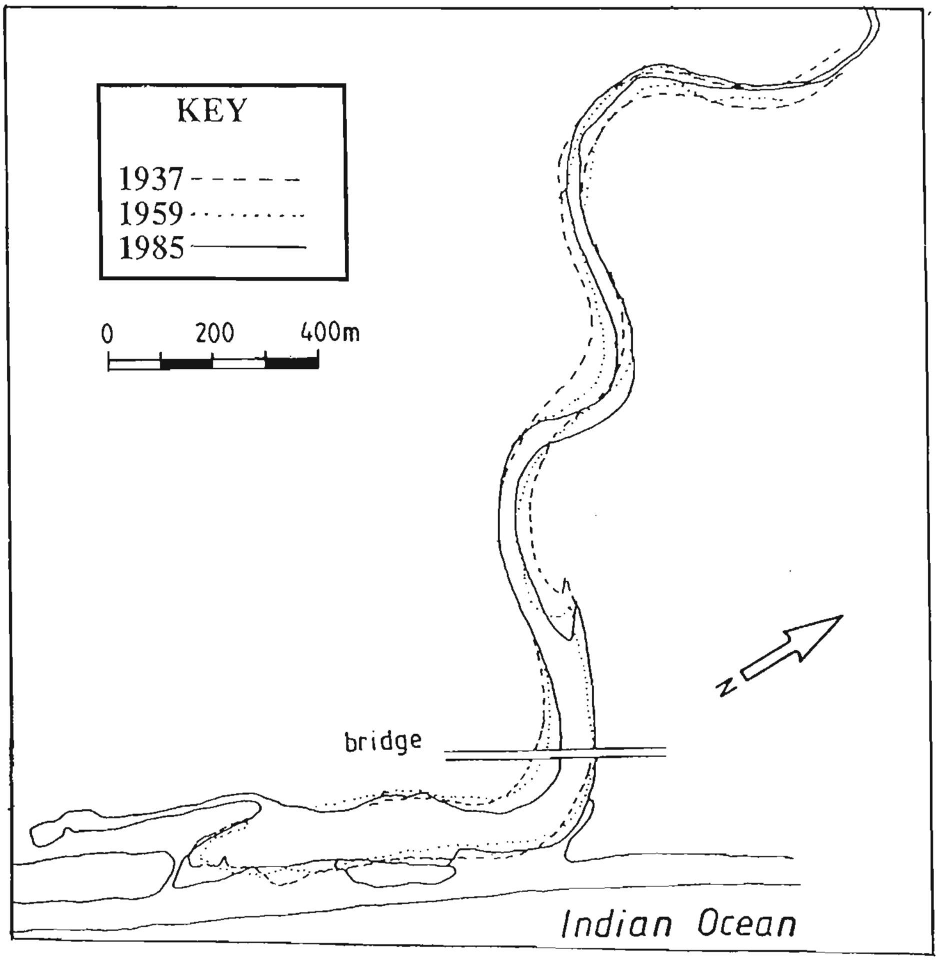


Figure 5.14. Diagram showing limited channel migration since 1937. Channel positions in 1937, 1959 and 1985 are shown. Point bar growth is not continuous but is strongly episodic and appears to be associated with floods.

cut banks and a lack of sustained growth of point bars. Episodic growth of point bars is best illustrated by reference to the most downstream bar. In 1937 this had a narrow fringe of *Phragmites* on the channel margin. In August 1953, a new increment of bar sediment was exposed above water level water adjacent to the previous *Phragmites* fringe. This bar may be associated with a severe flood in January of the same year when increased flow velocities may have promoted helical flow and cross-channel sediment transfer in the bend, thus elevating the bar above water level. (The 1937 feature might also have be associated with a flood as one had recently occurred in the adjacent Mgeni River). Lowered water levels after flood-associated breaching in February 1984 revealed a normally submerged sand body at the margin of the point bar. Subsequent photographs and field investigations show that this is still present at the time of writing. It has not been colonised by *Phragmites* , possibly because it is located in water too deep for the reeds to extend their roots into. Upward accretion of the point bar may be impeded by low flow velocities, insufficient to promote helical flow of large enough magnitude to entrain aeolian sand eroded from the opposite cut bank. Further upstream point bars are composed of fine grained sand which may require lower velocities to promote transport.

The apparently episodic pattern of channel migration may be linked to increased flows during floods, when sufficiently high flow velocities are generated to cause erosion. Under normal conditions when no outlet is present, flow velocities are extremely low and probably ineffectual in bank erosion. While the nest-building activities of Tilapia fish may produce undercutting under low flow conditions (Cooper & Harrison, 1991), the collapsed material requires increased flows to be dispersed. Thus breaching may promote channel migration, particularly if it is produced by a high-discharge flood.

In some rivers, episodic, flood-related point bar migration produces scroll bars with intervening swales (Fisk, 1947; Reineck & Singh, 1973, p231). In others sustained accretion occurs (Leopold *et al.*, 1964) during which deposition on the point bar keeps the channel width constant as the cut bank erodes. In Mhlanga river-mouth, scroll bars have not been formed and narrowing of the channel occurred in some places as point bars accreted. This may be attributed to erosion of a palaeodunes comprising unconsolidated sand which retreat more slowly because of their height than the opposing point bar whose elevation is low. A major difference between point bars in rivers and those in Mhlanga river-mouth, are that while in rivers, most deposition and transport on point bars is accomplished during high water levels associated with floods (McGowen & Garner, 1970), in Mhlanga river-mouth, high water levels are associated with tranquil conditions when no outlet is present and most point bar migration occurs during floods at lower water levels than normal. Thus point bars in Mhlanga are typically covered with mud drapes from suspension during low flow periods, while riverine point bars are subaerially exposed to wind action and bioturbation from fauna and flora during low flow. Land & Hoyt (1966) found that the only major differences between estuarine point bars and those in rivers lay in the presence of marine fossils in the former. In Mhlanga river-mouth the fauna, and in particular their lebenspurren are considered diagnostic of prevailing environmental conditions. Overbank deposition in Mhlanga river-mouth is also minimised by barrier breaching at high flows and consequent grading of the alluvial plain to the barrier elevation results.

5.8. SEDIMENTARY PROCESSES IN MHLANGA RIVER-MOUTH

Sedimentation in the Mhlanga river-mouth is characterised by long, tranquil periods punctuated by an irregular cycle of barrier breaching and draining, followed by barrier closure. Superimposed on this cycle, is episodic barrier overwash which is produced by storms and is an important process in Natal estuaries (Cooper & Mason, 1986).

Under present environmental conditions, sediment input from the catchment is low and is dominated by fine sediment which only resides temporarily in the river-mouth. Under fairweather conditions the dominant sedimentary process in the river-mouth is suspension settling of fines, which is controlled by wave action within the river-mouth.

Following breaching, seaward-directed currents enhance sediment-transport within and from the river-mouth. They carry suspended sediment from the catchment, erode fine sand from the river-mouth bed, and cause limited undercutting and slumping of eroding banks. Suspension settling is enhanced in backwaters during floods and in scour holes during the waning flood stage. During non-flood breaching it is eroded. Breaching during fluvial flooding has the greatest sedimentological impact.

In the case of Mhlanga river-mouth and, by inference, other small-catchment river-mouths on the Natal coast it appears that the transport of sediment coarser than suspended load from the catchment occurs only after breaching. Erosion of back-barrier sediment is limited to fine-grained material, due to the relatively low and short-lived peak flows arising from breaching.

Overwash-derived, medium-grained sand is unlikely to be eroded during breaching and consequently there is likely to be a long-term build-up of marine sand in the river-mouth, despite the fact that it is closed for most of the year. This sand is situated adjacent to the barrier and is responsible for the elevated bed level in the river-mouth. It is probable that rare events such as the 1953 flood could produce higher current velocities than those associated with the 1987 flood or normal breaching. These could conceivably erode coarser sand and reduce the buildup of marine sediment.

Mhlanga river-mouth does not appear to be shoaling and its major morphological change has been through channel migration. This implies that infilling of the former drowned valley is complete and a state of equilibrium has been attained in the river-mouth whereby a portion of the total sediment yield from the catchment and overwash accumulates in the river-mouth during each closed phase but is eroded and transported into the sea during breaching.

The relative importance of episodic events in clastic sedimentation has attracted considerable attention (Einsele & Seilacher, 1982; Dott, 1983). In marginal coastal areas such events include storms (eg hurricanes and tropical cyclones) and floods (both coastal and riverine). Fox and Davis (1976) and other authors have assessed the importance of hurricanes and cyclones in barrier overwash. The effects of river floods in estuaries of varying size have been described by Nichols (1977), Nichols & Biggs (1985), Reddering & Esterhuysen (1987b) and Cooper *et al.* (1990).

In contrast, the effects and importance of barrier breaching as an episodic sedimentological event, has received little attention in the literature. River-mouths and lagoons similar in size to those in Natal and with ephemeral outlets have been described from southeast Ireland (Carter *et al.*, 1984) and Maine in the United States (Duffy *et al.*, 1989). Both those studies dealt with hydraulic conditions necessary for breaching and the controls on location of the breach along the barrier. The impact of breaching on the back-barrier environment was not assessed. Duffy *et al.*, (1989) found, however, that the back-barrier stratigraphy of lagoons lacking an outlet for most of the year generally contained little marine-derived sediment. This contrasts with Mhlanga river-mouth which, because of its small catchment sediment yield and high marine wave energy, is dominated, in its lower reaches, by marine sediment introduced by barrier overwash.

The Mhlanga river-mouth is in a mature stage of development, having essentially filled its former drowned valley. However, the sedimentary processes observed at present are not necessarily those which operated throughout the Holocene, a point discussed in the following section.

5.9. HOLOCENE EVOLUTION OF MHLANGA RIVER-MOUTH

A reconnaissance survey of the topography and geology of the area around Mhlanga river-mouth (Fig.5.15) reveals the presence of a high red dune reaching elevations of 130 m. This rests on bedrock at elevations above present sea-level. Seaward of this is a locally-developed red dune which is banked against the previous one and rests on bedrock at elevations between +8 m and present sea-level. Seaward of this is a dune barrier composed of yellowish-white sands which is in places banked against the previous dune deviates seaward of it in front of Mhlanga river-mouth where it forms part of the Holocene barrier. It rejoins the mainland north of the river-mouth. The relationships and ages of the aeolian dunes of Natal and Zululand remain unresolved (McCarthy 1967; Maud, 1968), however in the light of current knowledge of Pleistocene sea levels (Chapter 1) it is now established that Pleistocene sea levels were generally lower than present. Thus the most landward dune cordon is probably of Tertiary Age. The next cordon seaward may represent a deposit of the Last Interglacial which is banked against the Tertiary dune. The Last Interglacial dune is reddened from the breakdown of feldspars, a period which requires a considerable period (Maud, 1968) The last dune cordon which is unweathered but supports a dense dune forest is probably of Holocene Age and, in view of its dense cover, contained iron-age middens, and fossil soils, may relate to the Late Holocene highstand. The dune which is present on the low barrier is entirely recent. The reason for the clear separation of the various dune crests at Mhlanga river-mouth as opposed to adjacent areas where they are banked against each other probably lies in a reduction in bedrock slope.

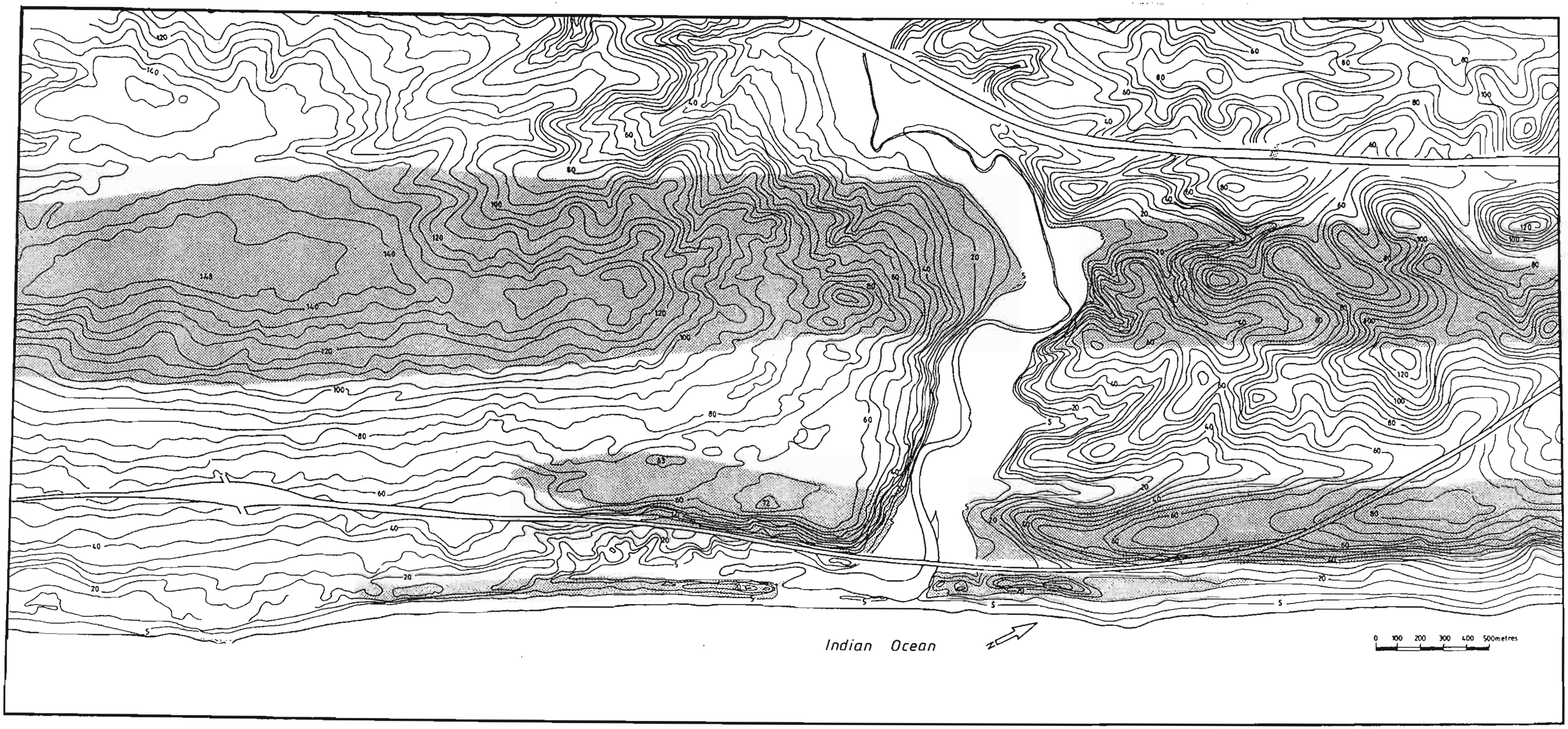


Figure 5.15. Topography of the coastal area around Mhlanga river-mouth. Most of the area shown is covered in aeolian sands but at a few locations underlying bedrock is exposed. Three different coastal dunes are suggested by the topography. The dune crests are shaded and are most distinctive where gradients are reduced around the Mhlanga river-mouth. Elsewhere they are banked against each other, making identification of individual dunes difficult. The dunes are tentatively assigned Late Tertiary, Late Pleistocene and late Holocene ages and young in a seaward direction.

The Mhlanga River incised a bedrock valley during the last glacial maximum when the sea fell to 130 m below its present level (Chapter 1). As the Mhlanga is located on the coast adjacent to the widest sector of the Natal continental shelf, the gradient of the river would have been reduced at low sea-level and the river may have become a tributary of a larger river. Boreholes for the road bridge penetrated fine sands and clayey sand to 16.5 m below MSL without reaching bedrock (Orme, 1974). The fine sediment in boreholes reflects both a lack of coarse-grained sediment in the catchment and the inability of the river to transport it.

During the Holocene Transgression the river valley was drowned and barrier sediment, transported landward from the exposed continental shelf, ultimately stabilised to form the modern barrier across the river-mouth which is part of a linear clastic shoreline apparently in equilibrium with dominant wave fronts (Cooper, 1991b). The drowned valley is now filled with sediment and the enclosed river-mouth is comparatively shallow. During transgression, the small catchment and low sediment supply probably meant that sedimentation could not keep pace with sea-level rise and thus soon after sea-level stabilised in the late Holocene the Mhlanga was probably comparatively deep. This may be reflected in the fine grained sediments which typify the lower parts of the succession Orme (1974). These therefore represent all the sediment supplied from the catchment before the river-mouth filled and was able to pass sediments into the sea.

Evidence from elsewhere on the South African coast points to several Postglacial relative sea level highstands up to 3 m above present MSL since 7000 years ago (Chapter 1.). At high sea-levels coastal river-mouths would have occupied a greater area than present. At Mhlanga several factors suggest a high Post-glacial sea-level: the alluvium surrounding the River-mouth is probably an exposed remnant of submerged river-mouth deposits from this period. The occurrence of hyposaline molluscan shells in eroded steam bank deposits supports this and suggests that then the river-mouth was more frequently open to the sea. This may be ascribed to a greater tidal prism which could form if barrier overwash had not raised the bed level sufficiently to exclude seawater when the barrier breached. Tidal currents could then have maintained an inlet for longer periods. Evidently the river-mouth had largely filled with catchment-derived sediment by this stage as subsequent incision of the channel, during a Late Holocene sea-level fall of up to 3 m, left the former deposits elevated above the modern river-mouth water level.

The presence of high dunes vegetated with a climax forest and fronted by small pioneering dunes also suggests a drop in relative sea-level and minor seaward progradation since formation of the older dunes.

The two lines of beachrock under the modern barrier provide further evidence for a Late Holocene sea-level highstand. Both lines of beachrock follow a shore-parallel trend and are dominated by medium-grained sandstones in which trough-cross-beds with shore-parallel azimuths predominate. Near Durban this facies type in Pleistocene beachrocks was interpreted by Cooper & Flores (1991) to represent deposition in the intertidal, ridge and runnel environment. At Mhlanga one line of beachrock is located in the modern intertidal zone while the other occupies a position 1.5 to 2 m higher and 15 to 20 m landward of it. The lower of the two lines is assumed to be recent and the other probably corresponds to a postglacial highstand. No dating is yet available on these deposits.

The approximate volume of the drowned palaeovalley may be estimated by making several assumptions. The barrier is backed by only 100 m of lagoonal sediment sediment including the postglacial elevated deposits, and bedrock outcrops at shallow depth at the rear of the river-mouth. If an estimate of 5 m is made for the mean depth to bedrock in that area then the cross-sectional area is 500 m^2. As the length of the back-barrier area is 1250 m then the volume of the coast-parallel section is 0.625 x 10^6 m^3. If upstream it is assumed that the bedrock channel is about 17 m deep and roughly rectangular in cross-section then the approximate volume of the coast-normal valley may be calculated by estimating the former upstream extent of the estuary. This occurs 1700 m upstream where the channel narrows markedly and intersects bedrock. The calculated volume of this part of the valley is approximately 11.56 x 10^6 m^3. Thus the total volume of the drowned bedrock valley is about 12.185 x 10^6 m^3. Assuming that this has been infilling only since sea-level flowed into the drowned valley when it reached a level of -17 m (about 8000 years BP according to relative sea-level curves) the rate of sediment accumulation in the river-mouth has been about 1523 m^3/year. Converted to a mass, using a porosity of 40% (Blatt *et al.*, 1980) and density of quartz of 2600 kgm^{-3} (CERC, 1973) this gives an mean annual retention of 2376 tonnes of sediment during the past 8000 years. Because almost all of the sediment would have been retained when the river-mouth was deeper, and the calculation is based on a long timespan, it may be regarded as indicative of the minimum annual fluvial sediment yield from the catchment. This is still 20 to 30 times less than the estimates of NRIO (1986). Under present conditions the river channel is apparently in equilibrium with the discharges which pass through it and thus a reduction in volume through fluvial sedimentation is unlikely. Consequently all of the modern catchment sediment supply passes through the river-mouth and is deposited in the sea.

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CHAPTER 6.

MVOTI RIVER-MOUTH

6.1. INTRODUCTION

The mouth of the Mvoti River (29°23' S; 31°20' E) is approximately 80 km north of Durban, near the small town of Blythedale Beach (Fig.6.1). The river has a catchment area approximately half that of the Mgeni and although its outlet to the sea is nearly always maintained, water in the river-mouth is commonly fresh: tidal exchange is excluded because the outlet channel flows over a dolerite sill.

From the N2 Freeway to the sea the Mvoti River flows through a wide floodplain, confined to a shallow, sinuous or braided channel. The biota of the river-mouth has received some attention (Begg, 1978; 1984a,b) and the presence of a river-dominated assemblage of fish and invertebrates led him to define it as a completely degraded estuary which had lost its nursery function for marine organisms. This caused Begg (1984a) to term the lower reaches of the Mvoti a "river-mouth" rather than an estuary. For ease of reference the same terminology is followed in this chapter but the problems of classification are discussed in Chapter 8.

Subsequent work (Ramm *et al.*, 1986; Harrison *et al.*, 1989) has suggested Begg's conclusions are incorrect, because of inadequate sampling of the fauna. Harrison *et al.*, (1989) found the Mvoti ichthyofauna to be dominated by estuarine-dependent marine fish and thus established that it does fulfil a nursery function. The salinity structure, circulation patterns and lack of tidal exchange, however, differ from most definitions of an estuary.

Widely held local preconceptions ascribe the alleged loss of estuarine characteristics in the Mvoti river-mouth to "siltation" (Begg, 1984a, 1984b; NRIO, 1983; Van der Merwe, 1989; Badenhorst, 1990; Chunnett, Fourie & Partners, 1990). The information presented in this chapter is inconsistent with the popular and published perceived state of the river-mouth, and the interpretations given as to how this occurred.

The aim in this chapter is to assess the geomorphology and sedimentology of the lower reaches of the Mvoti River and the adjacent coast, and to determine both the reasons for and the implications of, its broad, shallow channel and freshwater characteristics. The physical characteristics of the river-mouth area are assessed in the context of the controlling environmental factors, both temporal and spatial, and the apparent degradation of the Mvoti is assessed in relation to past and present physical processes.

6.2. CATCHMENT CHARACTERISTICS

6.2.1. Catchment topography and climate

The Mvoti River catchment is 225 km long and its source is at an elevation of 1464 m (Fig.6.2A). The overall river gradient is 1:154 or 0.0065 but significant downstream changes in gradient are evident

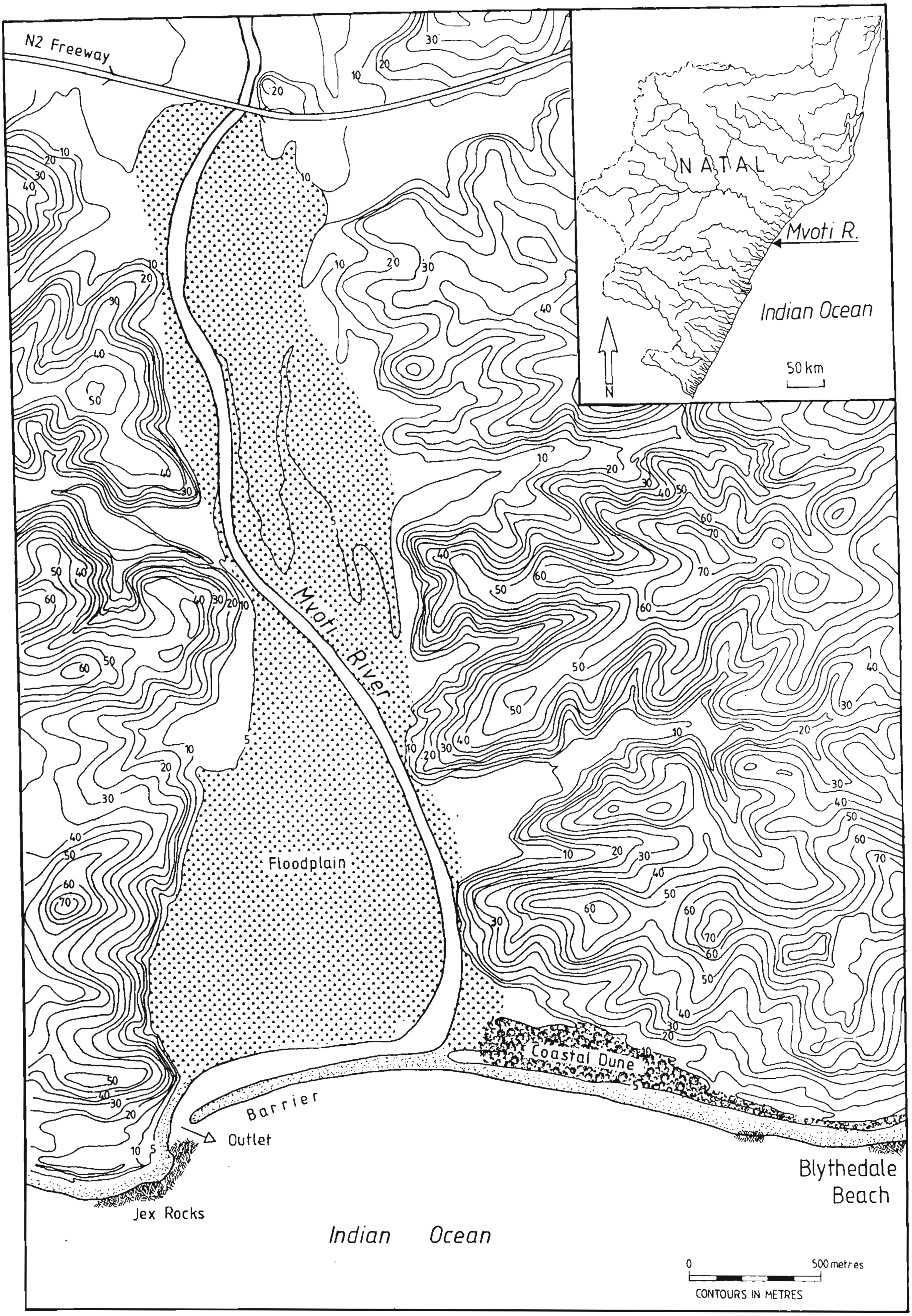

Fig. 6.1. Locality map of the Mvoti river-mouth showing typical morphology of the river-mouth and surrounding area. Note the width of the floodplain (shaded).

(Fig.6.2B) and in the lower 10 km the gradient is reduced to 1: 666 or 0.0015. Plateaux in river gradients along the Natal coast have been linked to former relative sea levels in the Cretaceous and Tertiary (Maud, 1968; Matthews & Maud, 1988). At maximum Pleistocene low sea levels, assuming a straight river course to the -100 m contour, the gradient over the last 10 km would have increased to 1:456 or 0.002 (Fig.6.2B).

The catchment area of the Mvoti (2728 km^2) is among the largest in Natal and the mean annual runoff amounts to 420 x 10^6 m^3 (Chunnett, Fourie & Partners, 1990). No major dams are present in the catchment but water abstraction and cultivation have reduced the present runoff at the mouth to 314 x 10^6 m^3 (Chunnett, Fourie & Partners, 1990). On the basis of a sediment yield map (Rooseboom, 1978) an annual sediment yield estimate of 813 000 tonnes was calculated (NRIO, 1986). A crude assessment of the validity of this estimate may be made by comparing it with measurements of suspended sediment concentrations. Total annual sediment yield divided by the mean annual runoff should give an indication of the suspended sediment concentrations required to transport such a volume of sediment. Assuming that sediment transport is constant and that all sediment transport is in suspension the average concentrations of suspended sediment required are about 2589 ppm. Figures given in Wylie (1966) of monthly suspended sediment concentrations range between 30 and 1570 ppm. Although the assumption of constant sediment transport is clearly invalid, because of the markedly erratic river flow (Fig.6.3) calculated from rainfall records since 1921 (NRIO, 1983) and discharge records from gauging stations (DWA, personal communication, 1991), even the maximum recorded values are too low for such a sediment volume to be transported. Calculation of the monthly sediment transport from Wylie's (1966) suspended sediment and discharge data gives an annual sediment transport in the river of only 132 000 tonnes. Clearly more work remains to be done on this subject. If both the sediment yield and sediment transport figures are correct then a large proportion of the sediment supply from the catchment remains in storage in the river system and only moves during major floods.

Mean annual precipitation over the catchment is about 900 mm and varies between 540 and 1380 mm (Chunnett, Fourie & Partners, 1990). Mean discharge varies from almost zero in winter to 14.95 m^3s^{-1} in summer (Wylie, 1966) but estimated flood peaks have been estimated to vary between 1000 m^3s^{-1} for a flood with a five year recurrence interval to 15 000 m^3s^{-1} for the probable maximum flood (Chunnett, Fourie & Partners, 1990).

The coastal climate is hot and humid subtropical but is cooler inland, with a greater diurnal temperature fluctuation. The winter/summer range of maximum daily temperatures in the interior is 12 to 21°C compared with a 17 to 23°C range for the coast (Chunnett, Fourie & Partners, 1990).

6.2.2 . Catchment geology

The geology of the catchment comprises a symmetrical arrangement of lithologies centred on a broad outcrop of Proterozoic lithologies of the Natal Structural and Metamorphic Province (Fig. 6.4). Megacrystic biotite granites and biotite gneisses dominate the Proterozoic outcrop, although several other varieties of gneiss and granulite are present (Linström, 1987).

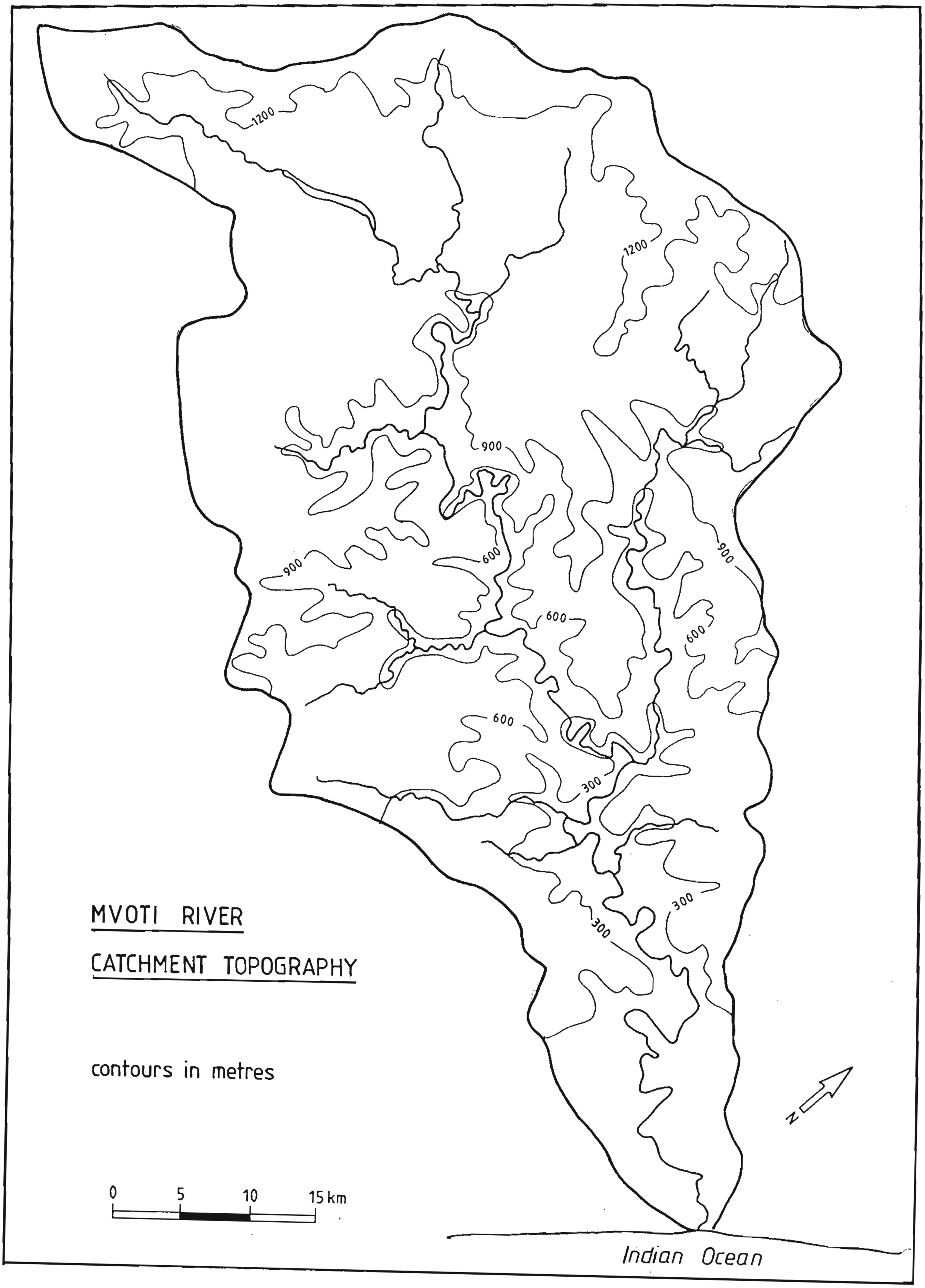

Fig.6.2A. Topography of the Mvoti catchment. Figure 6.2B (overleaf) shows the river's downstream profile.

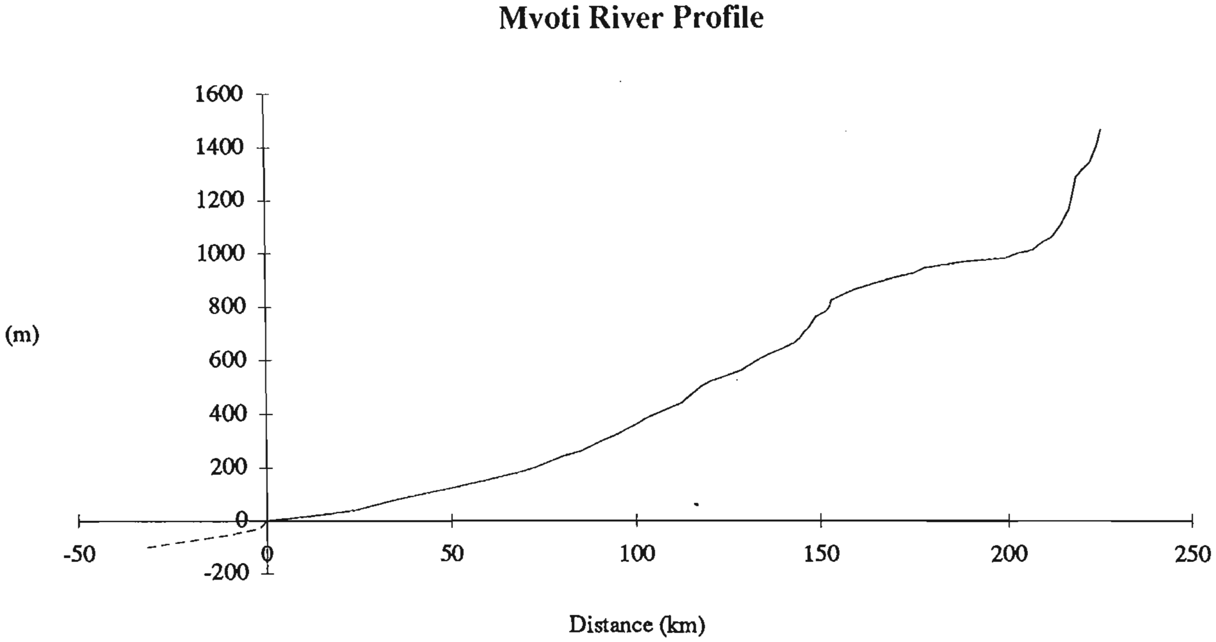

Fig.6.2B. Downstream changes in gradient of the Movti River. The dotted line shows the river gradient continued to the shelf break at -100 m assuming a straight course and represents a maximum estimate of the gradient during the last glacial maximum.

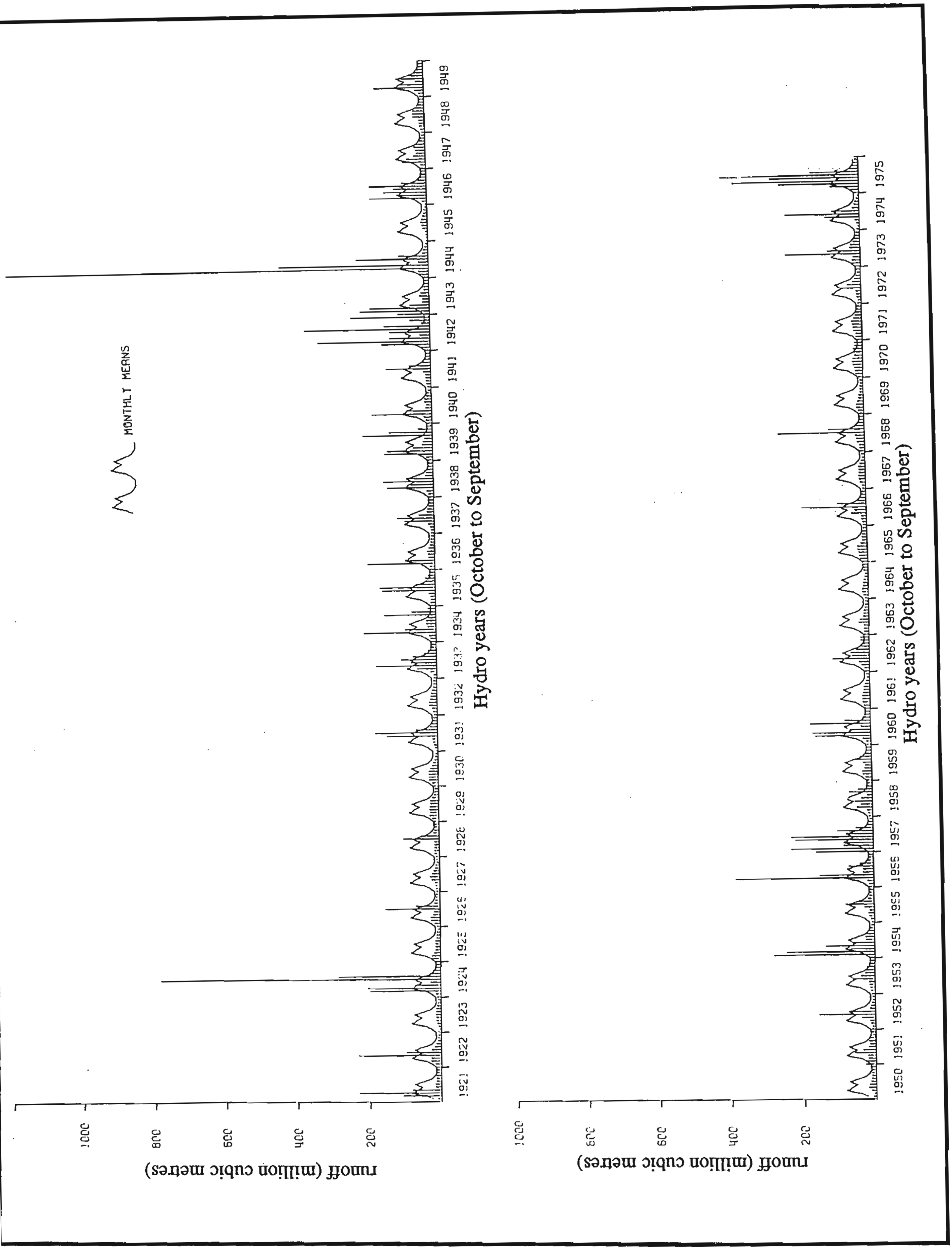

Fig.6.3. Simulated montly runoff in the Mvoti river 1921 to 1975, based on rainfall data. Note the seasonal rainfall patterns and large variation in runoff (after NRIO, 1983).

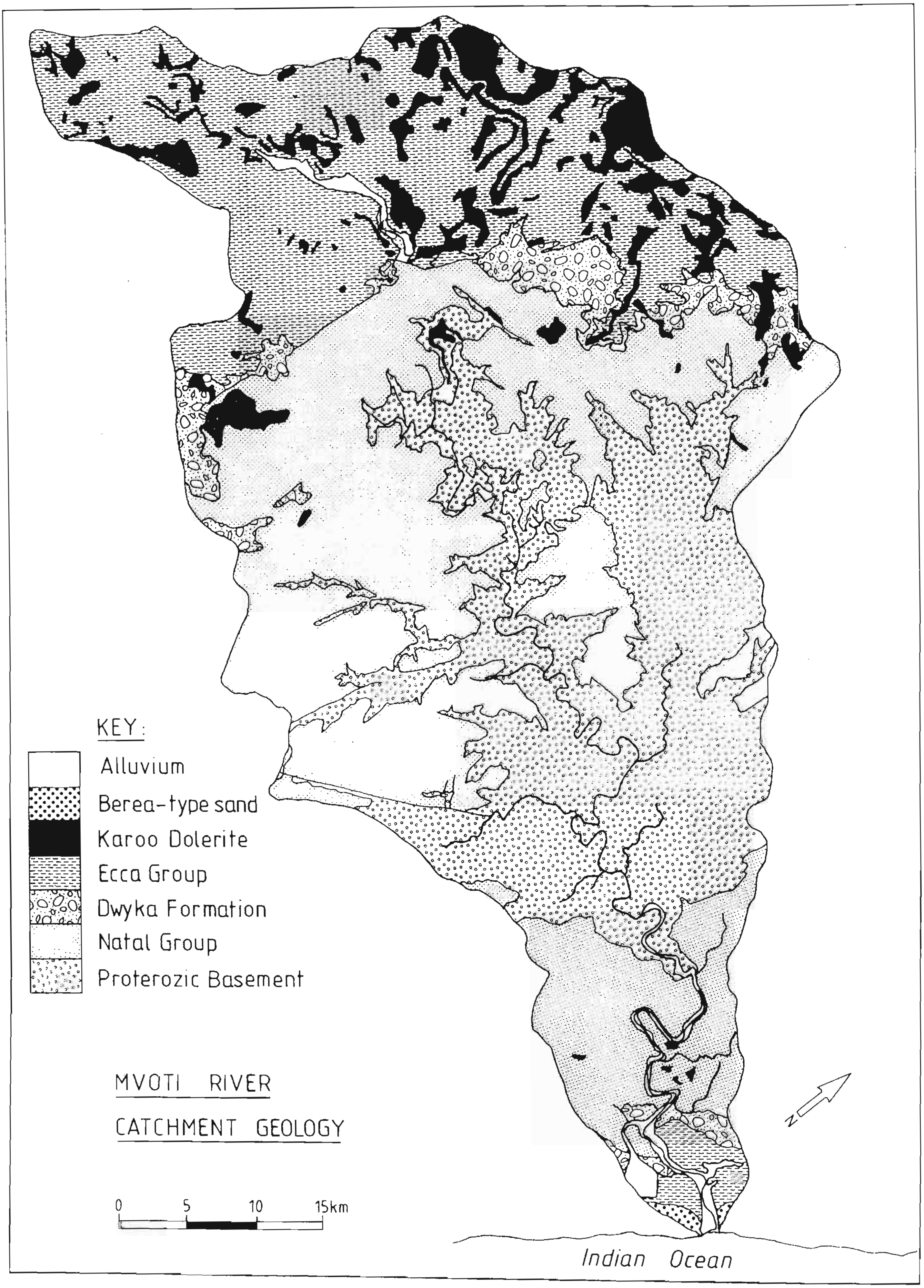

Fig.6.4. Geology of the Mvoti catchment (based on 1:250 000 series geological maps). The large area of Proterozoic basement lithologies supply most of the sand and gravel fraction of the river's load.

Natal Group Sandstone (NGS) comprises 35% of the catchment. It outcrops on either side of the Proterozoic lithologies and is mainly coarse-grained arkosic sandstone with subordinate conglomerates and siltstones (Linström, 1987).

The NGS is flanked on both sides by rocks of the Karoo Sequence. The glacial diamictite of the lowermost (Dwyka) Formation covers only a small area of the catchment and the Karoo Sequence in the Mvoti catchment is dominated by shales and fine-grained sandstones of the Ecca Group, principally those of the Pietermaritzburg Formation. The Vryheid Formation (middle Ecca) is poorly represented and thus coarse-grained Ecca sandstones are uncommon in the catchment. Sills of Karoo dolerite intrude the Ecca, particularly in the upper catchment, but are much less common than in the Mtamvuna River catchment, for example. Consequently the shales are less indurated. The lowermost reaches of the river valley are cut through shales of the Pietermaritzburg Formation which, at the coast, are unconformably overlain by Plio-Pleistocene coastal dunes composed of Berea-type red sand.

6.3. RIVER-MOUTH CHARACTERISTICS

6.3.1. Channel Morphology

The lower reaches of the Mvoti River are surrounded by a wide floodplain in a valley cut into Pietermaritzburg Formation shales (Fig.6.1). The wide floodplain may be attributed to the erodibility of the Pietermaritzburg Shale into which the river was incised during lowered sea-levels. Karoo mudrocks generally break down easily when subaerially exposed and have a low resistance to erosion (Brink, 1973; p 75). Lateral erosion by the river during multiple incisions of the valley was therefore possible and produced a bedrock channel with a large width/depth ratio.

The river generally occupies only a narrow channel on the floodplain. Several surveys and observations in the river-mouth area show the channel is very shallow. Begg (1984b) calculated the mean depth of the Mvoti river-mouth area to be 0.35 m with a maximum depth of 1.6 m near the channel outlet where scouring against rock outcrops occurred. Similar conditions prevailed during fieldwork between 1985 and early 1987. The river channel is commonly braided. A coastal sand barrier diverts the river course southward before it discharges into the sea across a dolerite outcrop at the south end of the barrier adjacent to the Jex homestead (Fig.6.1). The outlet seldom closes (Begg, 1978) due to turbulent flow across an underlying dolerite sill (Plate 6.1). The elevation of the sill prevents seawater from entering the river-mouth, although a rise in water level occurs due to the damming effect of the high tide. Water in the Mvoti river-mouth was fresh when sampled on periods between 1982 and 1984 (Begg, 1984b). However, sampling on several occasions between 1986 and 1990 consistently showed stratification in the coast-parallel river course. Salinity near the bed was frequently greater than 25‰ and as high as 30‰. The hyposaline water is attributed to overwash of seawater across the barrier, and settling of the dense, salty water to the bottom of the water column.

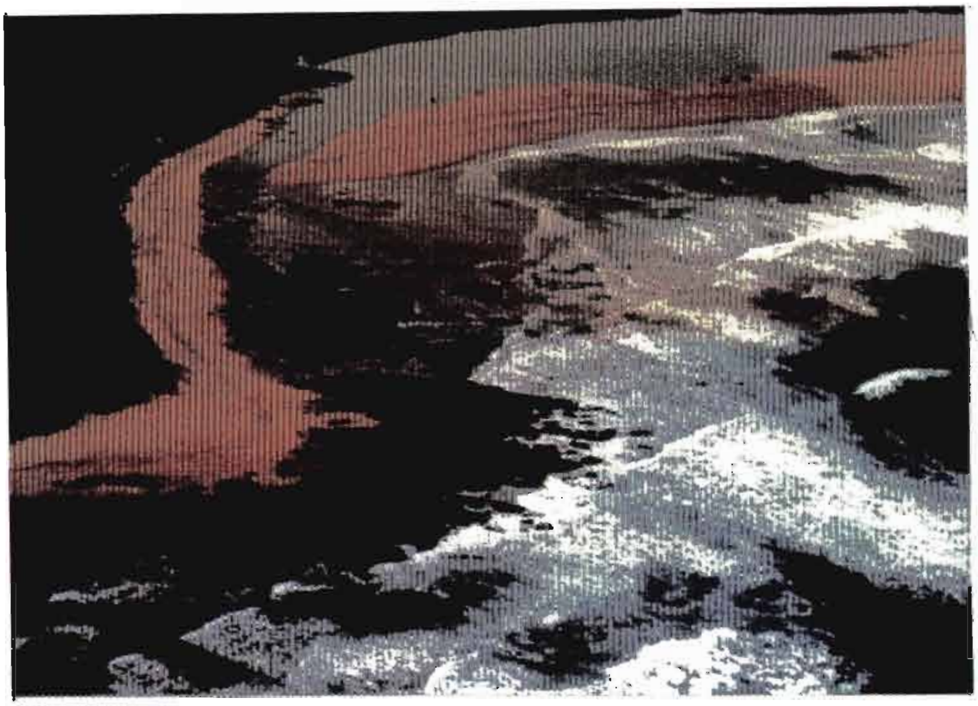

Plate 6.1. Low-level aerial photograph of the Mvoti river-mouth outlet in April 1986. This is the position commonly occupied by the outlet. The elevation of the underlying rocks prevents intrusion of seawater through the outlet.

Plate 6.2. Oblique aerial photograph looking north along the Mvoti river-mouth barrier on 14th April 1986. The outlet is located just out of view in the bottom right of the area shown.

Plate.6.3. Angas' painting of the Mvoti river-mouth on September 5th 1847 looking northward from the outlet at Jex Rocks (Fig 6.1). Note the narrow outlet and the smooth planform of the seaward barrier face. The narrow back-barrier channel and vegetated floodplain closely resemble the situation in Plate 6.2 above.

6.3.2. Barrier morphology

The Mvoti river-mouth is located behind a coastal sand barrier which extends for 1500 m across the floodplain (Plate 6.2, Plate 6.4A). The barrier occupies part of a shallowly indented embayment between two rocky headlands, one on the southern side of the Mvoti floodplain (at the Jex homestead) and the other at Blythedale Beach (Fig.6.1). A mainland-attached beach links the northern end of the barrier to the rocks at Blythedale Beach. On its seaward side the barrier and mainland-attached beach have a single smooth planform in the shape of a zeta bay. Maximum indentation occurs in the south, adjacent to the rocky headland at the Jex homestead, due to refraction of dominant southeasterly swells. The equilibrium planform, coupled with the rocky headlands to the south and north suggest that little longshore transport takes place along the embayment. The barrier is composed of quartz and feldspar sand grains with a low skeletal carbonate content, rarely exceeding 5%. Geomorphological variation is revealed by aerial photographs taken since 1937 and discussed in Section 6.4.

6.3.3. 1987 Sediment distribution and sedimentary facies

Channel sediments were sampled in the lower reaches of the Mvoti in February 1987. The results of this survey revealed the bottom of the channel to be covered in a few millimetres of unconsolidated "fluid mud" which was resuspended when slightly disturbed. The underlying solid bed was dominated by sand (Fig.6.5A) whereas accumulated muddy sediment was restricted to deep scour holes and backwater areas. The sand fraction comprised quartz with subordinate feldspar. Heavy minerals were concentrated in the fine fraction.

Only the sands adjacent to the barrier contained carbonate (Fig.6.5B) in the form of skeletal molluscan and barnacle fragments and foraminifera tests. Carbonate concentrations were commonly less than 5%, even in barrier sediments. The mean grainsize of channel sands was medium-grained sand but coarse and very coarse-grained sands were concentrated against the barrier, and at the southern end of the coast-parallel lagoon (Fig.6.5C). In the latter location the fact that the coarse-grained sands were associated with muddy sediment suggests that the coarse sediment was a channel lag deposit on which fine sediment settled during low flow.

Sands throughout the river-mouth were only moderately to moderately well-sorted (Fig.6.5E), typical of a low energy fluvial environment (Reineck & Singh, 1973). Adjacent to the bar the channel sand was well-sorted, reflecting its derivation from the high energy littoral environment. Channel sands were typically near-symmetrical or finely skewed (Fig.6.5D), even in areas where they were only moderately sorted. The sands therefore probably represent an amalgamation of all grainsizes available which statistically produce a normal grainsize distribution.

Depositional sedimentary environments in the Mvoti are generally riverine or deltaic due to the exclusion of seawater influences. As in river deposits (Visher, 1972) unidirectional currents dominate and are preserved in the ripples and braid bars which occur. The channel is typically braided and shallow, and riverine vegetation may occur on the braid bars and channel margins. The Mvoti river-

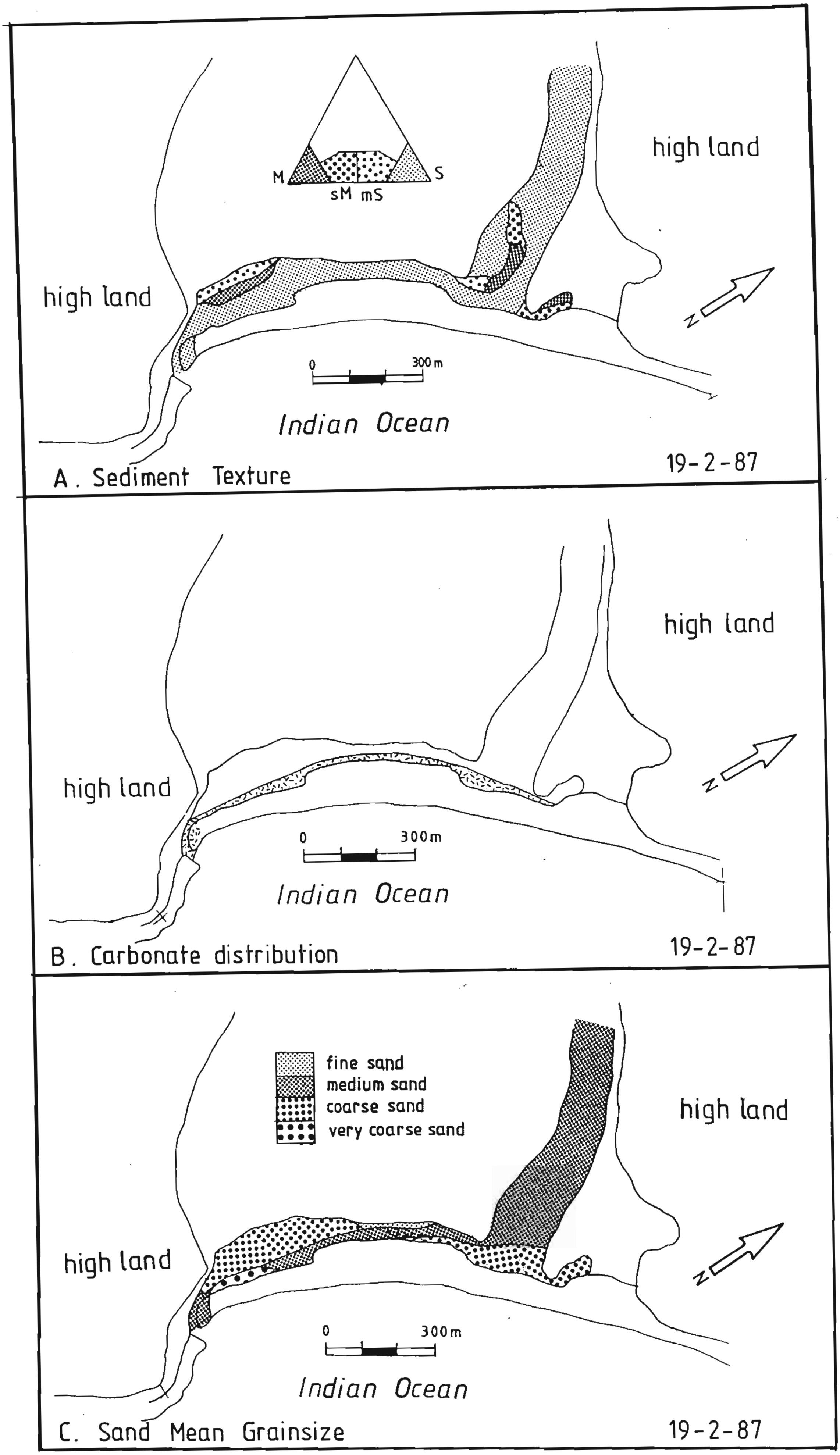

Figure 6.5A-E. Pre-flood sediment distribution in February 1987 (continued overleaf).

A. Textural variation in channel sediments.

B. Carbonate distribution in the river-mouth. Back-barrier areas containing over 1% carbonate are shaded.

C. Mean grainsize of the sand fraction

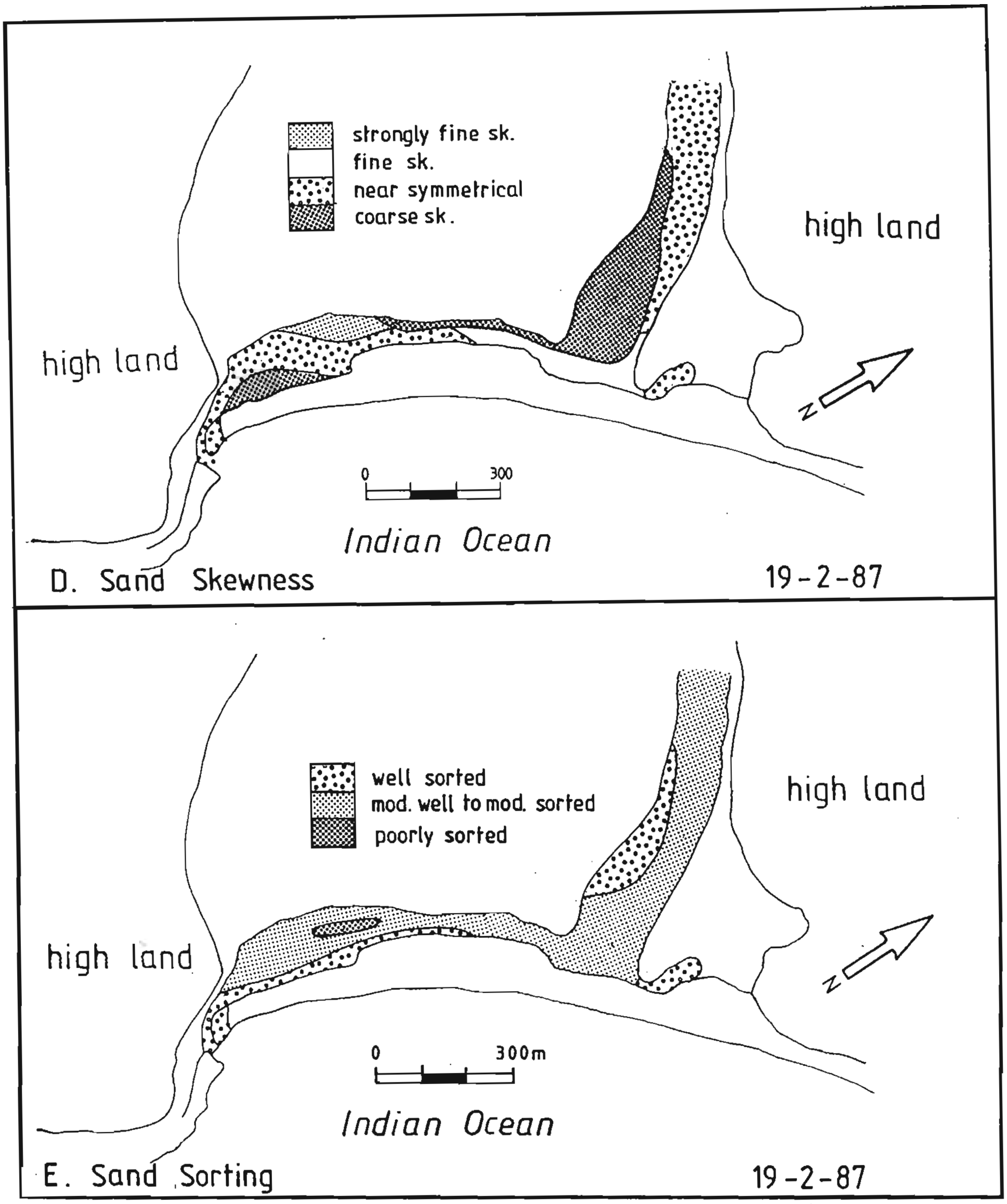

Figure 6.5A-E (continued). Sediment distribution in February 1987 (pre-flood).

D. Sand fraction skewness

E. Sorting in the sand fraction

mouth lacks a typical back-barrier lagoonal area, such as that found at the rear of the Mgeni barrier, because the main river flow passes through the back barrier area to a perennial outlet.

Biogenic structures in the Mvoti are uncommon due to the mobile bed but an abundance of water birds produce footprints and beak trails in the shallow, marginal areas. In addition to riverine organisms, estuarine and marine fish also occur in the Mvoti river-mouth. Of these, the mugilids produce distinctive feeding traces which potentially distinguish the Mvoti sedimentary facies from normal river deposits.

The presence of barrier-associated environments adjacent to the riverine facies are the main criteria which would distinguish an Mvoti-type environment in the sedimentary record. The barrier has a low carbonate content but the distinctive overwash lamination would be sufficient to distinguish it as a microtidal barrier. The outlet channel flows across a dolerite sill and consequently no channel base facies is likely to be preserved. Evidence of reversing currents would be lacking even if a thin veneer of sand was preserved. The marginal outlet beachface contains swash bars which cause limited migration according to discharge and wave conditions. No flood-tidal delta is present in the Mvoti as a result of the absence of flood tidal currents but a small ebb-tidal delta may occur, particularly when afforded protection from wave attack by the rocky headland.

6.4. HISTORICAL CHANGES IN MORPHOLOGY UP TO 1987

6.4.1. Morphological changes

Historical changes in morphology of the Mvoti river-mouth area are revealed by reference to aerial photographs, the earliest of which dates from 1937. Earlier historical records and old paintings give a subjective impression of river-mouth morphology. The earliest available record of the Mvoti river-mouth consists of a painting and description by the artist G.F. Angas who visited the area on September 5th 1847 (Plate.6.3.). Angas (1849) reported "descending by an elephant path to the shore, we found ourselves on the firm white sand, where the river, after taking a sharp angular turn, empties itself into the ocean." He noted the "reedy swamps that mark the mouth of the river" and that they "abound with hippopotami". His painting shows the river flowing south behind the barrier to the mouth which was located against the rocks at the southern end of the embayment, in the position normally taken at present. Hippopotami require water in excess of 1.5 m deep for daytime shelter and consequently at least part of the channel attained this depth. The floodplain was illustrated as vegetated with grasses and low bushes. The seaward margin of the barrier had a large concave planform with a steep forebeach and more gentle backbeach dipping into the back-barrier lagoon. Two prominent cusps are illustrated. To the rear of the lagoon the floodplain was low and vegetated.

In 1920 the farmer on the south bank, Mr Jex, noted, when consulted by G. Begg in 1977, that the floodplain was a "barren desolation", covered in sand with isolated tufts of *Phragmites* reeds. This he attributed to the floods of 1917. He also noted that the channel was in a more central position on the floodplain at that time then at present. Jex observed that subsequent floods deposited mud on the sand of the 1917 flood, thus permitting re-vegetation of the floodplain. When a suitable thickness of mud accumulated the floodplain was cultivated and planted with sugar cane.

Vertical aerial photographs from the 1st of May 1937 show the lower reaches of the Mvoti River comprised a 50m-wide channel flowing through a wide floodplain which was vegetated and partly cultivated with sugar cane (Fig.6.6A). Few channel bars occurred, suggesting the water was relatively deep. The coast-normal channel turned south before reaching the northern part of the river-mouth barrier and abutted against the barrier only along the lowermost 350 m of its course. The barrier extended across the floodplain from a rocky headland in the south for 1200 m, beyond which it formed a mainland-attached beach which continued north for 1000 m to rocks at Blythedale Beach. Between these rocky headlands the barrier and mainland-attached beach had a smooth concave plan form, suggesting equilibrium with approaching wave fronts. Behind the mainland-attached beach was a 180 m-wide forested dune fronted by lightly vegetated 50 m-wide foredunes.

The river-mouth was located across the prominent rock outcrop at the south of the embayment. A large area of unvegetated overbank sands was deposited at the most seaward bend in the river as a crevasse splay, indicative of a recent flood. Lineations on the floodplain showed the path of former river courses, south of the 1937 channel. These probably represent overbank flows generated during severe floods as similar lineations were produced after a flood in 1987 (see following section).

By June 1959 the lower reaches of the channel had shifted northward through 200 m since 1937 and flowed against the northern side of the floodplain for 1 km upstream of the barrier (Fig.6.6B). The channel was about 50 m wide with few braid bars and the floodplain was vegetated. The coast-normal channel had breached the barrier on the northern side of the floodplain during a recent flood and formed a mouth there but growth of a spit was starting to close the breach. The former mouth was still open in the south of the embayment but the coast-parallel lagoon which it drained was isolated from the main channel by a recently-deposited crevasse on the inside of the former 90° bend in the river. The general absence of overbank deposits upstream and the lack of bars in the channel suggests that the flood had not been of particularly large magnitude and was probably channel-confined. 1959 does not appear in any list of large floods in the Mvoti.

In August 1967 the river channel followed a similar path to that taken in 1959, however, the channel had narrowed to about 35 m and channel bars extended downstream to within 800 m of the barrier (Fig.6.6C). Between this point and the barrier, the channel was apparently deeper. The 1959 flood breach was sealed by a broad overwash apron and the channel flowed southward behind the barrier, to an outlet across the rocks in the south. The shallow coast-parallel channel section contained braid bars deposited since 1959. The former crevasse splay had been eroded and it is likely that the back-barrier braid bars were produced from downstream transport of that sediment. The outlines of large gullies remained on the floodplain behind the back-barrier lagoon. By comparison with subsequent observations (Section 6.4) these probably formed after a period of overbank flow. A small vegetated

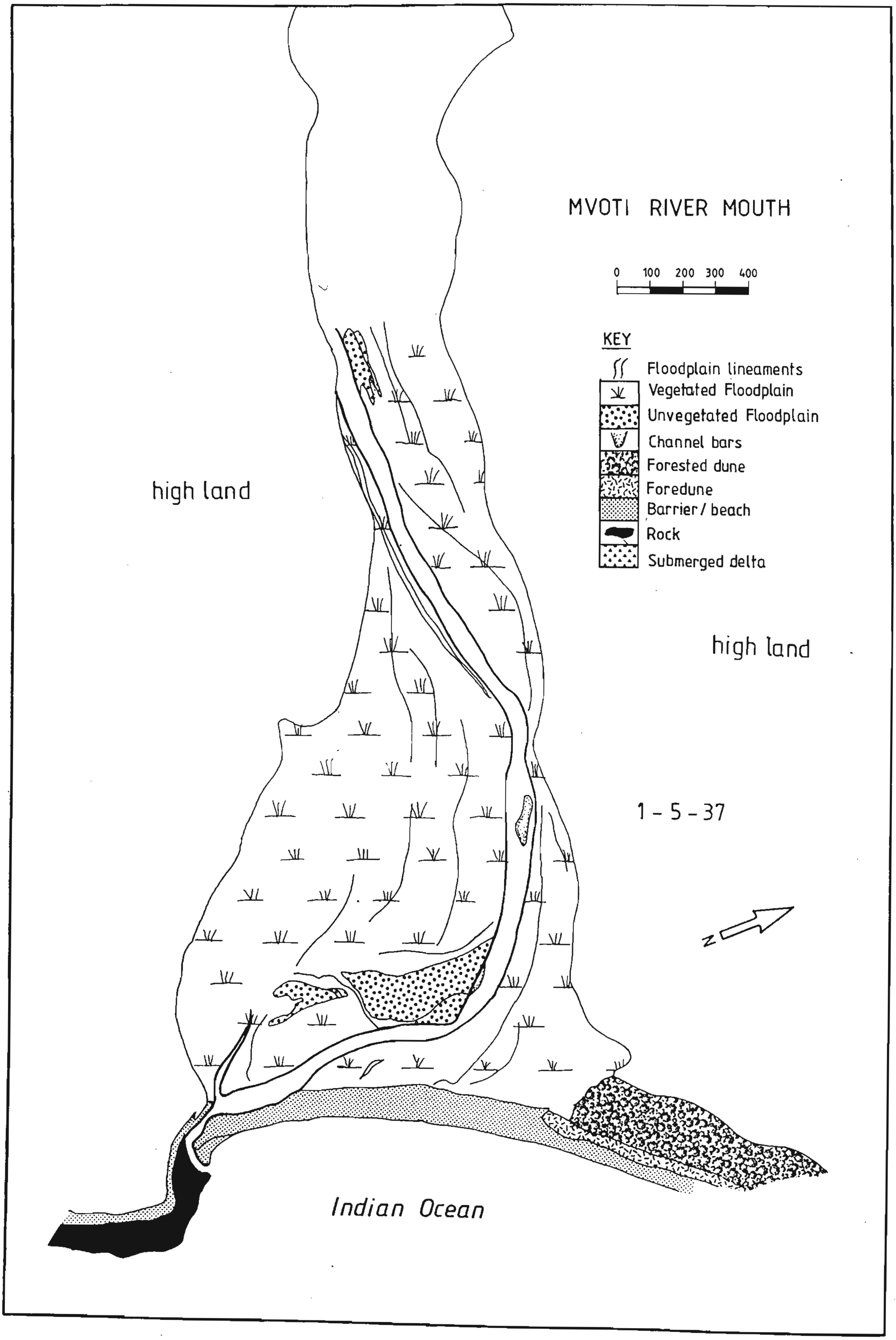

Figure 6.6. A-H. Temporal changes in river-mouth morphology 1937 to 1985.
6.6A. Mvoti river-mouth 1st May 1937 (continued overleaf).

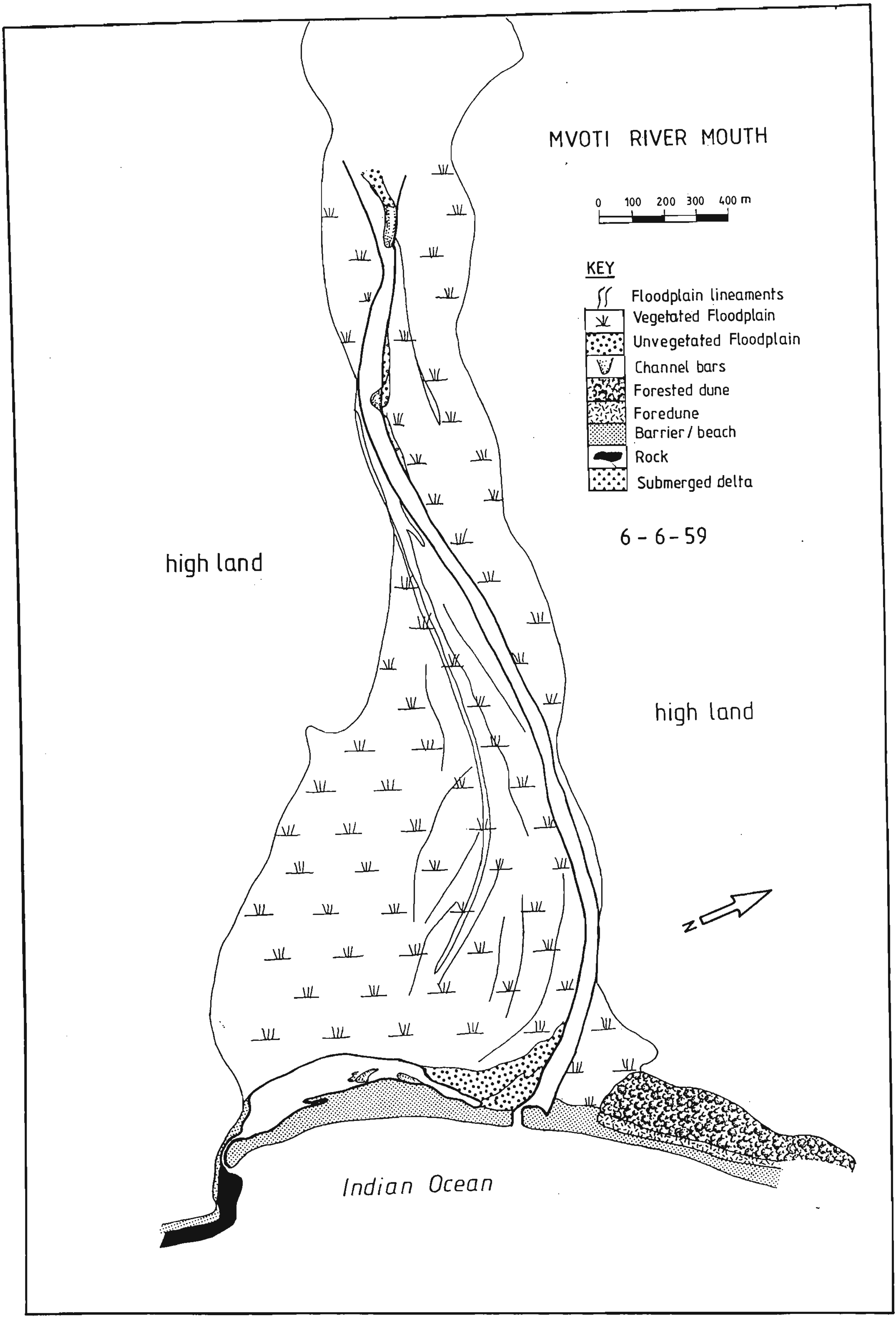

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued).
6.6B. Mvoti river-mouth 6th June 1959 (continued overleaf).

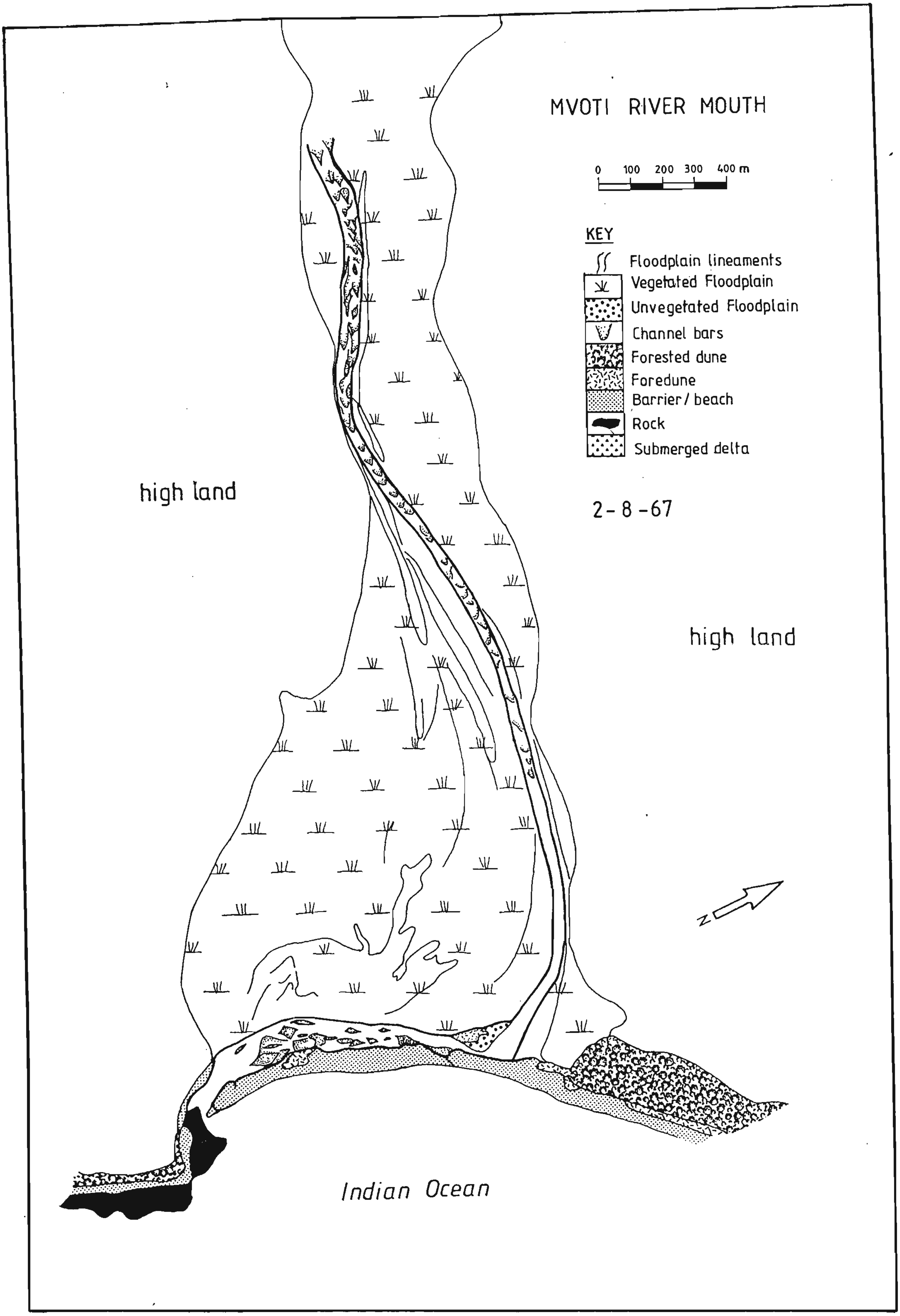

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued).
6.6C. Mvoti river-mouth 2nd August 1967 (continued overleaf).

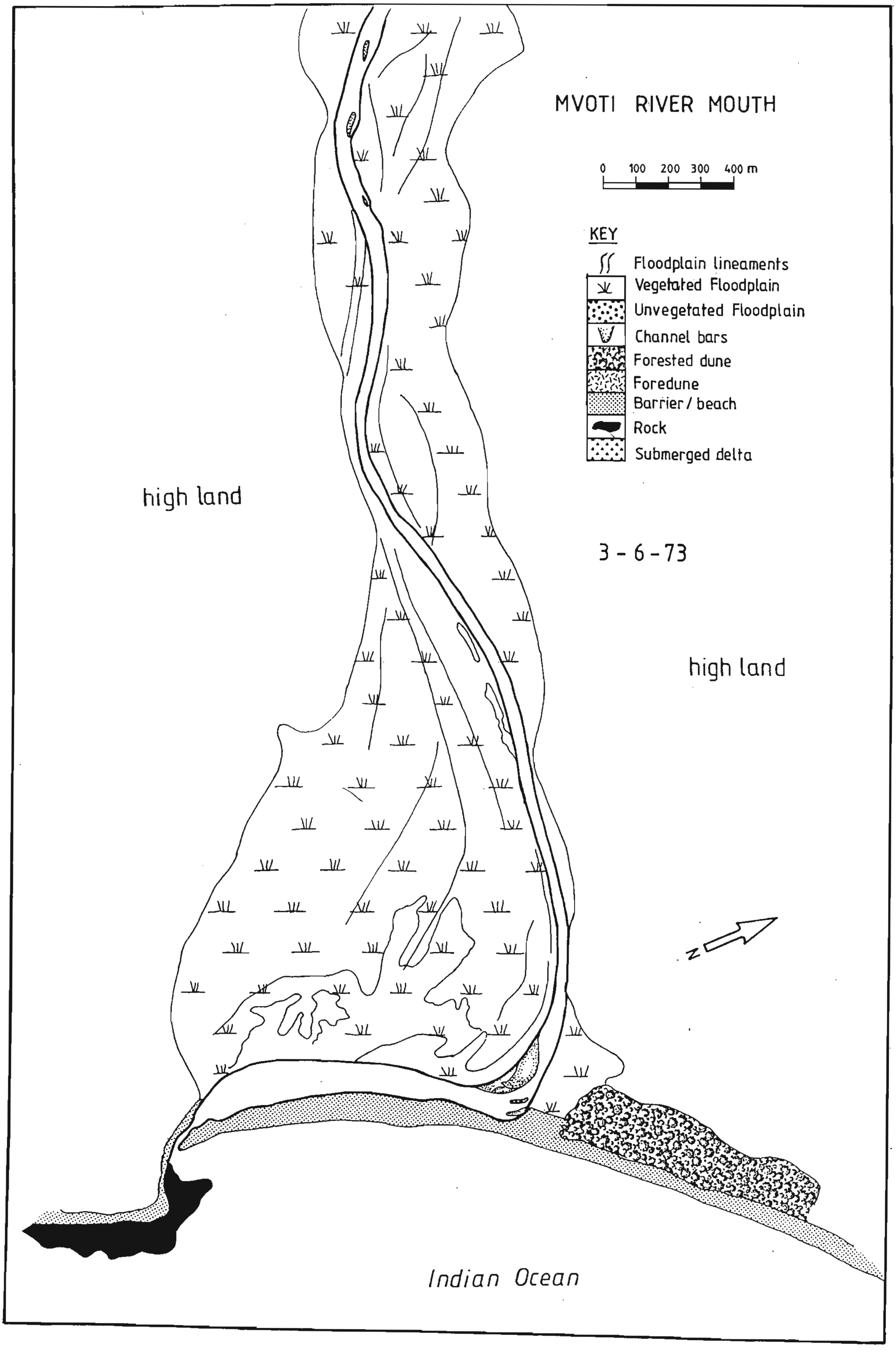

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued).
6.6D. Mvoti river-mouth 3rd June 1973 (continued overleaf).

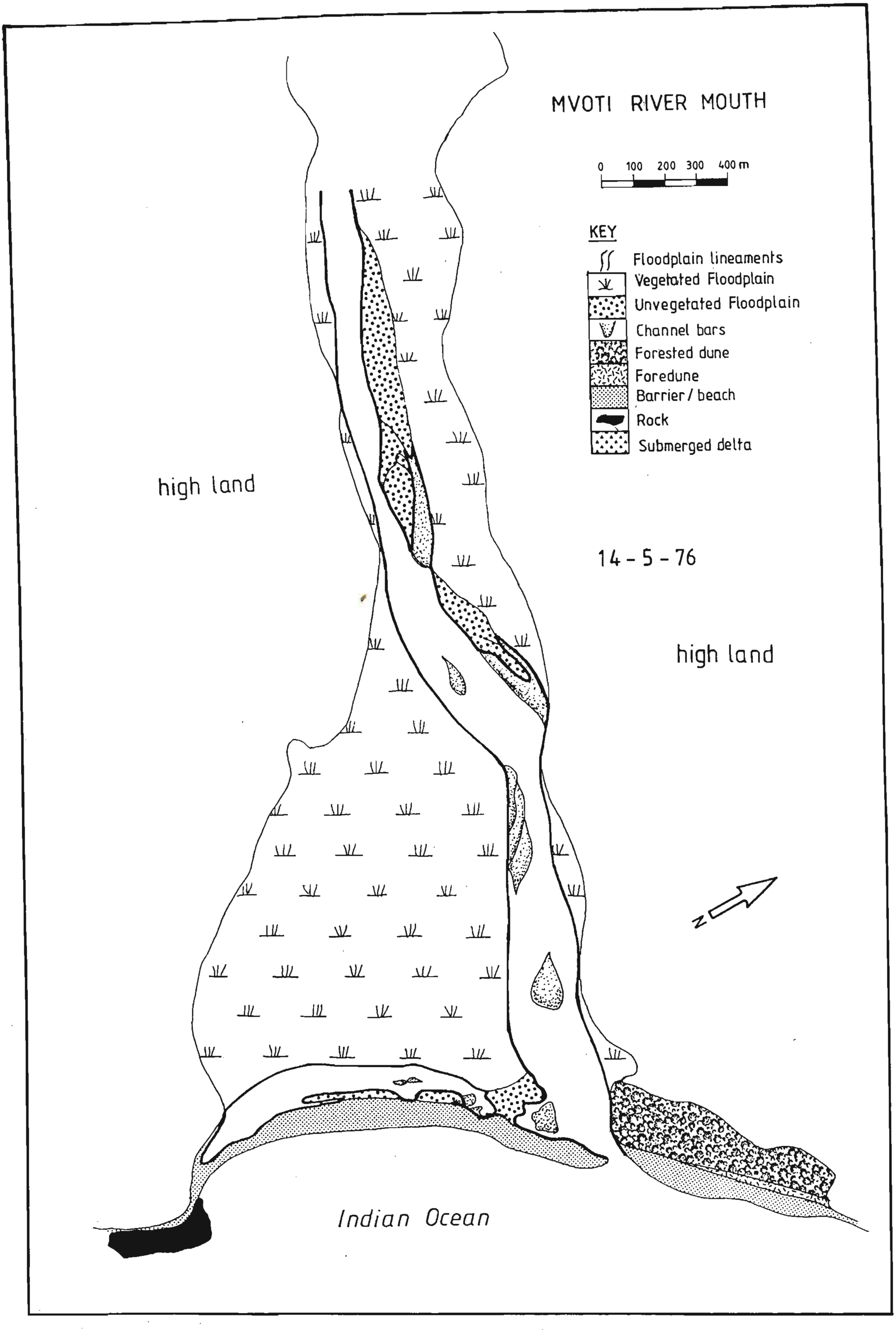

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued). 6.6E. Mvoti river-mouth 14th May 1976 (continued overleaf).

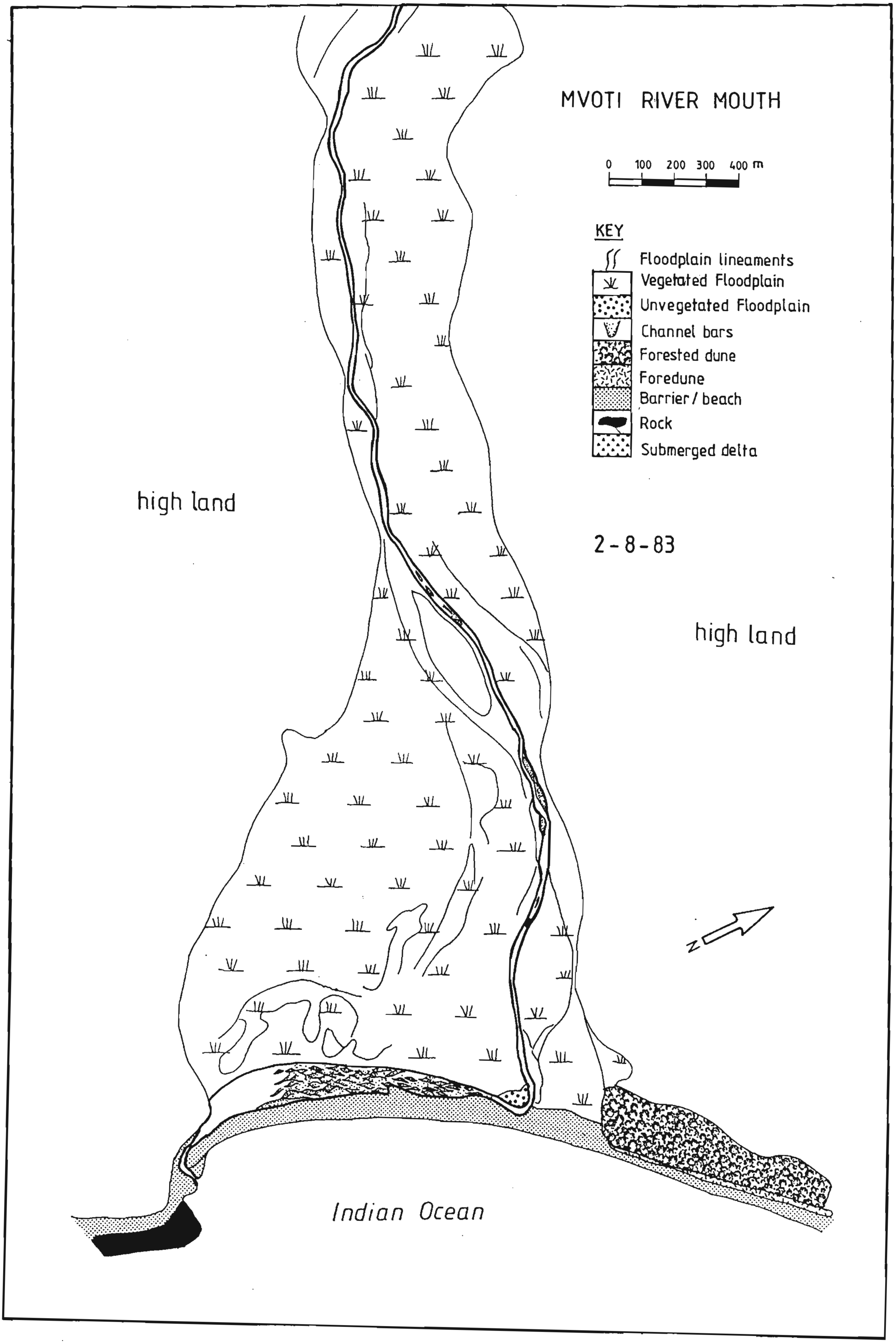

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued). 6.6F. Mvoti river-mouth 2nd August 1983 (continued overleaf).

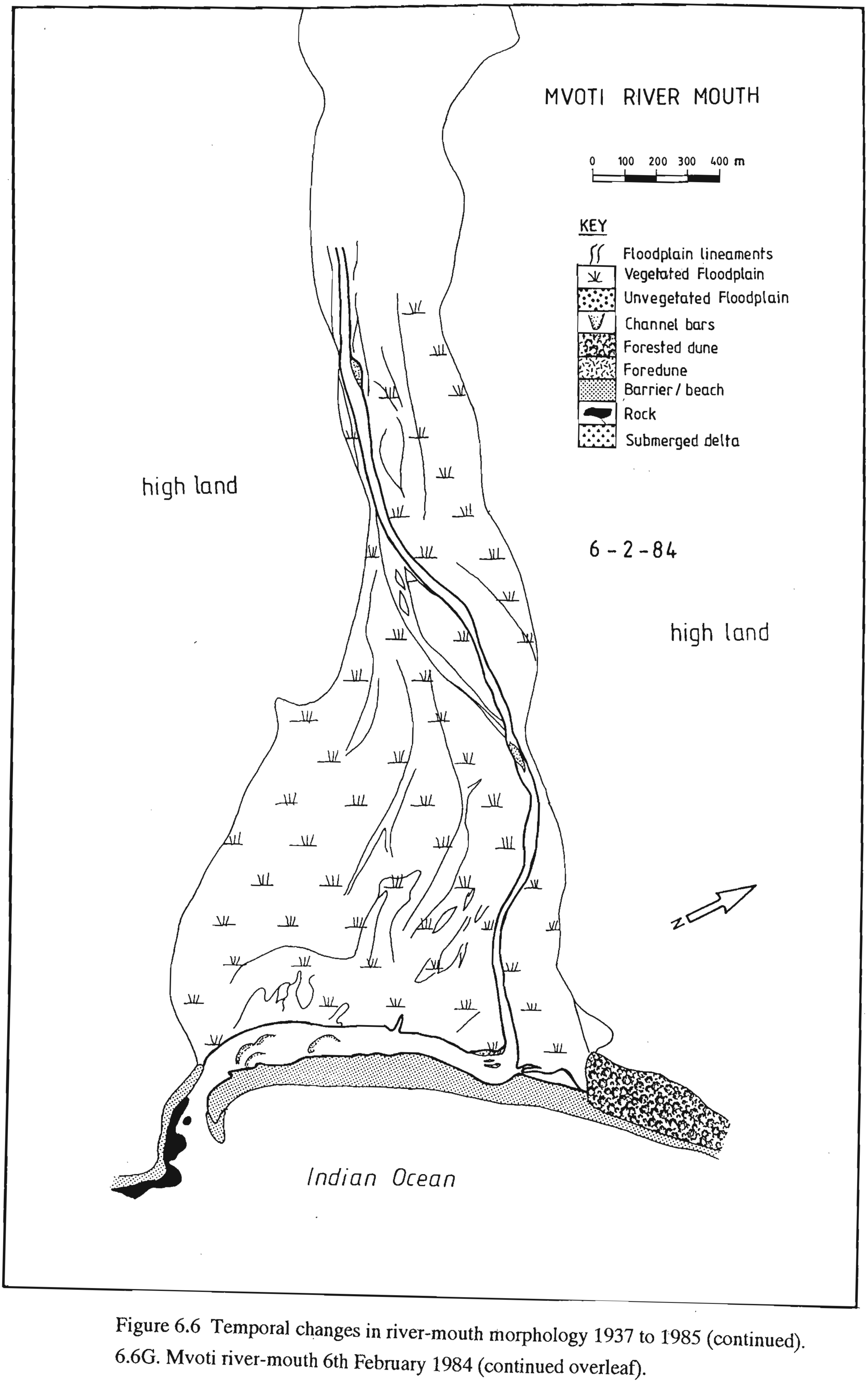

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued).
6.6G. Mvoti river-mouth 6th February 1984 (continued overleaf).

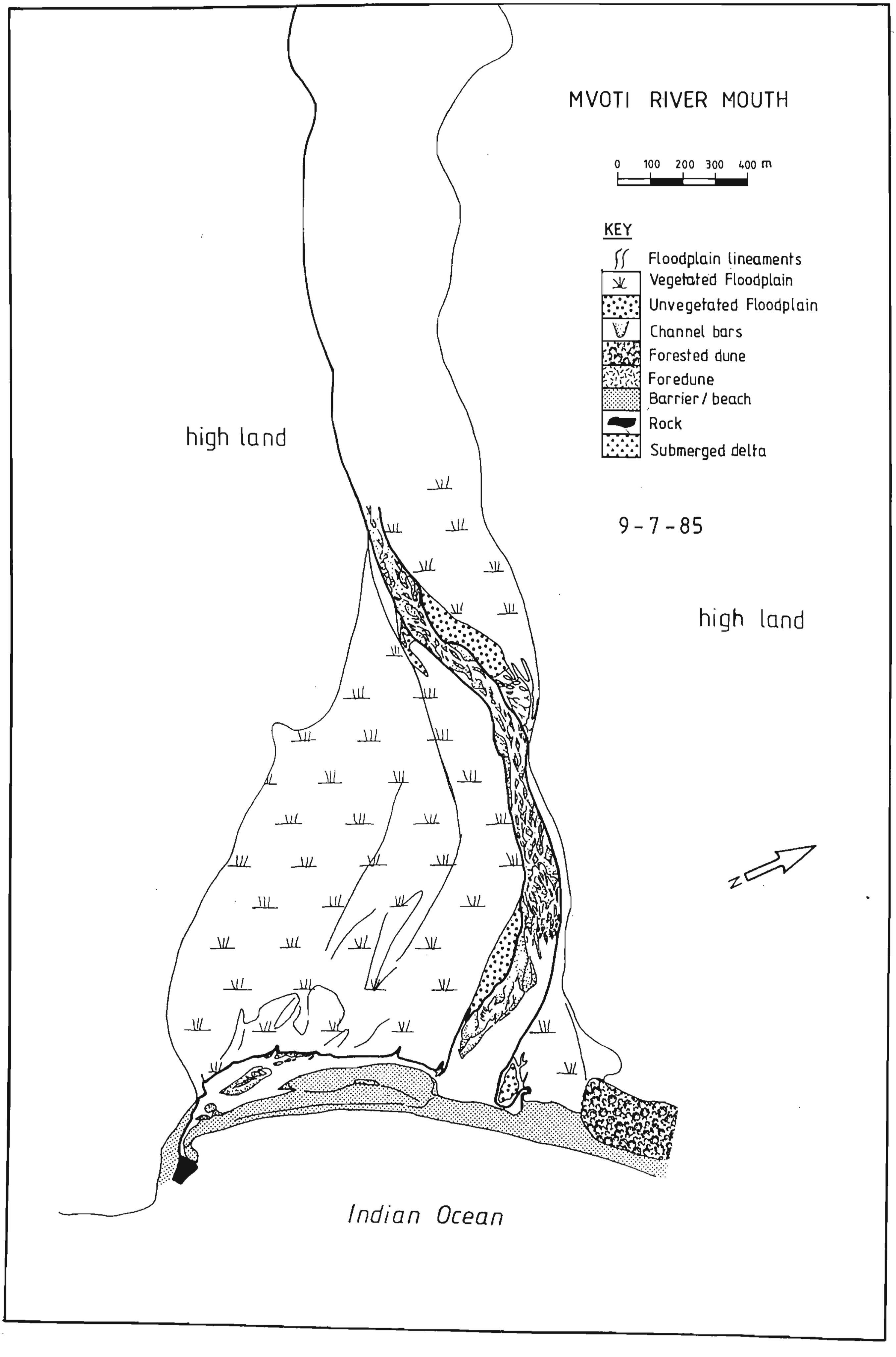

Figure 6.6 Temporal changes in river-mouth morphology 1937 to 1985 (continued)
6.6H. Mvoti river-mouth 9th July 1985

foredune had formed on the barrier but on the mainland attached beach north of the mouth, the foredunes had been partially eroded.

In June 1973 the river channel was only 30 m wide (Fig.6.6D). No bars were present in the channel, suggesting it was relatively deep, and the banks were thickly vegetated. The channel had migrated northward by 10-20 m partly eroding the landward side of the barrier opposite the 90° bend. The sandbars had been eroded from the back-barrier area and a small point bar was deposited on the inside of the 90° bend. The landward side of the barrier in the coastwise lagoon had been eroded (including the vegetated dune) and the seaward side had accreted adjacent to the mouth. Increased competence of flow within the channel, confined by cohesive banks, probably enabled erosion of the accumulated sand bars, eroded the landward margin of the uncohesive barrier, and transported the sediment through the mouth to nourish the adjacent beaches.

The first major floods since 1940 occurred in 1974 as a result of a cloudburst (Begg 1977; Perry, 1989) and the flood filled the entire floodplain. Subsequently in 1976 a particularly prolonged flood occurred (Begg, 1977), the effects of which are recorded in aerial photographs of May 1976.

Photographs from 14th May 1976 show the extent of the flood channel at that time. The southern end of the forested dune on the northern margin of the floodplain was eroded (Fig.6.6E). This had been stable since at least 1937. The flood breach on the northern end of the barrier was beginning to close. The channel was 200 m wide and contained several large sandbars. The upper reaches were surrounded by overbank sands but these were absent from the lower reaches. A crevasse splay completely isolated the coastwise channel from the main channel and the southern outlet was closed. The flood breach had narrowed to 40 m from its original 250 m, by landward reworking of the eroded barrier sediment. This diverted to flow and produced a sinuous channel, elongated obliquely northward across the barrier.

Mr Jex reported to Begg (1977) that the flood banks were not permitted to remain in a vertical profile because the sandy banks were undermined, causing collapse of the overlying mud. He bulldozed the steep banks to a more gentle profile and planted "water grass", which spread rapidly, stabilising the banks. This was followed by the natural colonisation of the banks by *Phragmites* reeds.

In August 1983 the extent of the 1976 flood-channel, was marked by lightly vegetated areas on the floodplain and the outlines of former channel bars were clearly visible. The 1976 flood breach was closed by a 250 m-wide washover apron and the crevasse which isolated the coastwise lagoon from the channel had been eroded (Fig.6.6F). The outlet had reverted to the south. The river channel had receded to the narrowest dimensions recorded by aerial photography: the channel was only 10 to 15 m wide and followed a sinuous path across the floodplain. This was probably as a result of the stabilisation of the banks by Mr Jex. Former overbank deposits from the 1976 flood had been vegetated and the channel margins were apparently cohesive. The channel contained several bars, many of them side-attached but some in midstream and was evidently shallow. In the coast-parallel section, the channel was at its widest (110 m) and this area was filled with braid bars. As on previous occasions, these probably derived from the erosion of crevasse deposits at the 90° bend after the flood waned and the flood-breach in the barrier closed.

In February 1984 the channel was slightly wider than 1983 (25 m) (Fig.6.6G). The outlet was located in the south of the embayment and a plume of turbid water extended into the sea, indicating high river flows at the time of photography. This water turbidity prevented assessment of channel bedforms but some bars were visible. The channel widening was accomplished by downstream movement of the subdued bends in the river channel and marked barrier erosion had occurred at the 90° bend at the coast. A small area of low-lying ground to the north of this was inundated suggesting higher water levels. This photograph was taken during the floods associated with Tropical Cyclone Domoina which devastated rivers and estuaries only 170 km further north (Van Heerden & Swart, 1986). The morphological changes in the Mvoti were unremarkable and the flood appeared to involve simply a rise in water level and suspended sediment transport rather than channel erosion.

In July 1985 (Fig.6.6H) the Mvoti had a morphology unlike any revealed by earlier aerial photographs. The channel was 150 to 200 m wide and braided throughout. Large overbank deposits were present and a well-developed crevasse splay was preserved about 1200 m upstream of the barrier. The river-mouth had recently experienced a flood, probably one noted elsewhere on the coast in February 1985 (Junor, personal communication, 1990), and although the flood breach position in the barrier was evident at the time of photography it was closed by a broad overwash apron. The flood breach had been located some 200 m south of the 1976 breach. By the time of photography the mouth had reverted to its usual southerly location across the rocks at the south of the embayment. A large sandbar which had been deposited in the back-barrier area was subaerially exposed and had become incorporated into the barrier through wind action. This sandbar reduced the open water area between the coast-normal and coastwise channel sectors to less than 30 m wide. A small vegetated dune had formed on the barrier. On its seaward side, the southern part of the barrier had retreated by 20-30 m while the northern part had accreted by a similar amount.

6.4.2. Discussion: Long-term geomorphological changes in the Mvoti river-mouth

The changes in morphology documented above may be divided into two categories: channel changes, and barrier changes. Each of these is discussed in this section.

6.4.2.1. Channel changes. The lower reaches of the Mvoti exhibit major changes in channel form through time. The presence of floodplain lineaments south of the channels recorded suggests periodic occupation of the floodplain there before 1937, most likely during flood-associated overland flow. Since 1937, channel changes reflect adjustment to fluvial discharge conditions and show no evolutionary progression. Under flood conditions normal thresholds are exceeded and dramatic changes occur, through channel erosion and expansion. The general trend is one of lateral expansion through bank erosion and overbank flow, however certain floods, such as 1959, appear to have been confined to the channel and caused downcutting within the channel, as suggested by the absence of bars after the flood. After a major flood much of the floodplain is composed of loose sandy deposits through which the river course flows. The unconsolidated margins promote formation of a braided channel but soon, as vegetation becomes re-established, bank cohesion confines the channel, which in turn diminishes in width and increases in depth.

In interflood periods there is a tendency for the channel to narrow and deepen and it is this which has given rise to the illusion of apparent modern siltation in the Mvoti river-mouth area. Up to September 1987 major floods had occurred in the Mvoti in 1913 (discharge 2150 m^3s^{-1}), 1917, 1925, June 1940, December 1944, January 1974 (discharge 3200 m^3s^{-1}), March 1976, (Begg, 1977; 1984b) and February 1985 (Junor personal communication, 1990). The 30 year period 1944 - 1974 without a major flood was one in which the river channel narrowed markedly as vegetation encroached on the river channel. The rapid narrowing after the 1976 flood was probably due to artificial stabilisation as reported by Jex to Begg (1977).

6.4.2.2.Barrier changes. The Mvoti river-mouth is within the zone of possible Holocene beachrock formation. However, the lack of beachrock cementation along the barrier or the adjacent mainland-attached beaches may be attributed to periodic barrier erosion by fluvial floods and lack of sufficient carbonate in adjacent coastal dunes for downward percolation. Up to 1987, the Mvoti barrier position fluctuated irregularly within a 30 to 40 m envelope of mobility (Fig.6.7) and showed no long-term migratory trend (Fig. 6.8). This is within the range of seasonal fluctuation indicated by studies of beach profiles along the Natal coast (CSIR, 1976). Flood breaches close rapidly by landward reworking of eroded barrier sediment (Cooper, 1990d) which restores the planform in the embayment. This suggests a long-term state of planform equilibrium with approaching wavefronts. The process of flood breach closure is discussed further in the following section.

6.5. EFFECT OF THE 1987 FLOODS

6.5.1. Introduction.

The morphology of river channels and floodplains is greatly affected by high discharge (Leopold *et al.*, 1964). Floods might therefore be expected to produce marked geomorphological changes on the coastal floodplains of large-catchment rivers. Up to 1987 flood effects in the Mvoti river-mouth were recorded by instantaneous photography, during or after the event. During September 1987 the effects of a high magnitude flood on the Mvoti river-mouth were observed first hand and from several sets of aerial photographs. In this section the impacts of the flood and the post-flood recovery are assessed.

6.5.2. Rainfall and flood discharge

Between the 20th and 25th of September the Mvoti catchment experienced widespread rainfall (up to 600mm). A peak discharge of 5530 m^3s^{-1} was calculated (Kovacs, 1988) from a gauging station of the Department of Water Affairs some 10 km upstream of the coast. This is the largest flood ever recorded in the Mvoti (Perry 1989) but is still just over a third of the 15 000 m^3s^{-1} predicted for the probable maximum flood (Chunnett, Fourie & Partners, 1990).

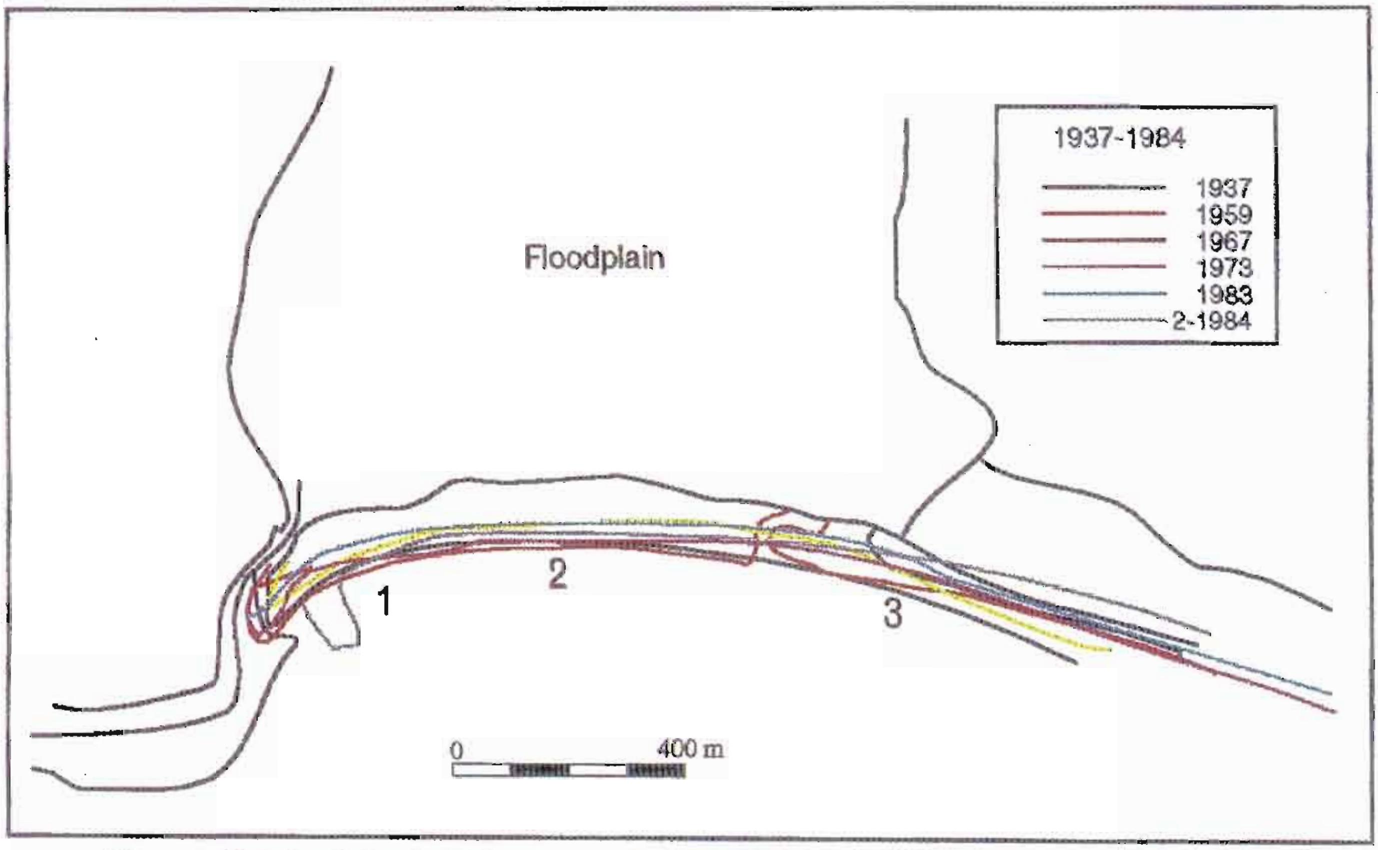

Figure 6.7A. Variation in high water mark 1937 to 1984. Note the low envelope of mobility, which is within the seasonal ranges observed along the coast. Compare with Figure 6.8. Numbered positions refer to locations in Figure 6.8.

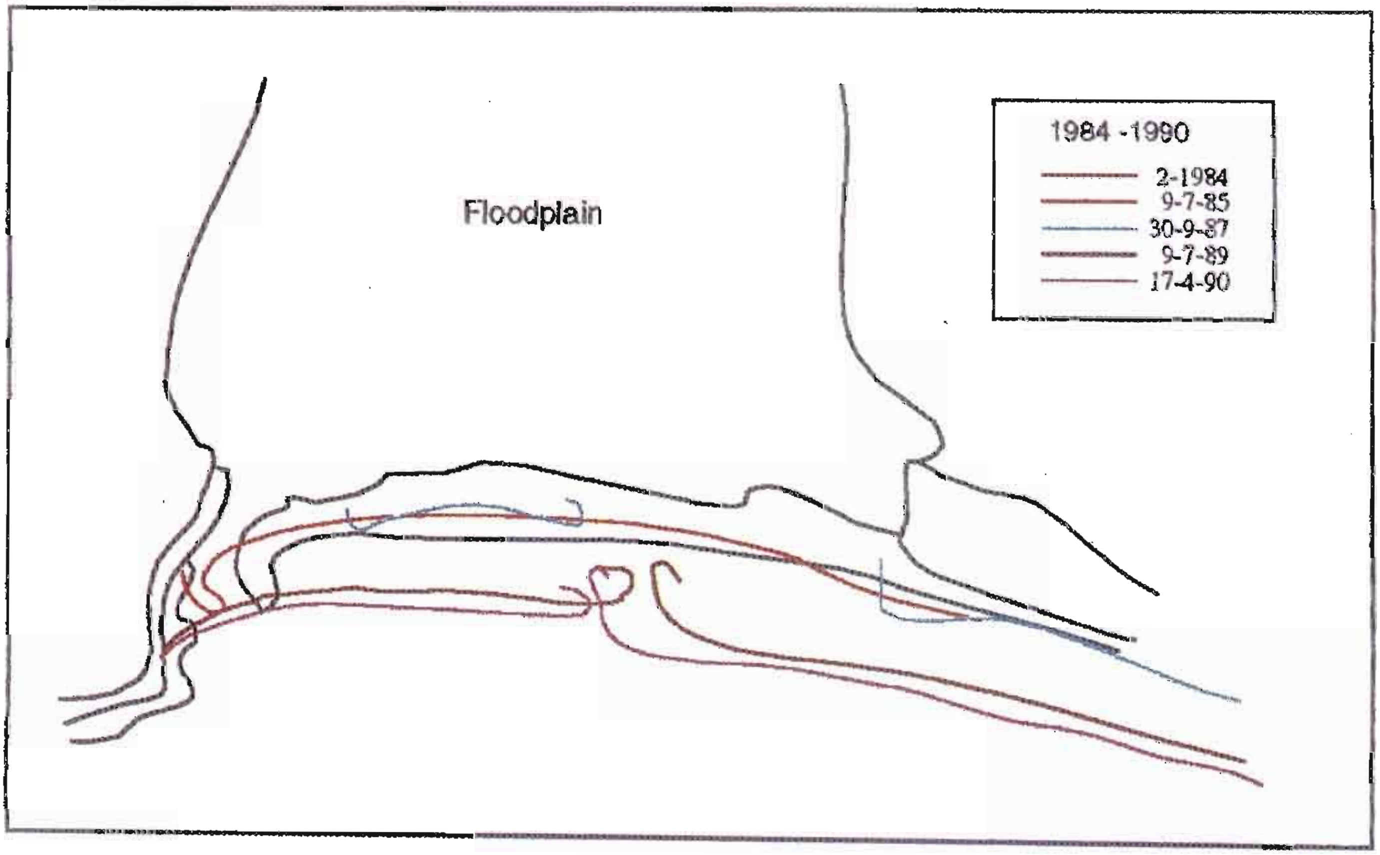

Figure 6.7B. Variation in shoreline position following severe floods in September 1987. Note the rapid accretion of the barrier due to excess sediment in the nearshore reworked from ephemeral flood-generated delta.

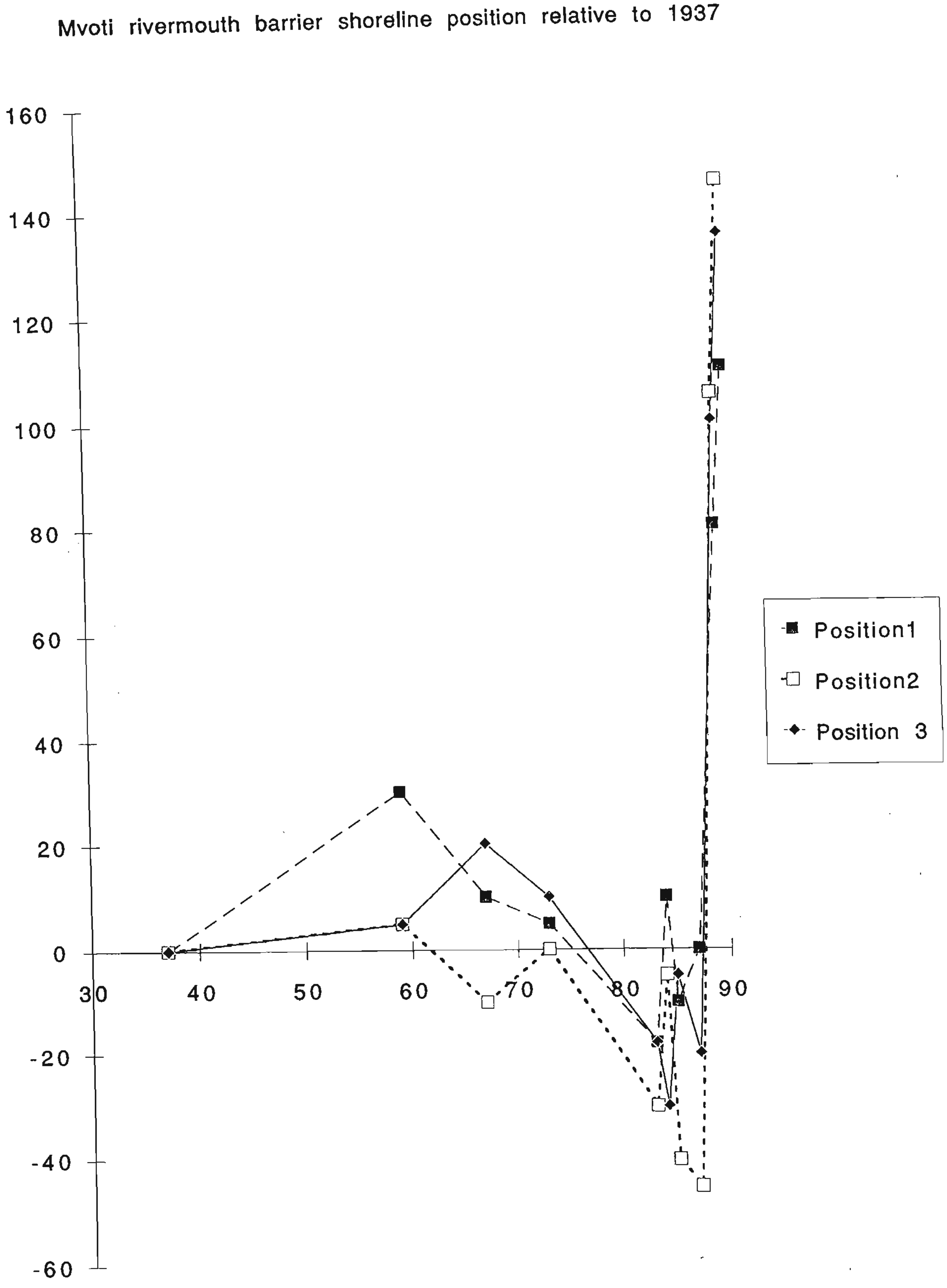

Figure 6.8. Graph showing variation in position of high water mark relative to the 1937 position for positions 1, 2 & 3 shown on Figure 6.7. Note the low envelope of mobility up to 1987 which suggests relative stability of the barrier with respect to ambient wave field. Rapid progradation after September 1987 is associated with a major flood.

6.5.3. Morphological changes

Successive changes during and after the 1987 flood are documented below, based on field observations and both vertical and oblique aerial photography.

30/9/87. Oblique and vertical photographs taken during the September 1987 flood event, about 5 days after the peak shows part of the roadbridge was washed away. The water level had dropped, revealing that almost the entire floodplain was covered in a layer of sandy overbank deposits (Fig.6.9.A; Plate 6.4B). Flow had evidently been concentrated against the valley sides, for the main channel in the north was still 450 m wide and had breached the barrier across that width. In the southern part of the coastwise lagoon deep gullies had been formed by overland flow and the barrier there had been eroded on a 250 m-wide front. Opposite each flood breach the positions of flood-generated, submerged deltas were revealed by breaking waves. Underwater features were indiscernible due to the turbid waters. However, the breaking waves suggested that the larger of the deltas was elongated perpendicular to the shore through a distance of 400 to 500 m. A small remnant of the pre-flood barrier was preserved in the middle of the floodplain. The flood cut a straight channel to the coast, unlike other post-1937 flood channels which maintained a degree of sinuosity. Large side-attached bars were evident in the channel and turbid water flowed into the sea. In the upper reaches new channels formed by overland flow from the adjacent hillsides, and these deposited overbank sands in elevated areas above the floodplain.

2/11/87. Aerial observations on 2nd November 1987, five weeks after the flood revealed the formation of an extensive emergent delta opposite the northern flood breach (Plate 6.4C). This resembled, and had the morphological units typical of, ebb-tidal deltas associated with barrier inlets (Oertel, 1975; Hayes, 1975; Cooper 1990d). The terminal lobe was situated some 300 m seaward of the barrier, and had been reworked landward to form a plug in the main breach channel (Plate.6.5A-C). Secondary channels, resembling small distributaries, were cut through the marginal swash platform (Plate 6.5C). Small swash bars were present on the swash platform. The outer margin of the swash platform on both the north and south delta margins, assumed a crescentic shape parallel to approaching wave fronts which were being refracted around the main body of the stream-mouth bar (Plate 6.5B). Opposite the southern flood breach, a formerly submerged delta had become emergent as an elongate bar which diverted the flow from the coastwise lagoon remnant, northward across the barrier. The elongate bar was attached to the rocks at the Jex homestead and extended northward for approximately 250 m.

12/5/88. The stream-mouth bar was reworked landward, and in May 1988, approximately 8 months after its formation, had decreased in size, reducing the intensity of wave refraction around it (Plate 6.4D). Most of the stream-mouth bar sediment had been reworked landward into the position of the former barrier. It had rolled over, pivoting anti-clockwise around the area in the north where it was initially welded to the existing beach. This initial welding of the stream-mouth bar in the north gives the false impression that southward longshore drift caused spit accretion in that direction, rather than wave-refraction controlled rollover. The mouth had narrowed to about 50 m, and was restricted to the southern portion of the flood-generated breach. A small stream-mouth bar, present at the mouth of the outlet channel, was only 70-80 m wide, and extended northeasterly for less than 60 m. In ebb-tidal

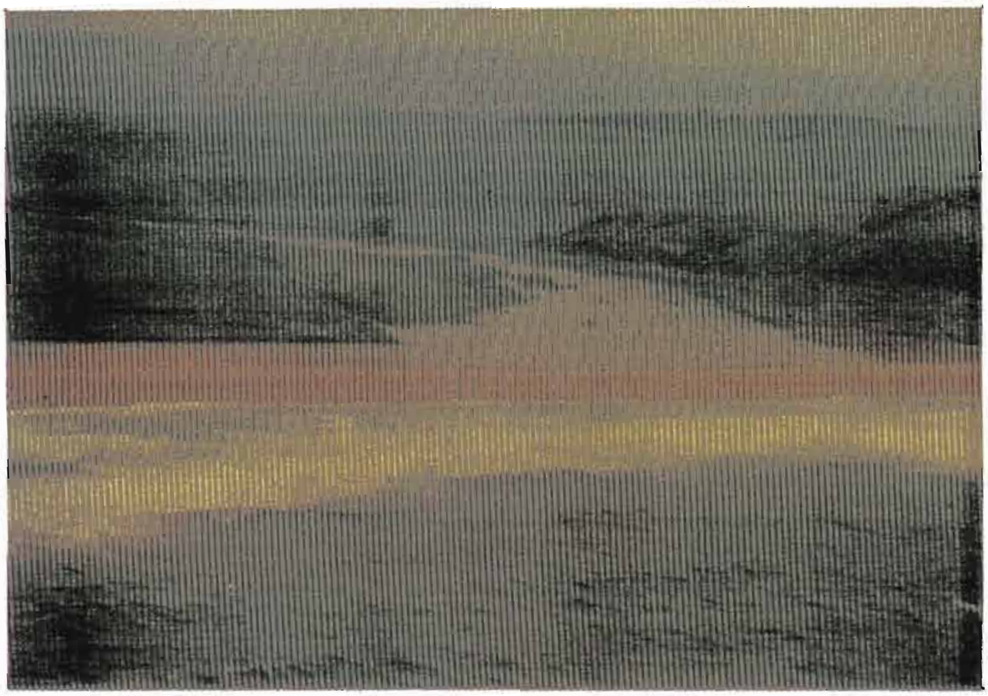

Plate 6.4A. Photograph of the Mvoti river-mouth looking landward on 14th April 1986.

Plate 6.4B. Photograph of the Mvoti river-mouth on 30th September 1987, showing the main flood breach

Plate 6.4C. Photograph of the Mvoti river-mouth on 2nd November 1987 after major flood in late September 1987. View similar to Plate 6.3A. Note the flood breach and emergent delta. To the left of the photograph is a second breached outlet. The extent of overbank sands on the floodplain is evident.

Plate 6.4A-E. Changes in the Mvoti river-mouth following the September 1987 flood

Plate 6.4D. Photograph of the Mvoti river-mouth on 12th May 1988. The emergent delta of the previous photograph has been reworked landward to reform the river-mouth barrier. The wide flood breach is reduced to a narrow outlet flowing obliquely across the barrier. Parts of the floodplain are becoming re-vegetated.

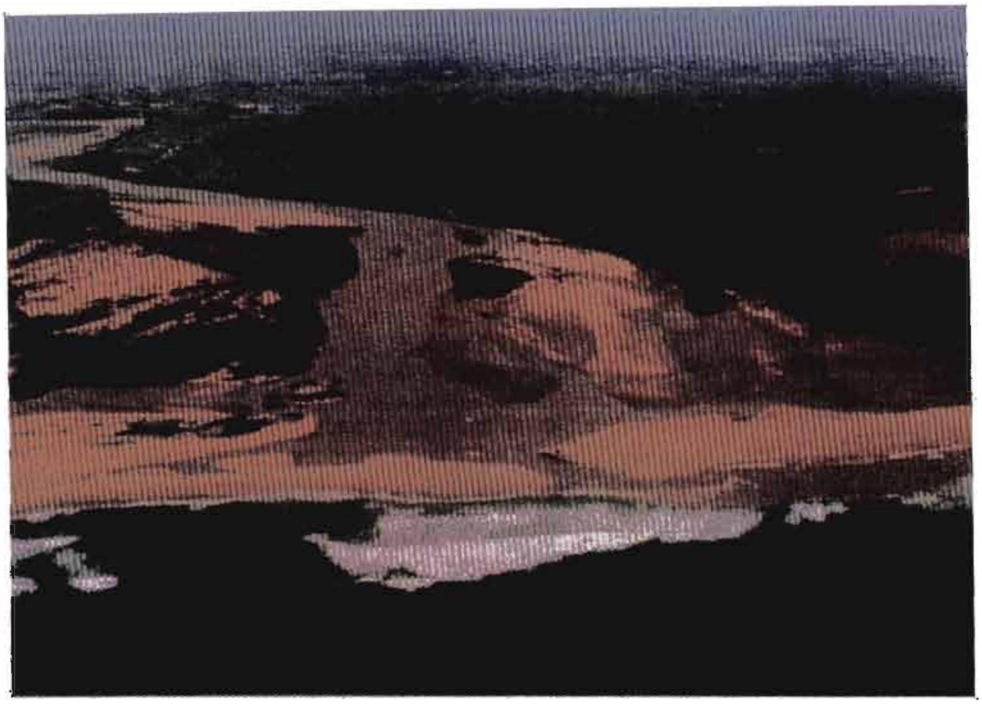

Plate 6.4E. Photograph of the barrier on 15th April 1990. A small outlet is present in the reformed barrier across the flood breach. Much of the floodplain is vegetated and the main channel is located in a position in the centre of the floodplain, similar to that occupied by the channel in 1937. Note the high water turbidity in the river-mouth and plume of turbid river water in the sea

Plate 6.4A-E. (continued) Changes in the Mvoti river-mouth following the September 1987 flood

Plate 6.5A. The emergent delta opposite the flood breached barrier. Note the shallow sandy channel behind the delta. Increased carbonate in this sediment suggests that at least part of it may have been derived by flood-tidal deposition.

Plate 6.5 B. View of the delta toward SE. The northern swash bar shows a smooth curved planform aligned with refracting wave fronts.

Plate 6.5C. Morphology of the emergent delta looking seaward (after Cooper, 1990d). "B" is the terminal lobe, The features marked "A" are marginal swash bars and "C" is a bar reworked landward into the former flood channel.

Plate 6.5.A-C Detail of the emergent flood-generated delta opposite the flood breach on 2nd November 1987. Note the waves refracting around the delta which protrudes seaward of the normal barrier planform. Wave refraction controlled delta morphology during reworking.

deltas this morphology is typical of longshore current dominance (Oertel, 1975). The bar across the southern outlet had connected with the barrier remnant in the centre of the barrier, closing the southern flood breach, and forming a smooth plan form along most of the seaward side of the barrier.

1/1/89. Fifteen months after the flood, aerial photographs of the river-mouth barrier showed the northern breach was still open although the barrier had partly reformed across it through landward reworking of the delta sediment by wave refraction around the submerged bar remnant. The reworked sediment formed two bars, one on each side of the delta remnant, and these were both mainland-attached at the ends distal to the delta. In other respects the river-mouth morphology was similar to that described below from more extensive photographic coverage of July of the same year.

9/7/89. Almost two years after the flood peak the wide river channel still persisted (Fig.6.9B) but it was shallow and filled with sand, commonly in the form of unvegetated braid bars. The barrier had been largely reformed but had accreted seaward by about 120 m along most of its length. The flood breach had been almost closed by continued landward reworking of the delta sands (Cooper, 1990d) but a 40 m-wide mouth was still maintained between the spits. The southern end of the barrier enclosed a large area of water formed by the drowning of the gullies produced during the flood. This was linked to the main river channel by a 10 m-wide connecting channel across the former overbank sand and barrier remnant. The floodplain was largely re-vegetated but large areas of loose sand remained.

During a field visit on the 25/8/89 the flood breach was closed completely and water levels in the river-mouth were up to 2 m higher than usual. The coastwise lagoon was connected to the main channel by a broad stretch of water which covered the former sandbars in that area. An outlet was formed at the rocks at the southern end of the embayment at the Jex homestead by overspilling across the barrier.

15 th to 17th April 1990. Some eight months later the outlet in the south had closed and a 25 m-wide outlet had reopened in a northern position, some 100 m to the south of the flood breach of July 1989 (Fig.6.9C; Plate 6.4E). This was either due to increased stream discharge during the intervening summer months (typically the rainy season) or artificial breaching to facilitate boat launching. The main river channel had narrowed as former channel bars became vegetated and incorporated into the floodplain. Most of the river flow was restricted to a shallow braided channel averaging 120 m wide. The link between the main channel and the southern end of the lagoon had widened and newly deposited sandbars in the southern part of the back-barrier suggested that flows were eroding sediment from the former shallow areas around the 90^{o} bend. Parts of the gullies were infilled through marginal vegetation (*Phragmites*) encroachment and suspension-settling of mud. The barrier had accreted seaward by a further 20-30 m. Lineaments recorded the path taken by overland flow across the southern part of the floodplain, similar to those recorded on photographs of 1937.

1/9/91. During a field visit at this time, flow had reverted to the southern outlet. The former sandy flood channel was infilled with muddy sediment, partly in the form of low vegetated islands, separated by shallow channels. The overall morphology was of a delta in which mud deposition was dominant.

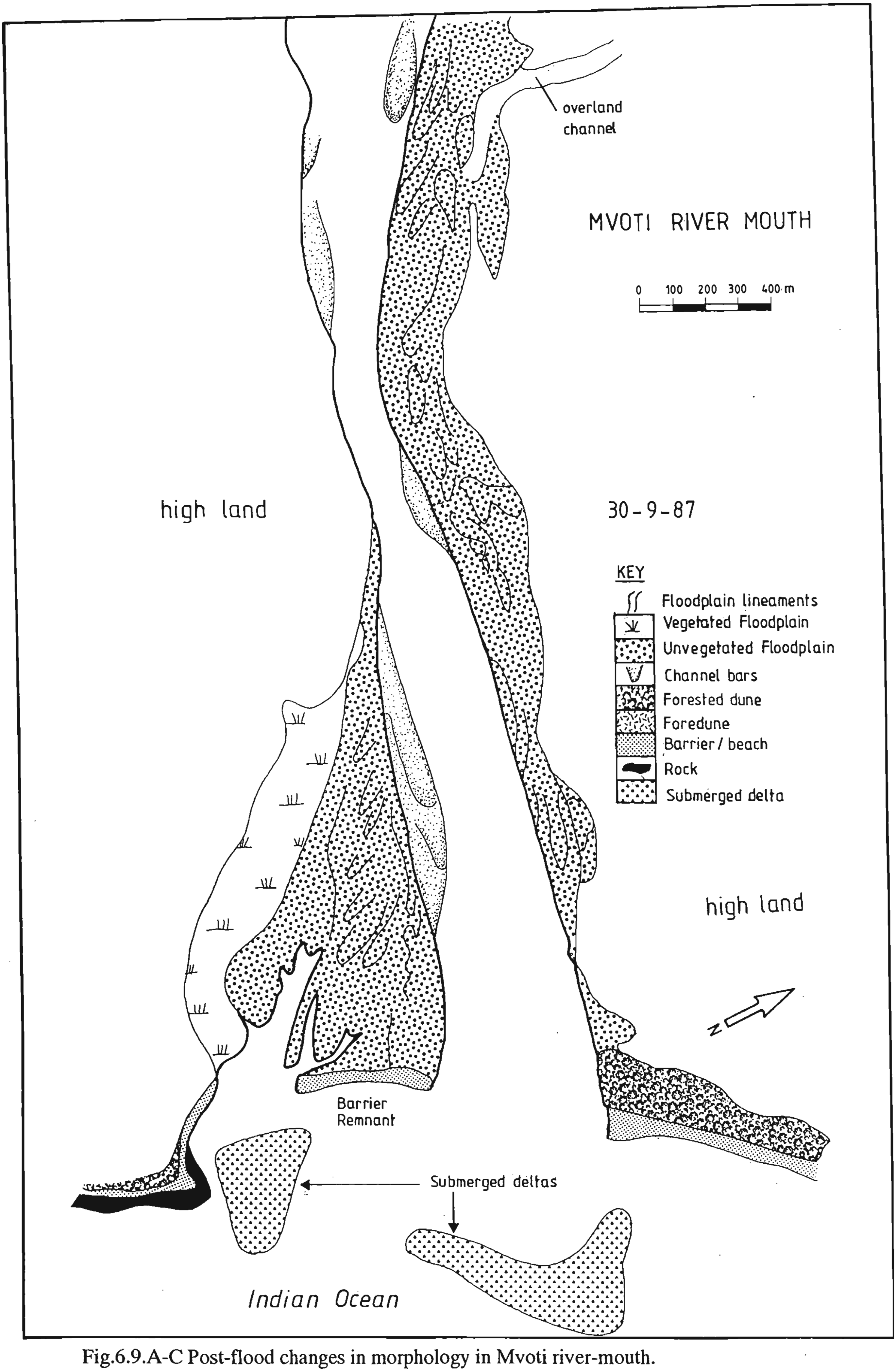

Fig.6.9.A-C Post-flood changes in morphology in Mvoti river-mouth.

6.9 A. Mvoti river-mouth on 30th September 87. Just after the flood peak a wide channel was present and submerged deltas were deposited offshore, their presence revealed by breaking waves (continued overleaf).

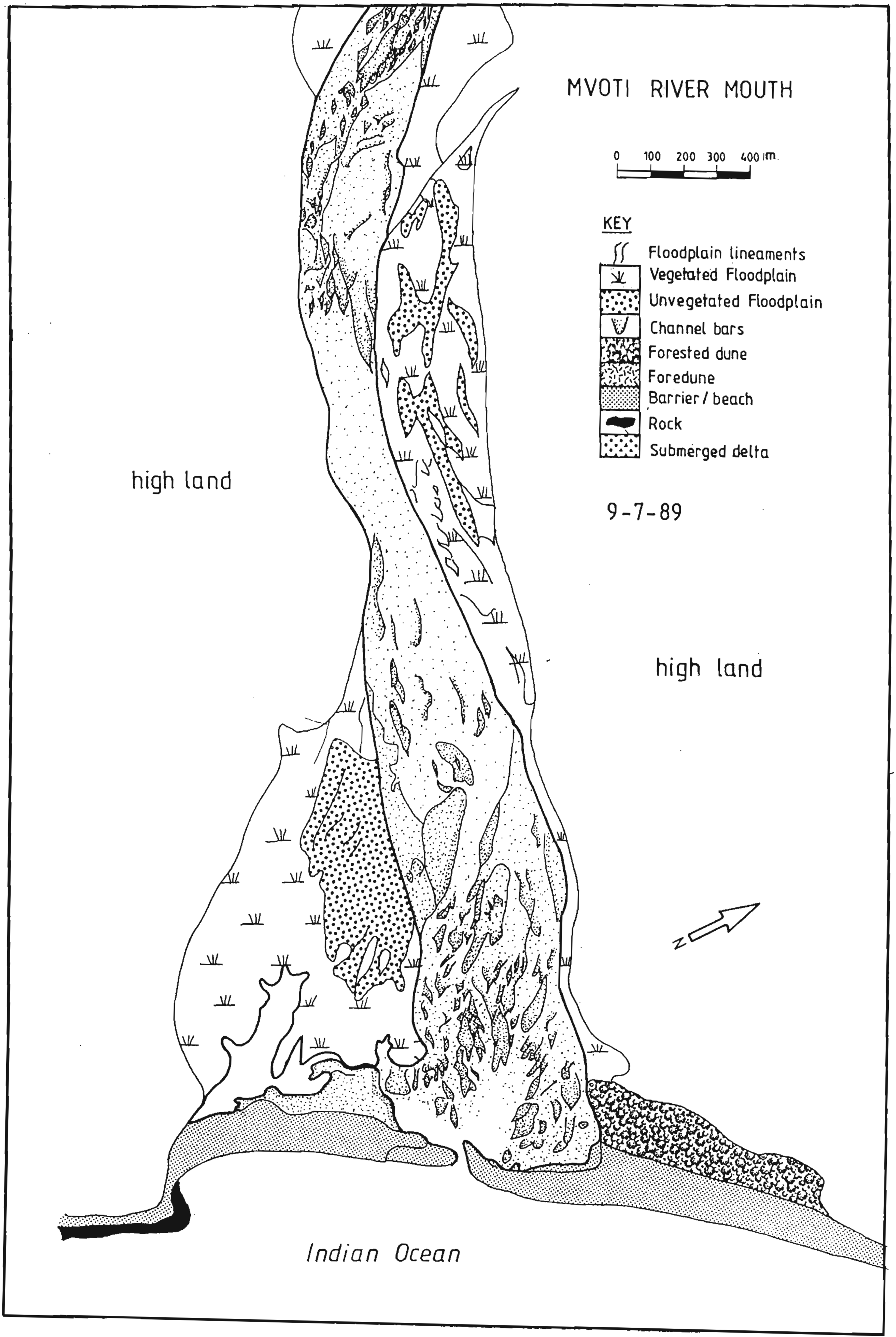

Fig.6.9.A-C Post-flood changes in morphology in Mvoti river-mouth (continued).
6.9B. Mvoti river-mouth on 9th July 1989. A shallow braided channel extended to the flood breach (continued overleaf).

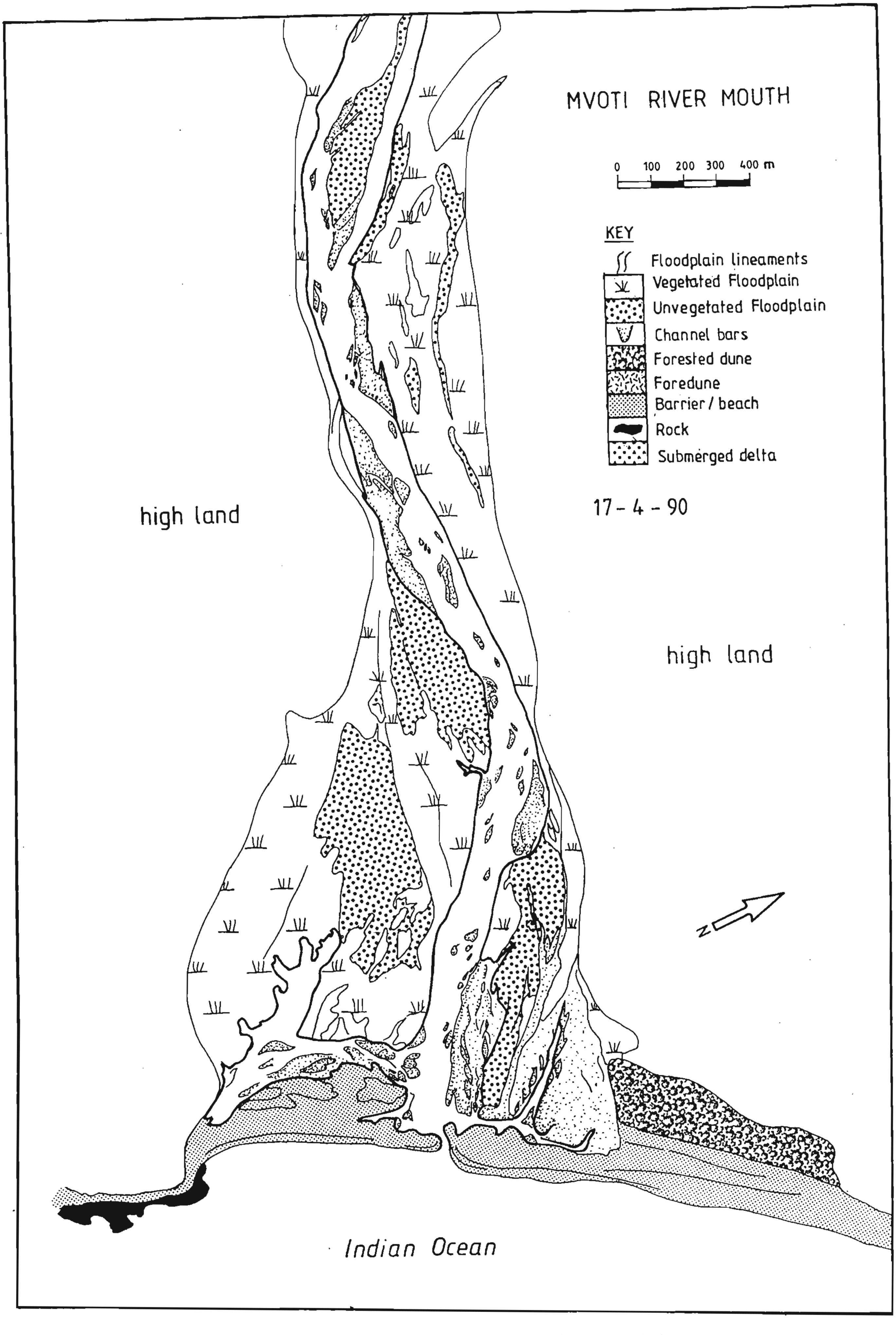

Fig.6.9.A-C Post-flood changes in morphology in Mvoti river-mouth (continued).

6.9C. Mvoti river-mouth on 17th April 1990. The channel had narrowed since the flood and parts of the adjacent floodplain were becoming re-vegetated.

Mud was present in the distributary channels and on the intervening islands where vegetation had stabilised them. The vegetation showed a vertical zonation from algae and lichen which occurred on the lowest section of the bars, passing upwards through successive fringes of small *Scirpus* reeds, large *Scirpus* reeds and on the uppermost parts, grass. The river discharge was contained mainly in a channel on the southern margin of the former flood channel, in a position similar to that occupied by the river in 1937. The area there was sandy, both within the channel and on the surrounding areas. It appears that the flow reverted to this area because the sand was more easily erodible than the now muddy deltaic areas of the former flood channel.

6.5.4. Sediment distribution

Sediment sampling during August 1989 when the flood breach had closed, almost two years after the 1987 flood, showed that the bed was again dominated by sand (Fig.6.10A). Mud was limited to backwater areas in the gullies and an isolated area on the northern bank of the former flood channel. The mud contained up to 20% organic material (Fig.6.10C). A small area of gravelly sand (34 % gravel) was located on the southern side of the former flood channel. This is probably a remnant lag deposit from the scoured flood channel which was not covered with post-flood or waning stage sand deposition. The carbonate distribution in the bottom sediments (Fig.6.10B) showed carbonate-bearing sediments up to 200 m landward of the barrier at the northern flood breach and on the landward fringe of the southern barrier sector. This indicated overwash of marine sands during landward reworking of the delta sediment and the augmentation of the delta sediment by a marine component. The distance to which carbonate-bearing sediment had extended into the northern part of the coast-parallel lagoon, suggest that flood-tidal currents may have assisted in its landward transport and imply that the breach permitted temporary reversing current tidal inlet conditions to operate. Overwash does not typically extend so far into lagoons on the Natal coast.

6.5.5. Channel cross-sections

Several channel cross-sections were surveyed before and after the flood (Van der Merwe, 1989) but no interpretation was attempted by the surveyors. Information from these cross-sections are here used as an additional data source to interpret the effects of the flood. Comparison of cross-sections from May 1987 (pre-flood) and 6th October 1987 (11 days after the flood peak) reveal the much larger channel cross-sections during the flood and marked changes in bed and floodplain level (Fig.6.11). Unfortunately the pre-flood surveys did not extend across the floodplain much beyond the narrow river channel and so volumetric calculations of erosion and deposition are not possible.

Section 5, the most upstream profile, showed an enlarged channel formed through lateral erosion of the left bank, which was on the outside of a bend, through about 80 m, at the same time lowering the floodplain level by at least 2 m. On the right bank lateral erosion was about 120 m and involved a similar depth of scour. The former channel was infilled by sediment which raised the level of the bed by an average of 1 m to equal the newly eroded flood channel base level. The flood water level at this profile was 12.2 m MSL.

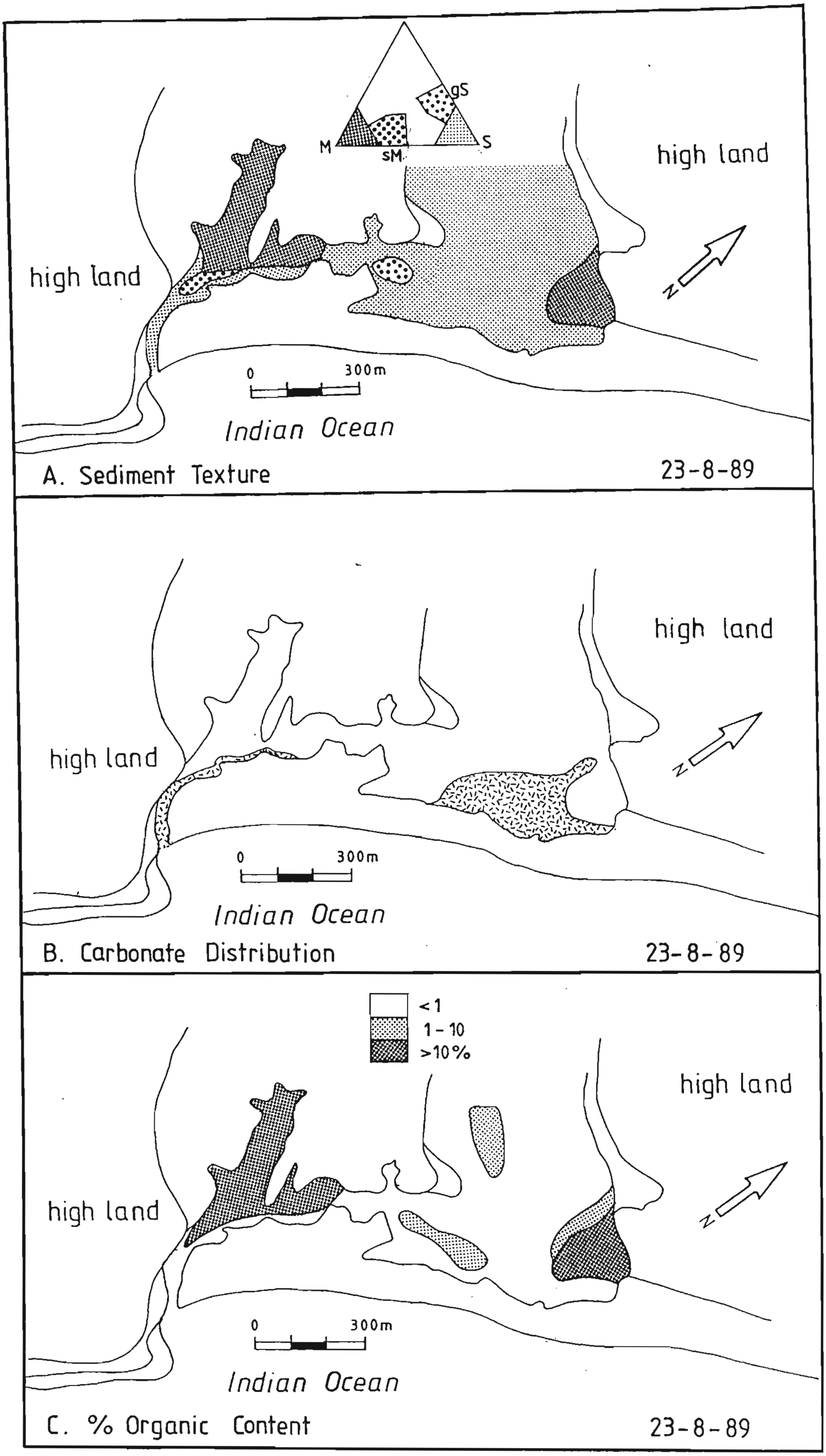

Fig.6.10A-C. Sediment distribution in the Mvoti river-mouth, 23rd August 1989.

A. Sediment texture. Sand dominates the channel while mud is restricted to backwater areas.

B. Carbonate distribution. Areas with over 1% carbonate are shaded.

C. Organic content. This is closely correlated with muddy sediments

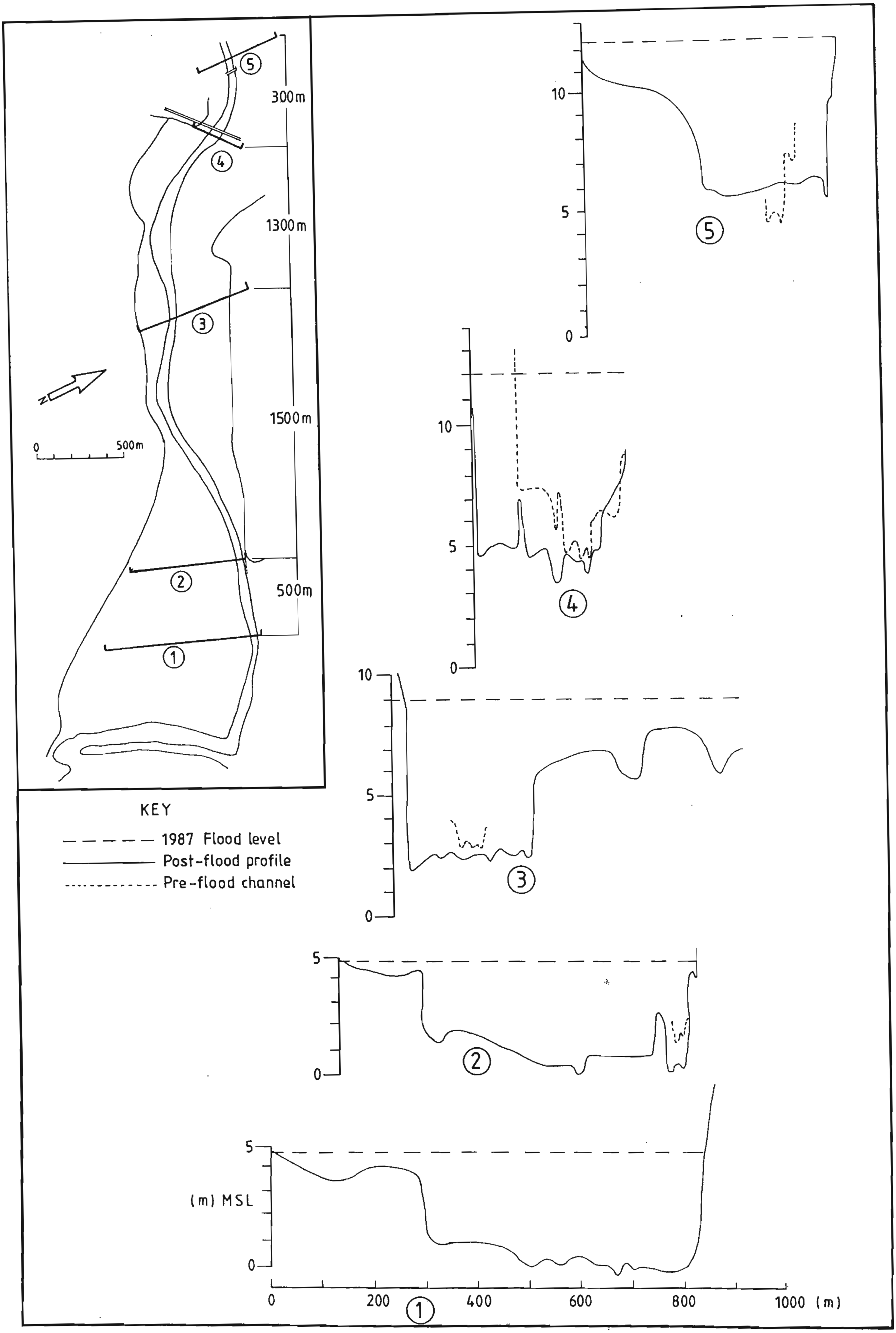

Fig.6.11. Cross-sectional profiles across the Mvoti river-mouth channel before the flood and across the whole floodplain after the flood. Redrawn using data of Van der Merwe (1989).

Section 4 at the N2 road bridge widened on the right bank by 180 m through lateral erosion to a depth approximately equal to the pre-flood channel bed level, consequently the vertical elevation of the channel bed remained the same, although it was much widened.

At Section 3, downstream of the roadbridge, the pre-flood channel cross-section which was about 50 m wide, was enlarged to 700 m at the height of the flood. The main flow was, however, carried in a 245 m-wide channel, with a bed level less than 0.5 m lower than that of the narrow pre-flood channel.

Further downstream at Section 2, the channel was located against the left margin of the floodplain and hence lateral expansion took place on the right bank through erosion of over 350 m of the floodplain. The flood channel base was locally up to 1 m lower than the pre-flood channel bed but averaged only 0.5 m lower.

Section 1 was not surveyed before the flood but a post-flood survey showed the flood occupied 800 m of the floodplain at that point and reached a water level of 4.7 m MSL, just 560 m upstream of the barrier. The downstream variation in elevation of the flood water surface (Fig.6.12) shows the gradient which was attained by the flood water. The water surface gradient was similar to the gradient of the river bed both before and after the flood and a similar depth of water was present across the entire floodplain during the flood. The rise in bed level upstream of the road bridge may have been due in part to the piling up of water there.

6.5.6. Discussion: Flood impacts

***6.5.6.1.Channel/floodplain impacts*.** The channel cross-sections and aerial photography reveal that the Mvoti river-mouth responds to greatly increased discharge by lateral rather than vertical adjustment. Lateral erosion of the floodplain by several tens or even hundreds of metres occurred at all cross-sections and this, accompanied by the increased water level, was sufficient to accommodate the flood discharge. Lateral erosion was possible because of the wide floodplain which, unlike the Mgeni and Mtamvuna River-mouth areas, did not restrict lateral erosion greatly. Consequently, downward scour was limited, and flood channel bed elevations and the downstream gradient remained close to the bed level of the pre-flood channel. The lateral expansion led to vertical aggradation of the former channel upstream of the bridge as the longitudinal river profile adjusted to maximum competency by increasing the downstream gradient. This may however have been due to water piling up at the bridge. Overbank flow had little erosive capability away from the main channel, as evidenced by the thin veneer of sandy overbank deposits which overlay pre-flood floodplain vegetation.

The gullying which occurred on the southern part of the coastwise lagoon extension was probably initiated by a hydraulic jump as the overland flow encountered deeper water in the former coastwise channel. The mechanism of growth through rapid headward erosion across the floodplain has been described by Leopold *et al.* (1964). Photographs reproduced in Perry (1989) also show post-flood gullies on the Mfolozi and Tugela floodplains at the downstream end of an area of overland flow, where

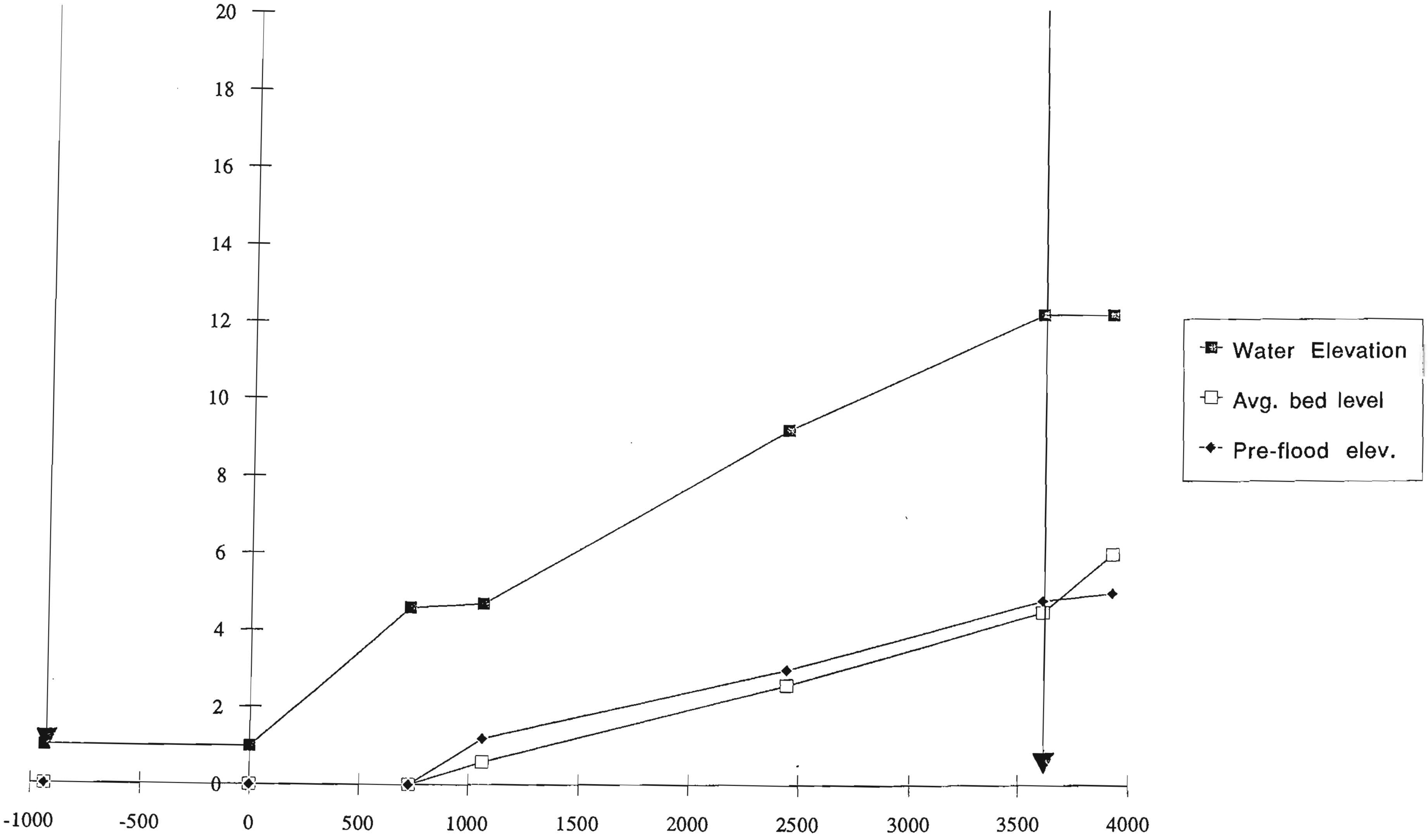

Fig.6.12. Downstream profile of flood water surface elevation during the flood and comparison of bed levels before and after the flood. The average channel base level was plotted.

a channel was again encountered. A hydraulic jump as the flow entered deeper water probably initiated the gullies in both instances.

The September 1987 flood eroded sediment from the floodplain through lateral erosion without greatly increasing or decreasing the channel bed level or changing the downstream gradient. This suggests that the Mvoti is in a state of long-term equilibrium whereby accumulated sediment from long-term buildup via successive minor overbank flows and channel margin accretion, is eroded almost instantaneously by a major flood and transported into the sea. The sediment storage volume of the river-mouth floodplain is increased and can accommodate deposition for a future series of low magnitude flows. In the interim, the separation of suspended load and bedload results in the preferential deposition of sand in the river-mouth and floodplain while, in the absence of deep calm areas permitting suspension-settling, the suspended load moves directly through the river-mouth into the sea or is deposited on the floodplain during low magnitude overbank flows.

Overbank deposits from the flood formed a thin veneer across the uneroded section of the floodplain, raising its level slightly. In the three years following the 1987 flood the Mvoti channel adjusted to the normal discharge regime mud deposition was resumed on the areas of the former flood channel. This was accompanied by and promoted by vegetation growth in the abandoned channel where a fluvial delta formed. Reversion of the main flow to a central part of the floodplain is a post-flood tendency brought about by mud deposition in the flood channel

Sediment grainsize distribution showed little overall change after the flood. The channel was dominated by sand but the extent of mud deposition increased after the flood as a result of the abandonment of flood channels and consequent settling from suspension of muddy sediment. A small gravel-enriched area marked the channel base where scour occurred near the mouth but a lack of vertical scour upstream and the similarity of grainsizes before and after the flood indicate that the sediment in the pre-flood channel had the same chgaracteristics as that transported during the flood. This indicates that the sediments of the Mvoti channel are deposited and transported mainly during floods and that low flows do not change the bedload sediment significantly. The fact that the 1987 channel was still in a recovery stage after the 1985 flood, however, urges caution in this interpretation.

The increase in extent of carbonate-bearing sands after the flood indicates flood-tidal currents operated through the flood breach before it closed. The implications of this are that were it not for the rock outcrop at the south of the embayment extending under the normal outlet, the Mvoti would experience a flood-tidal current and have more typically estuarine hydrology.

6.5.6.2.Barrier impacts. The flood eroded two sections from the sandy river-mouth barrier to accommodate the increased discharge. The northern and southern flood-breaches were initially 500 and 250 m wide respectively. Sand and gravel from the barrier, together with additional sand from upstream was deposited as submerged stream-mouth bars with coast-normal elongation. Shallow water deltas are unstable in high wave energy areas and are not temporally persistent along the Natal coast for this reason. After the flood waned, the deltas began to be reworked by wave action. The changes reported above are summarised schematically in Figure 6.13 A-F. The initially submerged deltas were transported landward through wave action and through swash action become emergent. Reddering (1983) drew attention to the importance of swash in the supratidal growth of barriers. Wave refraction around the submerged delta controlled the morphology of the emerging sandbars. Consequently two marginal bars formed, which assumed a curved outline in response to wave refraction around the maximum coast-normal axis of the delta. The emergent bar subsequently welded to the pre-flood barrier remnants through wave action, pivoting around the points of initial attachment because those points became little affected by refracted waves. Wave energy continued to drive the two bars landward into the remaining breach, which they did by overwash of the bar crest and transport of the forebeach sediment to the backbeach (rolling over).

Gradually they moved into a planform alignment with the rest of the barrier. When discharge reduced sufficiently, wave energy became dominant and sealed the remaining breach. This returned the entire barrier to an equilibrium planform and the outlet reverted to its stable position in the wave shadow in the lee of the southern rocky outcrop. This mode of barrier reconstruction follows exactly a rollover response, similar to that envisaged for a rising sea-level on wave-dominated coasts (Carter, 1988). The morphology of the welded emergent delta portions give a false impression of spit progradation alongshore but this is not the case: landward movement by rolling over, controlled by wave refraction dominates over longshore movement. Progressive inlet migration and alongshore spit growth is not common in Natal as it is in certain barriers in the Eastern Cape (Reddering, 1983) and other microtidal areas (Kumar & Sanders, 1974,1975). The barrier face prograded rapidly after the floods due the excess sediment in the nearshore being driven landward under wave action (Fig 6.7B). The position reached by April 1990 was more than 130 m seaward of the next most seaward position recorded since 1937 (Fig. 6.8).

6.6. LONG AND SHORT-TERM SEDIMENTATION IN THE MVOTI RIVER-MOUTH

6.6.1.Comparison of fairweather and flood impacts

The results presented in Sections 6.4. and 6.5. enable comparison of the long-term sedimentological processes during average flow conditions (including low magnitude floods) with those of episodic, high magnitude floods. The time series of aerial photographs between 1937 and early 1987 show that the channel responds to moderately increased flow by either overbank flow or widening (lateral expansion) or both. Under such conditions the river-mouth barrier is breached directly at the point where the channel meets the coast, thereby increasing the river gradient and facilitating the passage of the increased discharge. Lateral expansion was found to be dominant over vertical erosion in several Zululand rivers during flooding associated with Tropical Cyclone Domoina (Kovacs *et al.*, 1985, p41.) Those rivers also had extensive floodplains and it appears to be the floodplain width which controls this flood response.

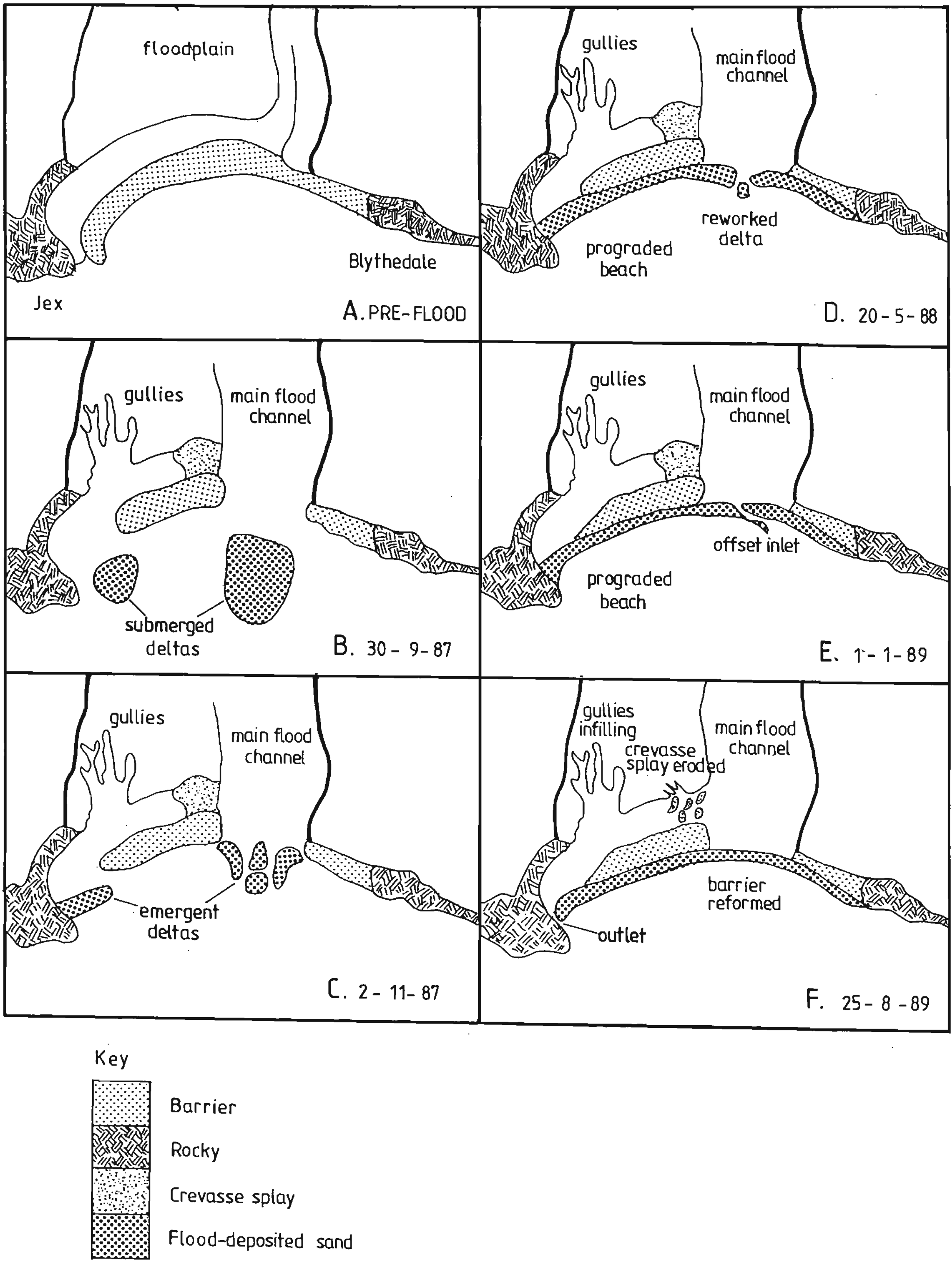

Fig.6.13. A to F. Schematic representation of post flood barrier response.

Ward (1978) emphasised that rivers and their floodplains form a single geomorphological unit and their separation in many texts is artificial. This is particularly true of rivers where lateral channel expansion is a dominant process. In the Mvoti, long term, low magnitude flows typically deposit silt and mud on the low energy parts of the floodplain, gradually raising its elevation. At the same time, the river channel may migrate slowly by lateral bar accretion and bank erosion. During prolonged low flow periods the channel narrows by bank accretion supoported by vegetation colonisation: the Mvoti river-mouth has even dried up several times in the past 30 years (Truen, 1990). The channel responds to varying discharge by changing its dimensions. When high-velocity flood discharge is channel-confined, downward erosion may occur. This appears to be the case when vegetation is firmly established on the banks and under such conditions, a major flood is required to erode the vegetation and and destabilise the banks to permit lateral channel expansion. When vegetation is firmly rooted, less energy is expended in eroding the stream bed during minor floods and consequently downcutting will occur in the channel.

During high magnitude events such as the 1987 flood, a large volume of accumulated floodplain sediment is eroded by the lateral expansion of the river channel to form a flood discharge channel. The distal parts of the floodplain, away from the main flow, may be covered with a thin layer of overbank sand. Thus, while the actual elevation at, for example, the position of the pre-flood channel, may rise or fall initially, the sediments are gradually reworked within the channel as it reduces to post-flood discharge dimensions and the banks regain cohesion. In order to maintain equilibrium the river gradient must return to its average condition and as the downstream elevation is fixed at the outlet, the river bed upstream returns to its pre-flood elevation. The channels formed by major floods are rapidly infilled when the discharge wanes and subsequent low flows deposit mud from suspension. This mud is typically deposited in areas away from the channel where flow velocities are low. The form of deposition is as a fluvial delta, confined within the former flood channel of the river and behind a coastal barrier. Distributary channels occur, separated by low, vegetated islands and the river discharge is diverted southward to the centre of the floodplain to a narrow outlet to the sea, through which mainly suspended sediment discharges. This post-flood morphology is similar to that of 1937, which was 20 years after a major flood. Photographic records during the ensuing 50 years, which lacked a major flood of similar magnitude to 1987, illustrate that the trend during low flows and the passage of minor floods is for the channel to migrate irregularly southward through the post-flood fluvial delta. At the same time, vegetation stabilises the channel margins and some of the braid bars. Northward migration occurs because smaller floods do not accomplish so much lateral erosion of the south bank (which forms the inside of a bend) and cut a direct path through the barrier at its northern end. Ultimately the channel would be expected to locate against the northern margin of the floodplain to gain maximum competence during low flows.

6.6.2. Current state of the Mvoti river-mouth

The Mvoti river-mouth has attracted some attention because of the unusual fauna reported by Begg (1984a,b) and is commonly cited as an example of a degraded estuary. A sample of current opinions on the state of the Mvoti river-mouth are given below in Table 6.1.

NRIO, 1983.	"The estuary shows severe siltation. The increase in bar areas is indicative of an abundant supply of silt from upstream and within the estuarine reach... The increase in bar areas is indicative of land-use malpractices providing abundant silt".
Begg, 1984a	p. 151 "nothing of the original Mzumbe and Mvoti estuaries remain" p. 103. " having been infilled by sediment the bed level of the Mvoti lies above sea-level and in this condition it is atidal....it has also become shallow and potamonic (ever-flowing)".
Chunnett, Fourie & Partners, 1990.	"The Mvoti river estuary and lagoon is considered to be a shallow water system which has recently been filled with sediment."
Badenhorst, 1990.	"......it is clear that the Mvoti is in a serious (sic) degraded condition from a sedimentological point of view. Due to high sediment loads this condition further deteriorates with time"
Quinn & Breen, 1990.	"Begg (1978) reported that 70 years ago large numbers of perch and mullet caught in the estuary were packed in barrels and transported inland. Since then infilling of the basin has altered the conditions so drastically that Begg concluded that the Mvoti no longer had an estuary.......Dramatic changes in ecosystem structure, functioning and productivity have accompanied the chemical and physical changes in the system"

TABLE 6.1. Contemporary opinions on the state of the Mvoti river-mouth

The evidence presented in this chapter suggests that the Mvoti has been full of sediment for some considerable time. Even had the volume of sediment in the river-mouth been less and the entire floodplain lower in the recent past, the fact that the mouth is located in the southern end of the barrier across a dolerite sill means that, except directly after floods when a northern breach occurs, the Mvoti river-mouth could not experience tidal incursion of seawater. Thus its apparent loss of estuarine characteristics cannot be ascribed to increased siltation.

The perceived "rise in bed level" related to several authors (Begg, 1978, Badenhorst, 1990) by local farmers has been a function of changing channel morphology and a lack of understanding of the floodplain and channel as a single geomorphological unit. Under confined channel conditions with well-developed bank vegetation the channel would be deeper than with unconfined channel margins which permit braiding. The observed changes have been interpreted as a rise in bed level which gets worse with successive floods and have been blindly attributed to increased sediment yield from the catchment due to agricultural development (NRIO, 1983).

The conclusion that an increase in bar areas means siltation (NRIO, 1983) lacks an appreciation of the basic geomorphological processes which operate in the Mvoti. Geomorphological changes in the river-mouth indicate that it acts as a temporary storage area in which sediment slowly accumulates during minor floods and low flows. During floods this is eroded and sediment is deposited in the sea. The consequent increase in storage volume for sediment on the floodplain acts as a focus for fluvial sediment accumulation until another major flood occurs. Suspended sediment passes readily through the river-mouth into the sea, frequently producing a turbid plume in the ocean. It does not appear to accumulate in the river channel. Thus any increase in sediment yield from the catchment would not impact on the river-mouth which is full of sediment, but would instead pass through the river channel and produce higher sedimentation rates in the sea. Along the high energy Natal coast where the continental shelf is narrow, and swept by the Agulhas Current (Flemming, 1981; Flemming & Hay 1988) fine sediment accumulates seaward of the shelf break (Martin, 1984; Goodlad, 1986). A marked increase in modern sedimentation rates compared to geological rates has indeed been documented there and attributed to human activities in the river catchments (Martin, 1987).

In the absence of this scapegoat the validity of the evidence relating to the alleged loss of estuarine characteristics in the Mvoti river-mouth must be questioned. The evidence cited arises from the salinity structure and biological community compared to other Natal estuaries Begg (1984a,b). It has been shown above that the salinity structure results from the unusually shaped dolerite sill across which the outlet flows, and as the dolerite sill has not changed in historical times, this must be discounted as a reason for environmental change. Therefore, all evidence for a loss in estuarine function relates to Begg's biological sampling. In this regard two points are relevant: firstly, Begg's (1984a) sampling of the river fauna was restricted to a single method which is known to be selective (Begg, 1984a) and secondly, he sampled following a prolonged dry period when the aquatic community may have been impoverished. Thus his sampling was inadequate. More adequate sampling using a variety of gear types (Ramm *et al* ., 1986; Harrison *et al.*, 1989) has shown that juvenile marine fish use the Mvoti river-mouth and consequently it cannot be said to lack a biological nursery function. Therefore, historical reports of mullet, an estuary-dependant marine fish, (Wallace *et al.*, 1984) being caught in the Mvoti are not at odds with the modern situation: large numbers of mullet were netted by Ramm *et al.* (1986) and Harrison *et al.*, (1989). Others (Johnson, 1990) have accepted the nursery function but assume that tidal incursion of sea-water is necessary for such utilisation.

Harrison & Cooper (1991) showed that juvenile mugilids could enter Natal estuaries against strongly outflowing water and were not dependent on flood-tidal currents for recruitment and Wallace & van der Elst (1975) noted that juvenile marine fish could be carried into estuaries by overwashing water. Thus, in a biological sense, the Mvoti fulfils an estuarine function and cannot be said to be degraded. "Degradation" implies a better state in the past and, as it has been shown above that the Mvoti has historically flowed across the dolerite sill and was consequently freshwater-dominated, it cannot have experienced degradation at present sea-level. The Mvoti may even qualify as an estuary geomorphologically according to Cameron & Pritchard's (1963) definition because it is a semi-enclosed basin which has a free connection with the open sea, (albeit a one-way connection) and it contains seawater measurably diluted by water from land drainage. The unusual fact is that freshwater is dominant but nonetheless seawater is introduced by overwash and is measurably diluted. In terms of hydrology, however, the Mvoti does not display estuarine circulation and therefore remains something of an enigma.

6.7. HOLOCENE EVOLUTION OF THE MVOTI RIVER-MOUTH

The channel of the Mvoti river-mouth was incised into Pietermaritzburg Formation shales during lowered Pleistocene and probably Tertiary low sea-levels. Unfortunately little evidence is available regarding the size and shape of the bedrock channel. Four kilometres from the coast, boreholes revealed the bedrock channel close to -27 m MSL. At this location the floodplain is 400 m wide. The floodplain width/maximum bedrock depth ratio is therefore 14.8. Jex reported that investigations for a nuclear power station in the vicinity were abandoned after it was found that the depth to bedrock on the lower floodplain was in excess of 50 m (Begg, 1977).

The modern Mvoti river-mouth is in a mature state, having filled its former valley to attain grade with the sea-level and river gradient. During the Holocene Transgression it was, in common with other estuaries along the Natal coast, probably confined behind a transgressive barrier, which rolled over as it translated onshore across the shelf. Whether sedimentation in the river kept pace with rising sea-level is uncertain because no cores are available from the floodplain. Descriptions of cores from the N2 roadbridge (Orme, 1974) make mention only of sandy sediment throughout the cores. The more subdued relief on the continental shelf compared to the modern coastline (Fig. 6.14) suggests that at lower sea-levels several rivers could have discharged into each of several large back-barrier lagoons, whose storage capacity would have been much greater than that of present estuaries which are confined to river valleys. In such a scenario, sedimentation probably did not keep pace with sea-level and consequently relatively deep lagoons with fine-grained sediment may have formed. The steep nearshore gradient landward of the 50 m isobath probably accelerated the rate of translation of the barrier under transgression and sedimentation may then also not have matched transgression.

If a deep water period had occurred during transgression, it is likely that some muddy lagoonal or estuarine deposits would have accumulated. The fact that the barrier enclosed a river valley may have allowed a period when fluvial aggradation in the form of a bayhead or estuary head delta, had not proceeded to the barrier, in which case a lagoonal phase would have occurred. Any lagoonal deposits from this period would be located seaward of the N2 roadbridge cores, under the present floodplain which has not been cored.

Once the river did fill, the barrier which hinges between rocks on the south side of the valley and others at Blythedale Beach could receive additional sediment during episodic floods. The wave climate would not have changed appreciably and consequently the barrier position must have remained relatively constant since sea-level stabilised. Sediment delivered to the coast in excess of barrier requirements would have been reworked offshore to the shelf and onshore to form dunes. The forested dune to the north of the river-mouth is a precipitation dune, which, from its location, probably originated from excess sand blown from the Mvoti barrier. The fact that it is not currently active suggests it may relate to the Holocene highstand. Foredunes which have been deposited and eroded in front of it periodically since 1937 relate to modern day processes. Periodic floods inhibit the formation of dunes on the river-mouth barrier itself. The lack of highstand deposits in the floodplain may be attributed to flood erosion in the ensuing 5000 year period. It is interesting to note that during a highstand the Mvoti outlet would have been sufficiently deep over the dolerite sill to permit tidal exchange and consequently the Mvoti may have had estuarine circulation at that time. The hydrology may also have been different in the past when at lower sea-levels the outlet was not located across a shallowy shelving rocky outcrop. At such times an estuarine circulation could have developed with a flood-tidal delta.

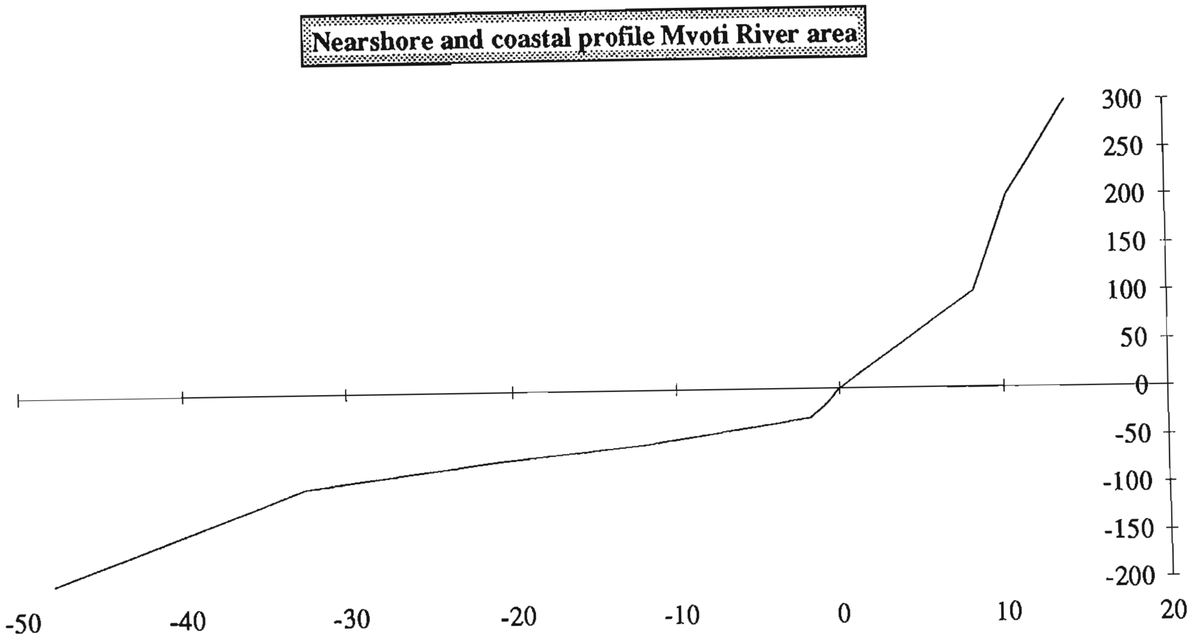

Fig.6.14. Coastal and nearshore profile at the Mvoti mouth. Note the reduction in gradient on the continental shelf below 50 m deep.

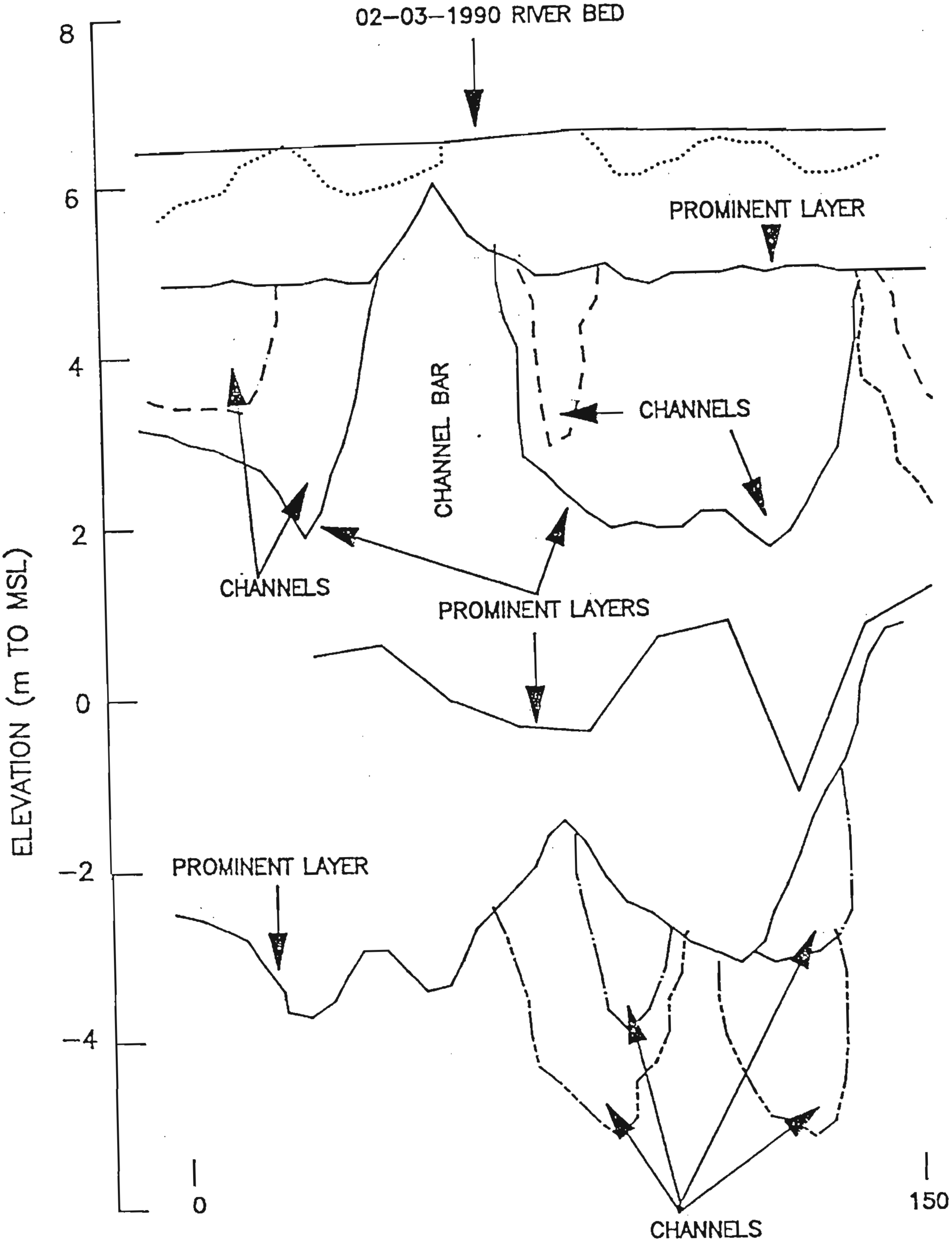

Fig.6.15. Seismic cross-section at Profile 5 (location on Fig.6.11) after Badenhorst (1990). The labels are those shown by Badenhorst (1990). The channel dimensions are inconsistent with modern conditions in the river-mouth.

Lamprecht (personal communication, 1991) has surveyed several seismic lines across the Mvoti River to depths up to 20 m but the results have not yet been analysed or made available for study. A single published 150 m-long seismic profile (Badenhorst, 1990), from upstream of the N2 roadbridge, penetrated through a 10 m sediment thickness (Fig.6.15). This revealed a number of low relief sediment bodies which are interpreted as channel bases and channel bars. Some profiles suggest that these former channels were 50 m wide and up to 2.5 m deep while others were as narrow as 15 m and 2 m deep. Such channels are not consistent with those observed at present and suggest some environmental change. The channels may relate to a different sea-level when the outlet was not located against the dolerite sill across which it flow presently. A tidal prism and associated tidal currents would have more scouring ability than the present low-discharge river flows and could downcut the inlet channel to produce lower channel bases upstream. Having previously noted the volume of sediment transported during a flood and the geomorphological processes and channel forms of the Mvoti river-mouth it is difficult to accept the alternative suggestion (Badenhorst, 1990) that these channels represent the Mvoti River about the turn of the century before increased siltation filled the channel. The channel dimensions indicated in the seismic profiles must relate to a different set of environmental variables with greater discharge, tidal exchange and/or different sea-level, either slightly higher or lower than present.

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CHAPTER 7.

VARIATION IN RIVER-MOUTH MORPHOLOGY: COMPARISON OF CASE STUDIES AND OTHER RIVER-MOUTHS IN THE STUDY AREA

7.1. INTRODUCTION

The preceding chapters illustrate the variation in morphology and sedimentology of only four of the sixty-four river-mouths in the study area. While they were selected to cover a representative range of morphologies they are by no means all-embracing. The aim of this chapter is to compare the river-mouths in the previous four chapters and, by reference to published and unpublished accounts and observations, to assess their morphological variation in relation to other river-mouths in the study area. Finally reasons are sought for the differences in morphology and process.

7.2. OBSERVED MORPHOLOGICAL VARIATION

7.2.1. Channel form

The Mtamvuna river-mouth has the deepest channel of the four case studies. The channel is confined between steep rocky or muddy banks and has near-vertical sides (Plate 7.1). It is bottomed by soft muddy sediments. The channel path is controlled by the limits imposed by the cliff-confined valley. Under mature, stable conditions, the Mgeni river-mouth channel is confined between cohesive muddy banks and is comparatively deep (2-3 m). Its central vegetated island, which also has cohesive muddy banks, causes flow separation and channel bifurcation in the river-mouth within the confines of the modern floodplain limits (Plate 7.2). After major floods, the Mgeni channel becomes shallow and sandy with intertidally-exposed bars (Plate 7.3).

The Mvoti river-mouth channel is typically slightly sinuous and shallow, with braid bars exposed subaerially at low flows (Plate 7.4). Its sandy banks enable braiding but the sandy channel sediment does not favour island stabilisation or major channel bifurcation, even on the broad floodplain. In the Mhlanga river-mouth, the sandy-bottomed channel is mainly confined between muddy banks and when no outlet is present, water depths locally reach 3 m. When the barrier is breached much of the channel is exposed subaerially (Plate 7.5). The Mhlanga river-mouth channel (Plate 7.6) is not sufficiently sinuous for formal classification as meandering but it is much more sinuous than the other case studies.

This range of channel morphologies appears to be broadly representative of the range observed in most river-mouths in the study area, however, several variations do occur.

Bedrock valleys similar to the Mtamvuna river-mouth are widespread, particularly among small river-mouths (Plate 7.7) in the granitic coastal terrain in the south of the study area. In them channel shape is controlled by the confining rocky margins. Their frequent association with granitic terrain and Natal

Plate 7.1. The Mtamvuna river-mouth channel is confined between steep rocky banks and has a deep channel, whose plan morphology is controlled by the surrounding bedrock.

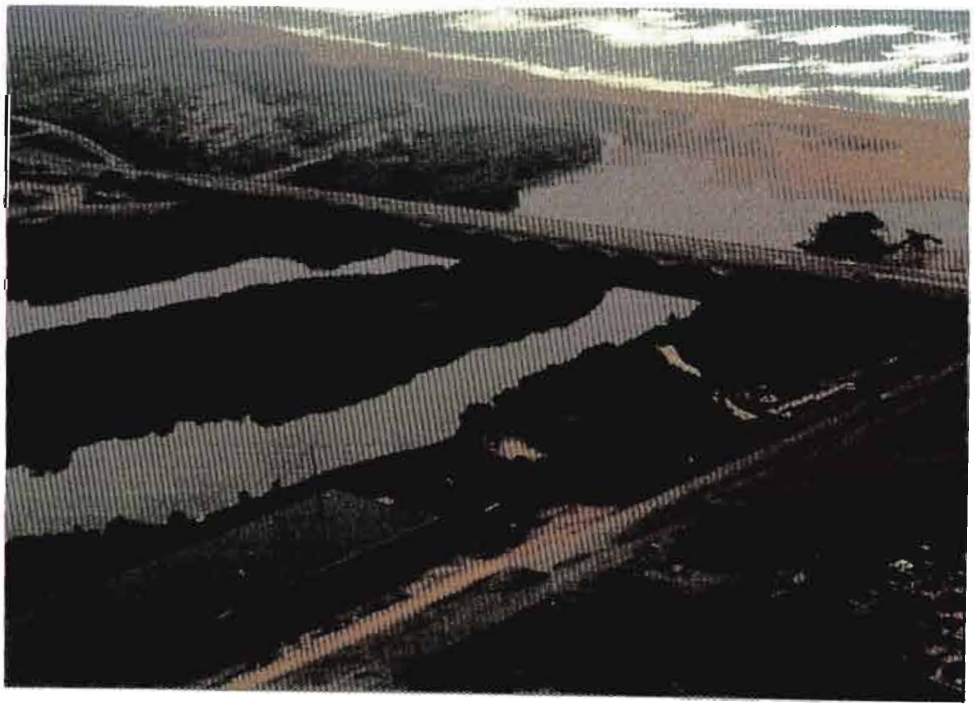

Plate 7.2. Under mature stable conditions the Mgeni river-mouth has confined relatively deep channe with few intertidally-exposed areas. The alluvial floodplain to the south comprises cohesive mud deposits while bedrock outcrops along much of the northern bank .

Plate 7.3. After floods the Mgeni regains a shallow sandy morphology with large intertidally exposed areas. This may be attributed to non-cohesive sandy sediment in the channel.

Plate 7.4. The Mvoti river-mouth commonly has a braided channel as a result of the sandy channel sediment and sandy floodplain.

Plate 7.5. After breaching much of the sandy bed of the Mhlanga river-mouth is exposed subaerially.

Plate 7.6. The sinuous channel of the Mhlanga river-mouth across the floodplain is confined by cohesive muddy banks. When the barrier is sealed, water depths reach 3 m in places.

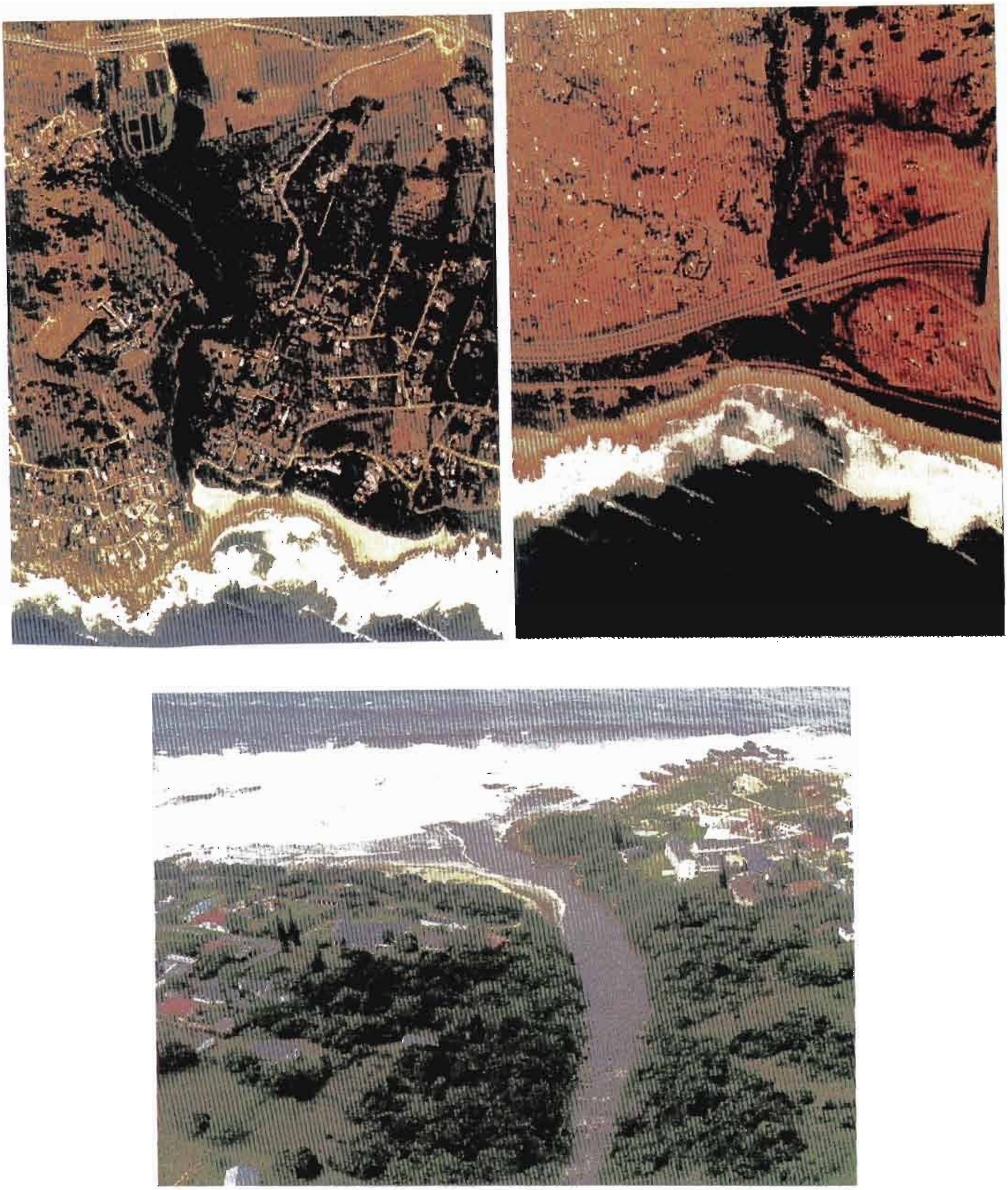

Plate 7.7. Bedrock-confined valleys typify small rivers cut into resistant lithologies. The examples illustrated are the Tongazi (top left), whose bedrock channel is confined behind a concave barrier located in a small embayment; and the Mnamfu (top right) whose bedrock channel reaches the coast behind an elongate barrier. This enables limited coast-parallel channel extension of the river-mouth channel. The lower photograph is an oblique view of the Tongazi river-mouth in flood, looking seaward.

Group Sandstone, suggests a bedrock influence on this channel type, possibly through exploiting vertical weaknesses (joints or faults).

Several river-mouths whose channels are confined between cohesive muddy banks lack central islands like that in the Mgeni. The Mkomazi (Plate 7.8) which has a similarly wide floodplain and cohesive channel banks, contains no island in its straight channel. This may be attributed to the river orientation at the head of the river-mouth area which promotes scour against a rocky bank.

Many small river-mouths such as the Zotsha and the Kaba which are generally closed, do not completely drain after breaching. This level to which water levels can fall appears to be influenced by rock outcrops under the breached outlet position which act to dam outflowing water at a specific level. This is well illustrated by the Kaba (Plate 7.9) where granite outcrops and boulders in the breached outlet hold back outflowing water and retain water in the river-mouth.

An additional channel form, not seen in the case studies, occurs in several small river-mouths including the uMgababa (Grobbler *et al.*, 1987) and Sezela (Plate 7.10) (Ramm *et al.*, 1986). In them the main channel is joined by a number of small tributaries on the coastal floodplain, producing a dendritic type of channel pattern. These channels are found only on wide floodplains with cohesive muddy sediments. Their origin is tentatively compared to that of the gullies produced at the Mvoti river-mouth after overbank flows intersect deeper water, causing headward erosion across the floodplain.

Based on the above comparisons and observations, river-mouth channels in the study area can be broadly divided into alluvial and bedrock channels. Bedrock-confined channels occupy the entire river valley and their plan shape is mainly controlled by the surrounding bedrock. Alluvial rivers have a greater degree of freedom to respond to hydraulic variables which influence their channel morphology and are as Leopold & Langbein (1962) noted, “authors of their own geometries”.

Alluvial rivers in the study area take many forms: braided; straight; sinuous; meandering; dendritic; and bifurcating. The controls on these channel types are unclear. Channel form in alluvial rivers is governed by a variety of factors (Mangelsdorf *et al.*, 1990) (Fig.7.1). The relationships between various factors have been investigated extensively for various channel types (Gregory & Walling, 1973). Braided and meandering channels may be distinguished on the relationship between channel slope and bankfull discharge (Leopold & Wolman, 1957) or between channel width and discharge (Ackers & Charlton, 1970). Whether these characteristics of various channel types are a cause of, or simply result from, a particular channel type is of vital importance.

Braids tend to develop in deposits coarser than those supporting meanders (Tanner, 1968) (Fig.7.2) and bedload is an essential prerequisite. Tricart & Vogt (1967) suggested that a combination of coarse sediment grainsize and irregular streamflow was essential for braiding. Braided rivers are also characterised by a distinct lack of well-developed river bends and are more commonly developed where bank material is uncohesive (Leopold *et al.*, 1964; Gregory & Walling, 1973).

Plate 7.8. The Mkomazi river-mouth, which resembles the Mgeni in its dimensions, has no central island in its channel, a fact which may be attributed to bedrock controls on channel orientation upstream.

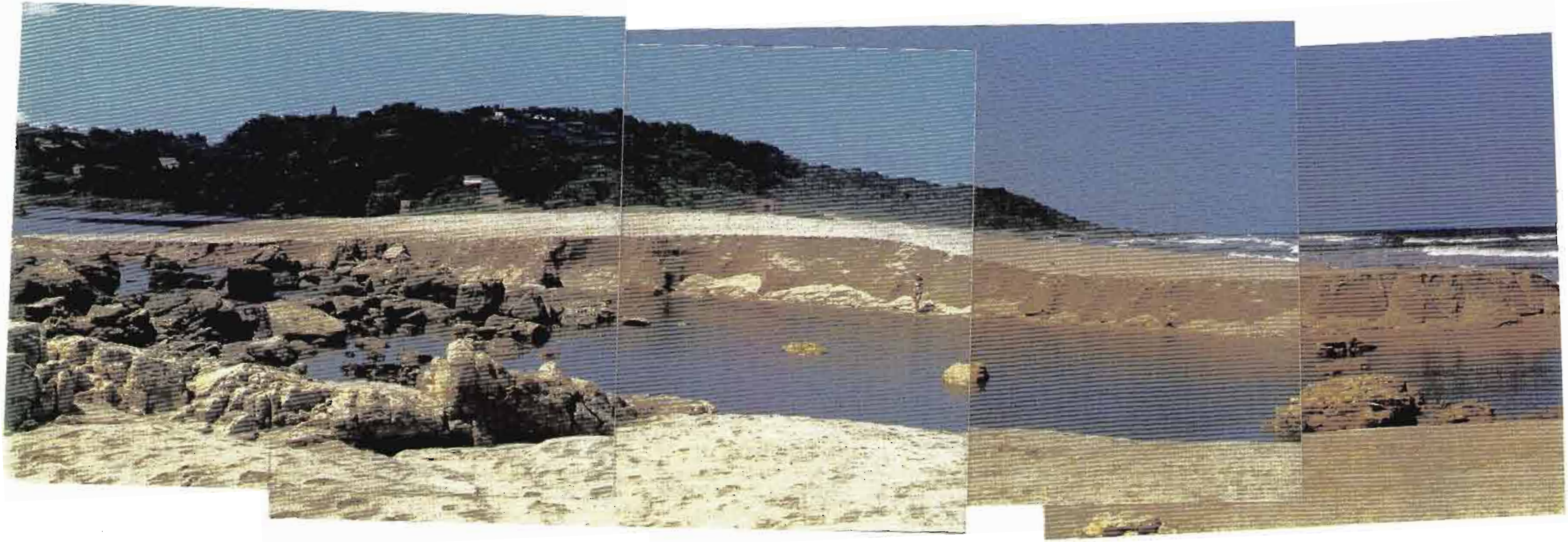

Plate 7.9. A photomosaic of the breached outlet of the Kaba river-mouth. The internal barrier structure is clearly visible. Bedrock outcrops and large boulders in the outlet channel prevent the channel from draining when it breaches by setting a lower limit to which water levels can fall.

Plate 7.10. The dendritic channel pattern of the Sezela may have arisen through gully erosion across the muddy floodplain. This type of pattern is apparently restricted to wide, mud-rich floodplains.

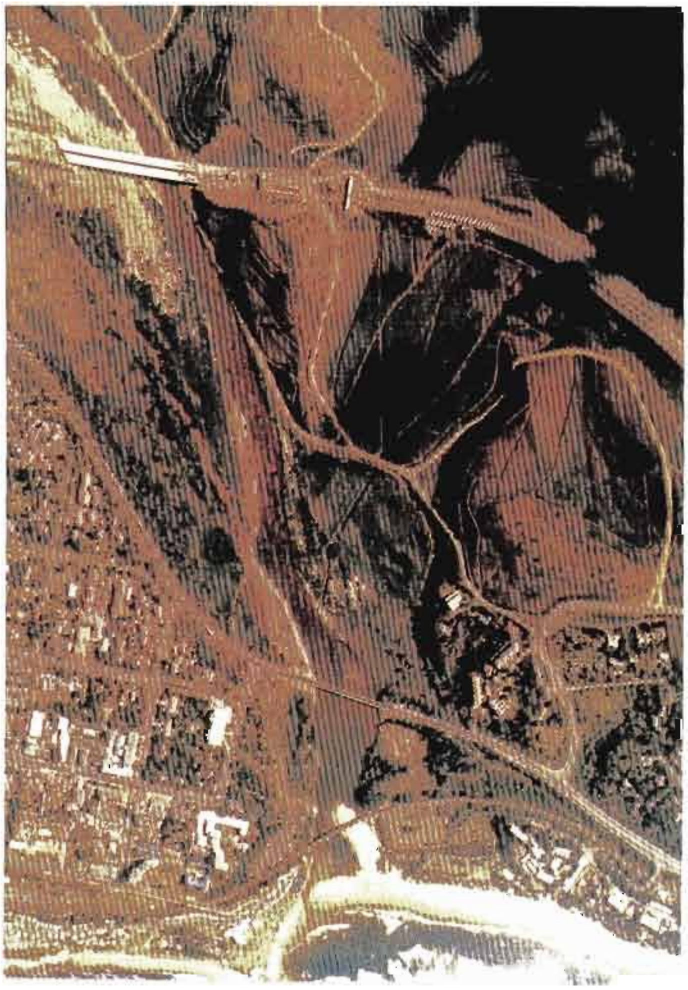

Plate 7.11. The Mpambanyoni river-mouth exhibits a braided channel pattern as a result of coarse-grained sand and gravel supply from upstream.

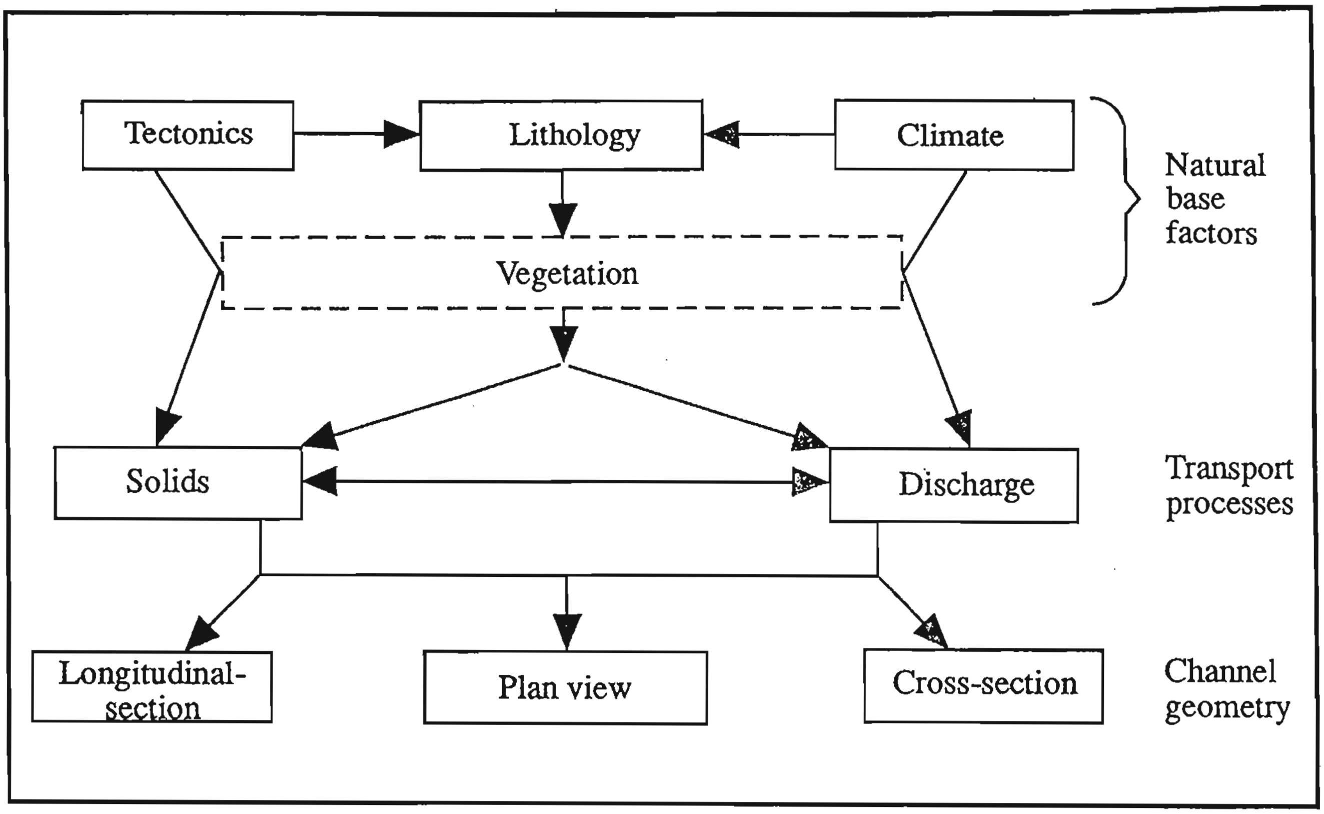

Figure 7.1. Controls on the morphology of river channels (after Mangelsdorf *et al.*, 1990).

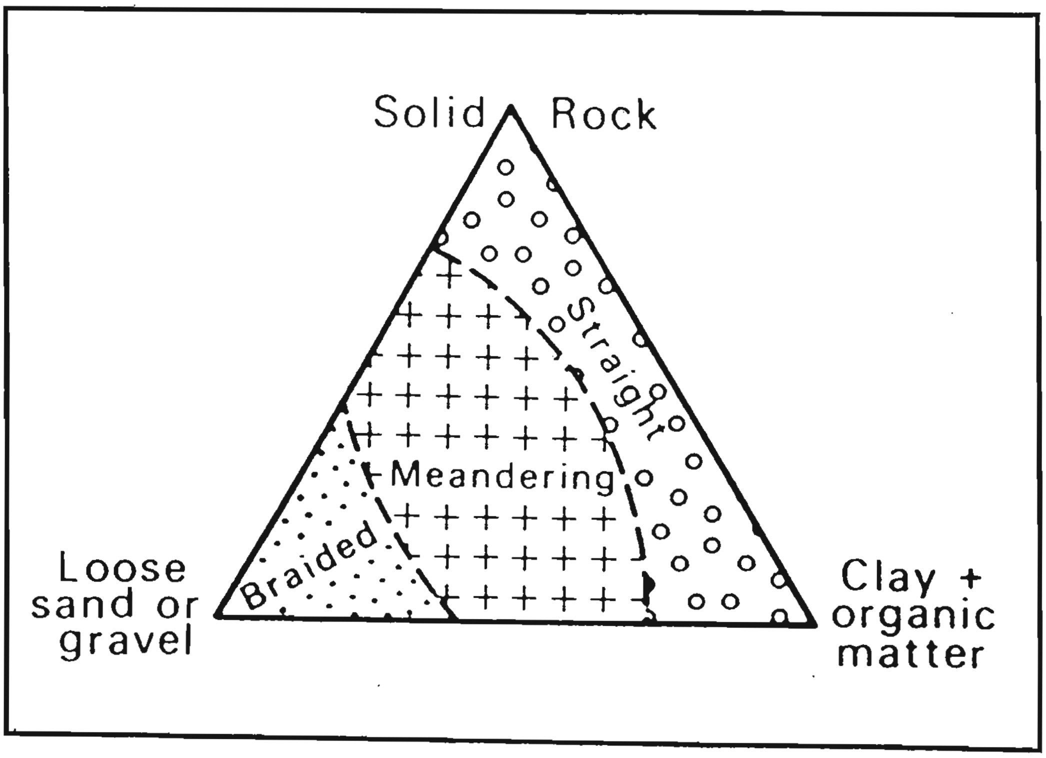

Figure 7.2. Relationship of locally-available material to channel type in rivers (after Gregory & Walling, 1973, originally after Tanner, 1968).

Langbein & Leopold (1966) concluded that a meandering pattern was the most probable form that a river would take and one in which the river does least work in turning. Subsequently Yang (1970) found that meandering offered a mechanism to adjust channel slope to maintain quasi-equilibrium with minimum energy expenditure. Ackers & Charlton (1970) indicated that there is a threshold rate of sediment load below which rivers meander. Meandering channels can often be shown to occur on lower angle slopes than those of braided reaches with similar discharge characteristics (Leopold *et al.*, 1964).

The size of meanders has been linked to catchment area and stream discharge (Gregory & Walling, 1973). Schumm (1967) found that meander wavelength also depended on the type of sediment moving through the channel: meander wavelength of rivers transporting sand and gravel is greater than that of rivers transporting silt and mud.

A common thread to most assessments of alluvial channel form is the grainsize of the transported load and nature of the banks and this may well be one of the most important factors in the study area. The preceding chapters showed the tendency of both the Mvoti and Mgeni river-mouths to braid after floods when the banks comprised uncohesive sandy sediments and to change to a deeper, confined channel when bank cohesion was regained. In these and other braided river channels such as the Matigulu, Tugela and Mpambanyoni (Plate 7.11), abundant sandy sediments are supplied from granitic rocks upstream.

7.2.2. Floodplain morphology

River-mouth floodplains are the elevated areas on the surface of formerly incised, and now sediment-filled, bedrock channels that are not normally occupied by flowing water. The size and shape of study area floodplains varies greatly. Bedrock-valley-confined rivers such as the Mtamvuna have little or no floodplain while the Mvoti floodplain, which is over 1000 m wide at the coast, narrows rapidly upstream, producing a funnel shaped basin. The Mhlanga river-mouth maintains a nearly constant 200 m-wide floodplain for over 1 km upstream. The modern Mgeni floodplain has an irregular plan shape which narrows and widens upstream, apparently in response to changes in the surrounding geology.

The four case study rivers vary greatly in discharge, which through its control on bedrock valley erosion during incision during low sea-levels, ultimately plays an important role in controlling the floodplain morphology. As a generalisation larger-catchment rivers have larger floodplains but there are noteable exceptions. The floodplain of the 37 km^2-catchment uMgababa River (Grobbler *et al.*, 1987) and the 20 km^2-catchment Sezela (Plate 7.10) is appreciably wider than floodplains of other rivers of similar catchment size such as the 16 km^2-catchment Mnamfu or 17 km^2-catchment Tongazi (Plate 7.7). The uMgababa and Sezela river-mouths are cut into shales of the Pietermaritzburg Formation which are easily erodible and this appears to have enabled formation of wider floodplains than in river-mouth valleys incised into resistant rocks.

In the Mgeni river-mouth, the floodplain is wide where it is underlain by Pietermaritzburg Formation shales but narrow where more resistant Dwyka Tillite and Karoo Dolerite outcrops. This, coupled with the other observations, suggests that bedrock geology, and stream discharge are major controls on floodplain shape and size.

7.2.3. River-mouth barriers

The four river-mouths studied show marked variation in the position and morphology of their barriers. The Mvoti and Mtamvuna barriers are confined largely to the river-mouth valley, although in both cases the seaward barrier planform extends along the adjacent mainland shore. In both cases the barrier and mainland-attached sand body is positioned between two headlands (Plate 7.12), in a shallowly indented coastal embayment, forming a headland-bay sedimentary cell (Carter, 1988). Aeolian dune development on the Mtamvuna is restricted by periodic complete barrier erosion during floods. In the Mvoti the central portion of the long river-mouth barrier is sheltered from erosion by episodic floods and supports a small aeolian dune. Similarly confined embayment barriers are common in the study area (Plate 7.7).

The Mhlanga river-mouth is located behind an elongate straight barrier which stabilised seaward of the mainland shore (Plate 7.6). In this case vacant space behind the barrier enabled the river-mouth to extend its course in a coast-parallel direction, forming an elongate back-barrier section. The Mhlanga river-mouth barrier is therefore not solely confined to the river valley and does not occupy an embayment. It is a near-linear feature which rests on rock outcrops which maintain its position. The same rock outcrops enabled the barrier to stabilise in its present position and have prevented its landward retreat (Cooper, 1991b). Modern aeolian dune development on the Mhlanga river-mouth barrier occurs in areas which are not commonly breached. Beachrock formation under the Mhlanga barrier was apparently enabled by barrier stability and suitable groundwater chemistry. Other elongate barriers may extend across wide floodplains such as the Mahlongwa (Plate 7.13) and this supports extensive dune development. The long-term stability of the Mahlongwa barrier is indicated by the fact that a major road has been built along it.

The barrier of the Mgeni river-mouth forms part of a large-scale coastal sand body that extends over twenty kilometres from the Durban Harbour mouth to Umhlanga Rocks. In its undeveloped state it had a smooth seaward planform, approximating a zeta bay, apparently in equilibrium with approaching wave fronts. The Mgeni river-mouth was located behind a portion of this barrier. The barrier appears to have stabilised seaward of the mainland shore in response to a reduced bedrock gradient produced by the fortuitous local preservation of Cretaceous siltstones and overlying Pleistocene deposits. Its planform equilibrium is controlled by wave refraction around the Durban Bluff. This barrier is without parallel in the study area but the Bay of Maputo in southern Moçambique exhibits a similar structure.

These barriers cover the full spectrum of variation in the study area south of the Tugela river-mouth. There are many combinations of the types described above: some small barriers have no aeolian

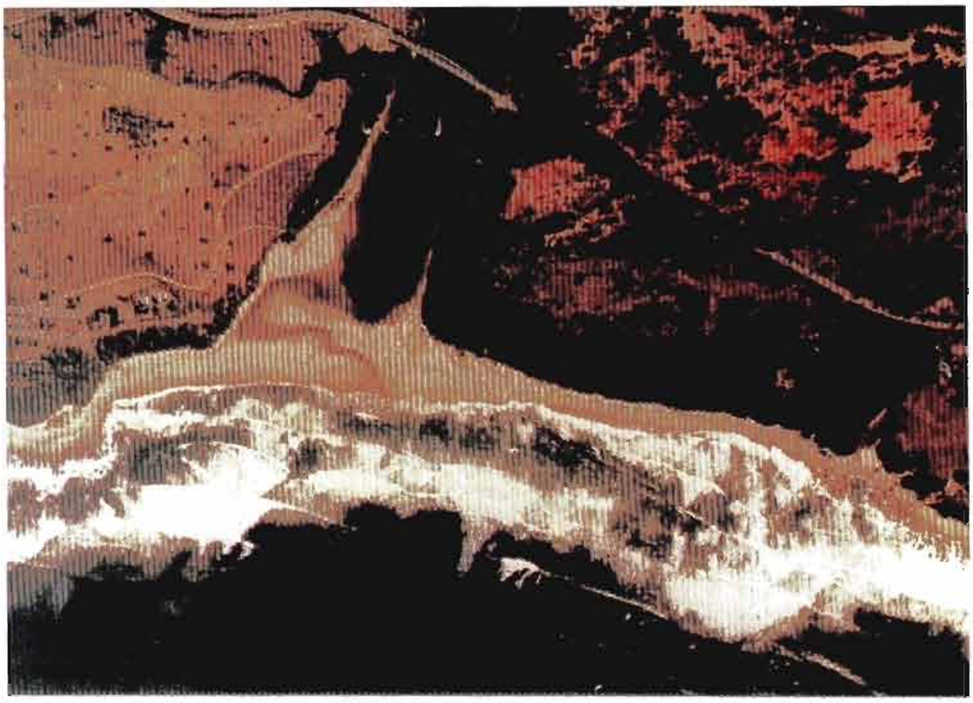

Plate 7.12. Detail of the headland-embayment cell at the Mtamvuna river-mouth. The barrier is located in a shallowly embayed area bounded by rocky outcrops to north and south. This type of coastal cell is common in the study area and must limit longshore transport.

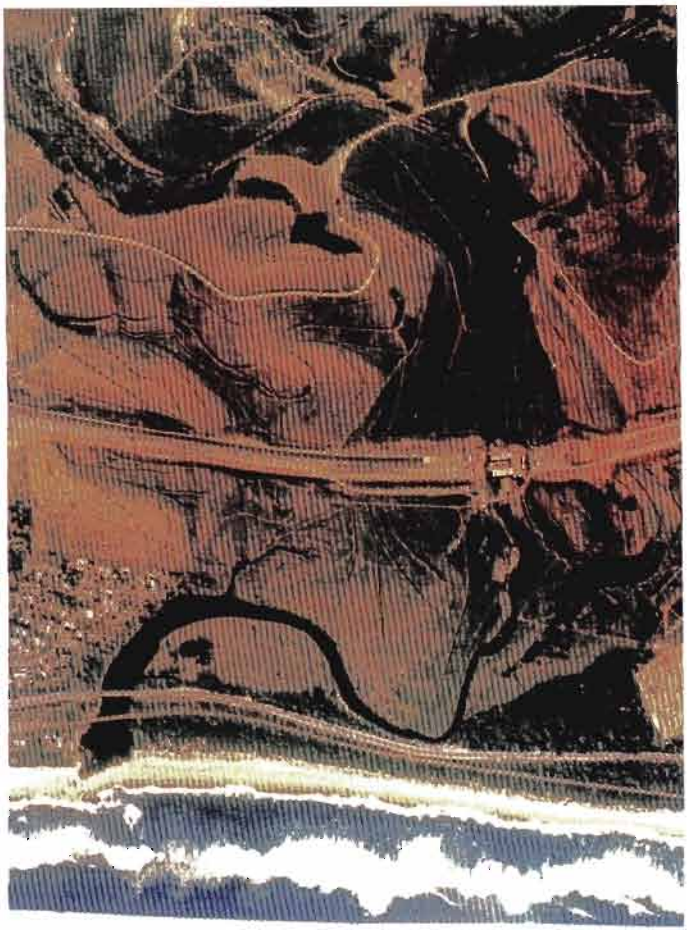

Plate 7.13. The channel of the Mahlongwa river-mouth is elongated across its floodplain, behind a barrier whose stability is indicated by the presence of a thickly vegetated dune. The road which crosses the dune crest was sited there in view of the long-term barrier stability.

component while others are almost entirely covered with vegetated aeolian dunes. Barriers located on top of rocky outcrops may limit the level to which water levels may fall and enhance scouring of outlets while others are completely sandy and water drops to lower levels. Beachrock formation in barriers is determined by barrier stability. The lack of beachrock in barriers in the southern part of the study area also implies a climatic control: it appears that modern conditions in the study area are only marginal for beachrock formation.

North of the Tugela river-mouth several rivers reach the coast behind a prograding coastal beachridge plain. Beachridge growth is sustained by sediment derived from the Tugela River. This beachridge plain is prograding at rates up to 5 m/year (Cooper, 1991a) and as it does so, is diverting the courses of the rivers behind it. This has resulted in:

a) some small streams discharging underground;
b) elongate coast-parallel river courses;
b) the capture of the Nyoni River by the Matigulu (Begg, 1978); and
c) the northward extension of the Mlalazi river-mouth (CSIR, 1991).

Barrier morphology is apparently controlled by nearshore topography. This determines where transgressive barriers stabilised. It also controls the historical and modern wave-refraction patterns which influence barrier location and stability. Many of the bedrock-confined river-mouths do not exhibit aeolian dune development due to the complete erosion of their short barriers during floods. Consequently, barrier length in relation to the erosive power of river floods is a further important control on barrier facies. A final factor influencing barriers appears to be sediment supply: only north of the Tugela is sediment supply sufficient to promote modern barrier progradation.

7.2.4. Outlet presence and form

The presence or absence of an outlet exerts a vital influence on sedimentation and water chemistry and biology of river-mouths. Of the four case studies examined, the three largest commonly have an outlet to the sea, which suggests a strong fluvial discharge control on outlet maintenance. The Mgeni and Mtamvuna river-mouths experience tidal exchange and flood-tidal sediment transport through the outlet as the channel base is below sea-level. The Mvoti, however, does not experience tidal exchange because of the elevated rock outcrop beneath its outlet channel. The Mhlanga river-mouth breaches occasionally and drains as its channel cuts into the sandy barrier below sea-level. Rocks under the barrier are not continuous and so during brief open periods salt water may enter the river-mouth through the outlet. These outlet types span most of the variation observed.

The type and presence of an outlet appears to be controlled mainly by catchment size and discharge in relation to seepage through the barrier, but outlet presence is enhanced where rocky outcrops promote turbulent flow and scour. The nature of the outlet is dependent on the level to which it can drop and in many cases this is limited by bedrock.

7.2.5. Sediment

In the case studies examined sediment provenance and grainsize varied temporally within a single river-mouth and from one river-mouth to another. Sediment in the Mtamvuna river-mouth derived from the catchment, from adjacent cliffs and from the sea. The Mgeni river-mouth contains sediment from the sea and the catchment but the marine component is much less important than in the Mtamvuna. The Mvoti receives sediment from the catchment and the marine component is limited to localised barrier washover fans. The Mhlanga is also dominated by fluvially-derived sediment but receives minor inputs from barrier overwash and bank erosion.

Sediment texture in the Mtamvuna exhibits a clear tripartite division into sand-dominated upper and lower reaches with muddy sediments in the deep middle reaches. In the Mgeni and Mvoti river-mouths sediments are sandy to gravelly and in the Mhlanga river-mouth fine-to medium sand dominates. Clearly sediment texture and provenance in these case studies is not solely discharge controlled, as the Mtamvuna is more muddy than the Mhlanga, despite having a larger catchment. The gravelly sand of the Mvoti and Mgeni is due to the presence of a suitable upstream source (weathered granitoid metamorphic rocks) and the ability of the river to transport it. The Mtamvuna, although it has the capacity to transport such sediment, has no suitable source. Because its catchment is dominated by tillite and shale, it yields mainly fine-grained sediments. The Mhlanga River does not have the capacity to transport coarse-grained sediment (Cooper, 1989) and also lacks a suitable source of such sediment. Consequently its channel contains mainly fine to medium-grained sand.

Comparison of these case studies suggests that catchment geology, coupled with river discharge characteristics are the main factors controlling sediment grainsize in river-mouths in Natal. Certain river-mouths (Mhlanga, uMgababa) which temporarily accumulate fine-grained sediments in their channels do not retain them (Cooper *et al.*, 1988) but flush them to sea when breaching occurs. Organic deposits in river-mouths suffer a similar fate, unless they are mixed with underlying sediment by infaunal organisms. The range of sediment grainsizes encountered in the case study river-mouths appears to be representative of all river-mouths in the study area.

7.2.6. Flood response

Response to major floods varies greatly between the four case studies. In the Mtamvuna river-mouth flood impacts were restricted to the barrier and flood-tidal delta because the great water depth inhibited downward effects and the bedrock-confined channel prevented lateral erosion. Post-flood barrier reconstruction was accompanied by landward barrier transport and flood-tidal delta progradation which is enabled by relatively deep water in the back-barrier area.

In the Mgeni river-mouth major floods cause downward channel erosion in the narrow sections of the floodplain, particularly adjacent to bedrock outcrops. Floodplain erosion is limited to areas where downward scour is limited by bedrock outcrop (Cooper *et al.*, 1990). Post-flood channel adjustment takes place mainly through vertical accretion but limited eroded floodplain sections accrete laterally.

Barrier reconstruction through landward transport of eroded sand is comparatively rapid. The shallow back-barrier river channel limits flood-tidal delta progradation in comparison to the Mtamvuna.

Major flood response in the Mvoti river-mouth takes the form of lateral erosion. The wide floodplain permits bank erosion in preference to downward scour. Consequently lateral expansion, sometimes accompanied by bed aggradation, accommodates increased flood flows. Overbank deposition is more widespread on the large Mvoti floodplain than on the restricted floodplains of the Mgeni and Mtamvuna. Post-flood channel recovery occurs through lateral accretion and bank stabilisation, rather than by vertical accretion as in the Mgeni. Barrier reconstruction produces more spectacular emergent deltas, probably in response to a shallower offshore gradient (Cooper, 1990d) but flood-tidal deposition is prevented by the rock-based outlet channel.

Flood response in the Mhlanga river-mouth is less marked and results in the scour of only fine-grained sediments from the back-barrier, without significant depth increase. A similar response was noted in the uMgababa (Grobbler, 1987; Grobbler *et al.*, 1987; Cooper *et al.*, 1988). This may be attributed to lower peak discharge in small catchment rivers which consequently have less erosive capability. Barrier erosion is limited to the breached area and post-flood barrier recovery takes place through outlet channel elongation in the direction of dominant wave approach until stream competence drops below the ability of overwashing waves to close the breach.

A much greater morphological response to lesser floods of 1976 and 1984 was apparent in vertical aerial photographs of the Mvoti than in the Mgeni. This is because of the wider floodplain, uncohesive floodplain sediments and the ability of the channel to avulse and laterally erode within a much greater margin of variation. Horizontal channel changes are, however, much more apparent on aerial photographs than vertical changes.

In the Mgeni river-mouth erosion of muddy estuary banks and coarse-grained channel sediment only occurs during high discharges associated with catastrophic floods. Non-cohesive sand in the flood-tidal delta and sandy barrier is eroded and re-deposited during lower magnitude seasonal floods.

Under high discharges river-mouths generally follow one or a combination of the following responses:

a) gradient is increased by taking a shorter course through the barrier;
b) gradient is increased by scouring at the downstream end;
c) channels expand by vertical erosion;
d) channels expand by lateral erosion;
e) sediment is eroded until the remaining lag grainsizes exceed the transport capacity of outflowing water;
f) overbank flow accommodates increased discharge without associated erosion.

Under low discharge river courses lengthen to reduce channel gradient either by meandering or by elongating behind the barrier or by depositing sediment at the downstream end. If back-barrier channel extension is insufficient to reduce energy expenditure, then the channel will tend to become sinuous across the floodplain as well. If neither of these options are available through bedrock constraints on the channel and lack of coast-parallel extension, then the river-mouth will probably maintain an outlet.

Flood response in Natal river-mouths is influenced by the magnitude of the flood which depends on the catchment size and amount of precipitation. Consequently, floods in small catchment rivers effect fewer changes than those in large-catchment rivers for equivalent rainfall. In addition flood response in large catchment rivers, is mediated by water depth, which determines the capacity of a river-mouth to absorb flood discharge and floodplain width which induces either downward scour (narrow floodplains) or lateral channel expansion (wide floodplains). There may be an additional grain-size control on this process, because if a floodplain consists of non-cohesive sand covered protected by only a thin vegetation cover, it may be more easily eroded than coarse-grained channel base sediments. A muddy floodplain, however, will be more erosion resistant than coarse-grained fluvial sand in a river channel and such a situation would favour downward scour in the channel.

7.3. DISCUSSION: PROBABLE CONTROLS ON MORPHOLOGICAL VARIATION.

In the preceding comparison of river-mouth morphology, several common factors emerged. Most of the differences can be at least qualitatively related to variations in catchment size, river-mouth geology, coastline type, and catchment geology.

Catchment size appears to control discharge and the sediment transporting capacity of rivers and so influences sediment yield. The size of a catchment also sets a limit on the flood peak for any given rainfall and in this way determines flood discharge and geomorphological response in a river-mouth.

The surrounding river-mouth geology in combination with catchment size exerts an important control on floodplain morphology and channel type, both of have been shown to influence flood response and sedimentary processes in the river-mouths studied. For a given catchment size, wider floodplains tend to be associated with softer lithologies while more resistant lithologies are dissected by steep bedrock valleys.

Catchment geology exerts a control on sediment type in certain river-mouths. The Mtamvuna, which has the capacity to transport coarse sand and gravel downstream lacks a source for such sediment and so is mainly muddy and deep in its middle reaches. Sediment grain-size in the Mvoti and Mgeni, however, is strongly influenced by the upstream proximity of gravel and coarse-sand yielding rocks of the Natal Structural and Metamorphic Province. The lack of very fine-grained sand in the Mhlanga was also linked to lack of a suitable source in the catchment (Cooper, 1987, 1989). The depth of the Mtamvuna river-mouth may also be linked to low yield of sedimentary grains of suitable size for deposition and retention in the narrow river-mouth channel.

Coastal morphology in each river-mouth area has a marked influence on barrier position and stability and this determines how river-mouth morphology develops in the back-barrier area. Coast-parallel channel extension or restriction are influenced mainly by barrier position. Nearshore topography in relation to the ambient wave field also influences river-mouth evolution by promoting barrier accretion, erosion or stability.

It therefore appears that these four factors: catchment size; catchment geology; river-mouth geology; and coastal topography, exert major influences on river-mouth morphology in the study area.

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CHAPTER 8.

A GENETICALLY-BASED GEOMORPHOLOGICAL CLASSIFICATION SCHEME FOR NATAL RIVER-MOUTHS

8.1. INTRODUCTION - WHY CLASSIFY?

A vast amount of morphological variation is evident in those transitional fluvio-marine environments which occur where a river discharges into the sea. The observed range of morphological variation may have little apparent order and the variety of forms necessitates classification. No two environments are, strictly speaking, identical although some differ only in minor respects. Others differ widely. The whole population of these landforms is too heterogeneous to enable generalisations to be made and similarly, one cannot speak in terms of individual fluvio-marine areas because they are far too numerous. To bring some order to the study of such a population it is essential to establish classes which subdivide the range of morphological variation. Such classes must group like individuals and separate them from unlike individuals and by so doing, reduce the number of entities to be comprehended. "Without classification one cannot hope to remember or manipulate the individuals or see relationships between them" (Van der Eyk *et al.*, 1969).

In Natal, a particular need for classification of river-mouths arises from the frequently expressed desire to return a coastal water body to its "pristine state". This implies the state which existed before human impacts and has often been used, as illustrated in the case of the Mvoti river-mouth (Chapter 4), to express the speaker's subjective estimate of what a river-mouth should be. If the basic controlling factors can be identified, then a scientifically-based assessment can be made as to whether or not a river-mouth is in a "pristine state", and if not, how it differs from it.

This chapter firstly sets out the rationale and outlines the importance of an effective river-mouth classification based on physical parameters. Existing classifications are then discussed firstly, on a global and then on a South African scale. Existing schemes are shown to be inadequate for application in the study area for various reasons. Finally, a genetically-based geomorphological classification of Natal river-mouths is presented.

Natal's steep and narrow hinterland is characterised by a high frequency of small river systems, which enter the Indian Ocean to form a large number of coastal water bodies. While these are typically small in area they display a wide range of morphologies. Previous attempts to classify Natal's river-mouths had the objective of measuring their present biological and physical state (Begg, 1984b; Perry, 1985b; Ramm, 1990). These approaches commonly lacked an appreciation of the inherent differences in processes between individual river-mouths, and took the broad view that each follows the same long term evolutionary sequence. This has led to the general assumption that shallow river-mouths are more "silted" than deeper ones. This ignores the fact that they receive different types of sediment from their catchments at different rates and that the receiving basins have different sizes and shapes.

The river-mouth channels show much morphological variation. Sandy river systems tend to form wide, shallow channels, while predominantly muddy rivers maintain a sinuous channel between cohesive muddy banks (Leopold *et al.*, 1964; Gregory & Walling, 1973). This is reflected in the extent to which a floodplain is present or whether the entire valley is occupied by water.

The aim of this chapter is to establish which factors are the most important in defining river-mouth morphology in Natal. In this way it may be possible able to predict the impact of changes in any of the controlling factors.

This chapter attempts to:

a) assess existing river-mouth classifications;
b) identify the genetic controls on river-mouth morphology in Natal;
c) classify each estuary into morphologically similar groups;
d) assess the relationship of Natal river-mouths to other environments in different settings.

Many of the problems of river-mouth classification and definition arises from the fact that "far more effort has gone into making studies of individual systems than into either comparing results from a variety of estuaries with similar physical and geological characteristics, or into critical evaluations of processes" (Emery & Uchupi, 1972; Schubel & Hirschberg, 1978). It is hoped that this chapter will provide a comparison of a variety of transitional fluvio-marine environments on both a global and regional scale and promote a broader understanding of the morphogenic controls.

8.2. TRANSITIONAL FLUVIO-MARINE ENVIRONMENTS

On a global scale a wide range of environments are associated with the mouths of rivers. Variations in climate, sediment supply, topography, river size, coastal morphology, rainfall/runoff, amount/regularity, tectonism, sea-level changes are but a few of the factors which govern morphology (Friedman & Sanders, 1978).

The most studied transitional fluvio-marine environments are deltas, estuaries and coastal lagoons. The problems of precise classification of these environments are well known and are frequently encountered in sedimentological literature. The term "estuary" is apparently the most enigmatic and most authors find it necessary to define what they mean by an estuary. Thus there is an abundance of definitions suited to the needs of the particular paper. Healey and Harada (1991) aptly summed up the problem of classification of estuaries thus: " they are rather like pornography, difficult to define but you know it when you see it". Thus the reason for use of the more generic term "river-mouth" throughout this thesis.

In the study area, estuary and lagoon are the most common locally applied terms used to describe these transitional coastal environments but as shown in the preceding chapter a wide range of variation in morphology and process is evident.

Transitional fluvio-marine environments vary greatly around the world's coastlines. The different environments associated with the mouths of rivers range between deltas, beachridge plains, chenier plains, estuaries, and coastal lagoons. Each has its own range of morphologies, sedimentary environments, facies architecture, and preservation potential in the geological record. As there are basic physical parameters which control the development of particular transitional fluvio-marine environments on a global scale, deltas, estuaries, river-mouths and so on must be seen as a continuum of morphological features. Friedman & Sanders (1978) proposed that mean concentration of suspended sediment is the differentiating variable between deltas and estuaries (<160 mg/l = estuary; > 160 mg/l = delta). They, however, suggest no reason as to why this should be so and list several exceptions. Estuaries are only one of a number of transitional marine/terrestrial environments which are difficult to define rigidly. All are affected to varying degrees by fluvial and marine inputs, and occasionally aeolian inputs (Reddering & Esterhuysen, 1981). Fluvial inputs themselves may influence the adjacent coastal morphology (Cooper, 1991a) and so there is an interplay between the various inputs.

What is required is a basic definition which recognises the range of genetic factors controlling the morphology of these transitional landforms. The limited range of morphological variation observed in Natal on a global scale, results from the constancy of certain controlling factors while the range in variation may be attributed to differences between the remaining factors. Thus, while it may be appropriate to group them on a global scale, the differences in a regional context are of importance in terms of sedimentary facies development preservation potential, formulation of sedimentary models and development of environmental management guidelines.

Transitional coastal environments vary not only spatially but also temporally. Friedman & Sanders (1978) for example, note that many deltas originated as estuaries (eg Mississippi) and that after the estuary is infilled a delta may then extend seaward to produce a typical delta morphology capped with an alluvial plain. This implies a temporal morphological evolutionary path for transitional coastal environments, mediated by sediment supply. A similar assessment was made by Davies (1974) that estuaries eventually infill with sediment. This oversimplified view overlooks the fact that some estuaries may never fill with sediment if sediment supply is low in relation to sea-level change or tectonic movements (Nichols & Biggs, 1985). Schubel & Hirschberg (1978) suggested that climatic variations and sea-level fluctuations control the origin and distribution of estuaries and that their lifetimes are limited to a few thousands or tens of thousands of years. In essence, the basic difference between estuaries and deltas lies in the rate of sediment supply versus rate of dispersal and therefore a continuum of environments must exist between the two. The prime problem in classification is definition of the point when an estuary becomes a delta.

Even when in a mature state, with their valleys filled with sediment, rivers still discharge water and sediment to the sea and the water volume though which this passes may still have estuarine characteristics, albeit of a different form to that of the original bedrock valley. What is most important for effective environmental management of river-mouths is an understanding of the evolutionary path of a river-mouth, the starting point and the ultimate finishing point and how far along that path the river-mouth has progressed.

For purposes of environmental management it would also be advantageous to assess and predict which evolutionary path a fluvial/marine transition will take. Thus a genetic classification scheme is required which classifies environments in terms of several evolutionary pathways mediated by several controlling factors. In Natal, high wave action, a steep nearshore gradient and strong coastal currents generally prevent seaward delta progradation. In instances where coastal sediment accumulation does occur it is in the form of coastal dunes or a prograding beachridge plain. Certain classifications, however, identify river-mouth-associated beachridge plains as a form of delta (Galloway 1975; Wright & Coleman, 1975).

Definition of a transitional environment also depends largely one's viewpoint: a biological definition may differ from a geomorphological or hydrodynamic one, for example. As Barnes (1980) observed, "any attempt at rigid compartmentalisation will therefore be, to a degree, artificial and arbitrary". Although the typical estuary and the typical lagoon are very different, there is a range between them". He suggested that the main difference between estuaries and coastal lagoons was in the relative width of the entrance channel and the related volume of freshwater or tidal input. Estuaries have wide mouths and lagoons have narrow mouths with little tidal exchange. Such a distinction is entirely arbitrary.

The most frequently cited estuary definition is that of Cameron & Pritchard (1963) that, "an estuary is a semi-enclosed coastal body of water with a free connection with the open sea, and within which seawater is measurably diluted with fresh water from land drainage". With reference to South African estuaries, Day (1980) modified this to, "an estuary is a partially enclosed coastal body of water which is either permanently or periodically open to the sea, and within which there is a measurable variation of salinity due to the mixture of sea water with fresh water derived from land drainage". CERC (1973) define an estuary as either ,"that part of a river which is affected by tides" or, "the region near a river-mouth in which the freshwater of the river mixes with the salt water of the sea". Friedman & Sanders (1978) define an estuary as, "a coastal indentation, at the mouth of a river, in which seawater can circulate freely". "An estuary is an inlet of the sea, reaching into a river valley as far as the upper limit of tidal rise " (Fairbridge, 1980). Nichols & Biggs (1985) point out that this does not define the seaward limit.

Geologists tend to define estuarine sequences as "the deposits found within drowned paleovalleys" (Curray, 1969). A more refined geological definition was given by Zaitlin & Shultz (1990) who defined an "estuarine complex" as, "all tidally influenced deposits, seaward from the limit of tidal marine influence to the major facies change with normal marine deposits, occurring within a constrained (paleo-) valley setting, affected by the mixing of marine and fresh waters". Schubel & Hirschberg (1978) suggested that estuarine deposits could rarely be unequivocally delimited from other shallow water marine deposits in the geological record. Part of this problem may be due to differences in opinion about what is and is not an estuary.

Deltas, also have been given a variety of definitions. CERC (1973) define a delta as, "an alluvial deposit, roughly triangular or digitate in shape, formed at a river-mouth", while Hayes & Kana (1976) describe it as, "a river-fed depositional system that results in an irregular progradation of the shoreline". To

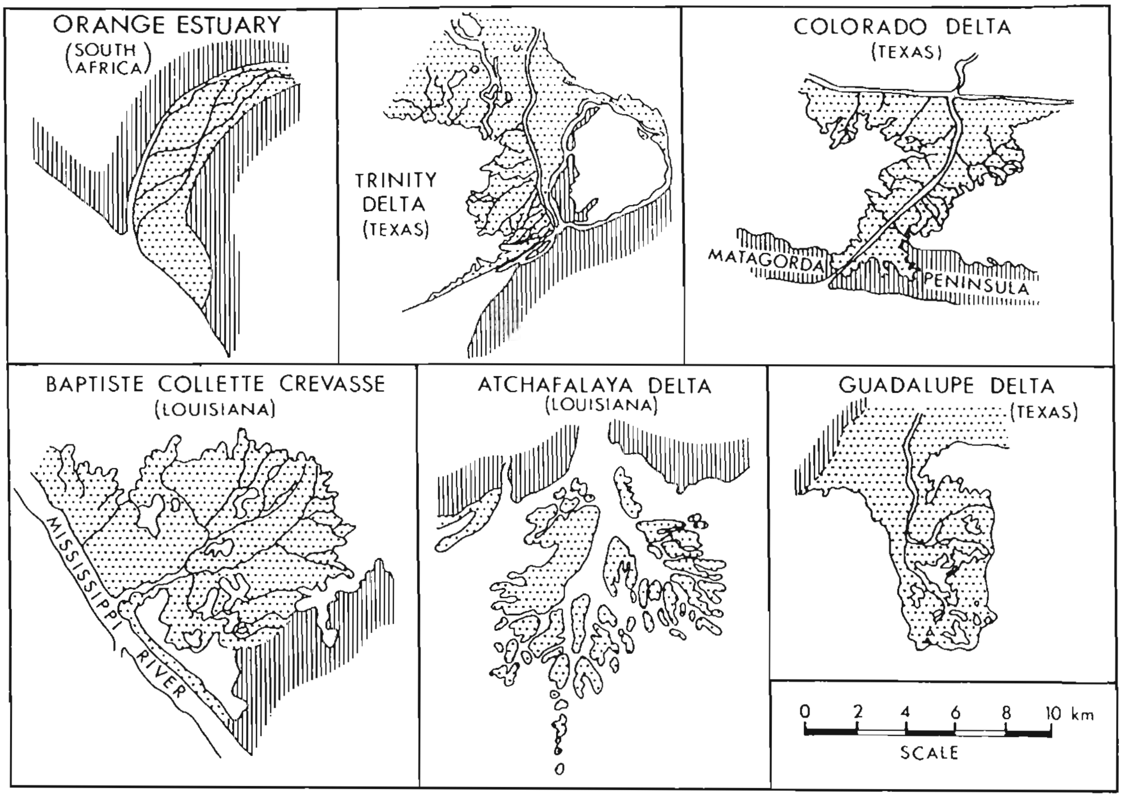
Friedman & Sanders (1978) a delta is, "a lobate body consisting of sediment that has been transported to the end of a channel by a current of water and deposited mostly subaqueously but partly subaerially at the margin of the standing water into which the channel discharged or is still discharging". Common usage among geologists according to Miall (1979) reserves the term "deltaic deposit" for "those bodies of clastic sediment formed in subaerial and shallow water environments (marine or lacustrine) in which the influence of a river or rivers as the main sediment source can be recognised, and in which a gradation into an offshore, generally finer-grained facies can be traced".

Coastal lagoons have even more definitions. CERC (1973) define a lagoon as, "a shallow body of water, as a pond or lake, usually connected to the sea", while a "barrier lagoon" is, "a bay, roughly parallel to the coast and separated from the open ocean by a barrier islands". Barnes (1980), citing the Oxford English dictionary defined a coastal lagoon as, "an area of salt or brackish water separated from the adjacent sea by a low-lying sand or shingle barrier . A fresh water lagoon is termed a fresh water coastal lake or pond." Colombo (1977) defined them thus, "Lagoons are shallow bodies of brackish or sea water partially separated from an adjacent coastal sea by barriers of sand or shingle, which leave only narrow openings through which sea water can flow". Ward & Ashley (1989) highlight the problem when they submit that many lagoons are, "also considered as estuaries by the criteria of Cameron & Pritchard (1963)". Ward & Ashley (1989) proposed that, in a geomorphological sense, lagoons are, "coastal water bodies which are physically separated, to a greater or lesser extent, from the ocean by a strip of land".

It is not necessary or desirable to add any further definitions but instead to recognise the considerable overlap which exists through failure to recognise, or acknowledge the fact that all transitional fluvio-marine environments form part of a continuum, mediated by various genetic factors. Within that continuum divisions and terms are necessary to avoid long-winded descriptions but an all-embracing classification is required for comparison of different geographical areas.

It is apparent that there is considerable overlap in morphology between deltas, lagoons and estuaries, particularly if scale is considered. A delta may, for example, exhibit estuarine circulation in its distributary channels, a lagoon or estuary may contain a delta at the tidal head and an estuary may enter a coastal lagoon. Van Heerden (1986) terming the mouth of the Orange river-mouth an estuary, concluded by referring to it simultaneously as a delta and estuary and compared it with other progradational features (deltas) of similar size (Fig.8.1). This highlights the problems of rigid compartmentalisation but also outlines the need for some improvement in terminology. At the seaward side of the Niger Delta (Allen, 1972; Oomkens, 1978) are a series of barriers which enclose lagoons and several of the distributary channels in deltas described by Coleman & Wright (1975) display estuarine circulation. Thus a further problem in definition arises according to whether one is considering a micro- or macro-scale landform.

Despite the close relationship between transitional environments no all-embracing scheme has yet been applied to include estuaries, deltas and so on. The classification scheme for river-mouths proposed by Boyd *et al.* (1990) is to be welcomed as it precludes the often difficult designation of a coastal water body into one or other group. It is best that they are viewed as a continuum of features whose morphology is



mparison of the Orange “estuary” with small “deltas” (after van Heerden,
s the problems of terminology of transitional fluvio-marine environments.

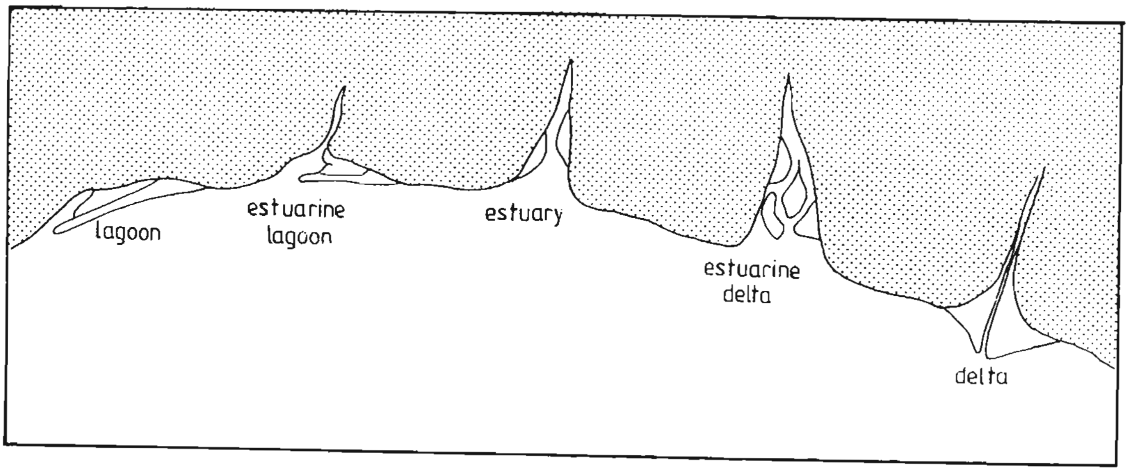


Figure 8.2. Conceptual classification of “coastal inlets” proposed by Davies (1972), encompassing lagoons estuaries and deltas.

controlled by external variables. Davies (1973) recognised that there was a continuum of what he termed coastal inlets, produced where freshwater from the land meets salt water from the sea (Fig. 8.2). At one extreme were lagoons produced solely by marine action and at the opposite extreme deltas in which river action is so strong that it causes progradation in one of many forms. In between he recognised a variety of landforms which vary in the relative importance of marine and fluvial processes.

Mangelsdorf *et al.*, (1980) concluded that the problems of bedload transport and depositional processes at river-mouths are so complex that no comprehensive theory for all has yet been established. They identified several factors of special importance:

a) incoming sediment yield;
b) tidal range;
c) Coriolis Force;
d) stratification;
e) coastal hydrodynamics;
f) winds.

Mangelsdorf *et al.* (1980, p 169) suggested that estuaries are formed preferentially in macrotidal areas and deltas in microtidal ones. However, they go on to agree with numerous published articles that deltas may originate as estuaries.

Terminology of Natal river-mouths is particularly problematic because, depending on definition, they exist as coastal lagoons, estuaries, deltas and freshwater lakes, naming but a few possibilities. The generic term "river-mouth" is therefore preferred for the open water area and associated sedimentary deposits which occur where a river meets the sea.

8.3. GLOBAL/REGIONAL RIVER-MOUTH CLASSIFICATION SCHEMES

8.3.1. Introduction

Classification of river-mouths is necessary for the purposes of comparison, establishing functional models, and in formulation and application of management principles. Classification has been approached from a variety of scientific and non-scientific standpoints. As stated by Dyer (1973), "Many different schemes are possible, depending on which criteria are used. Topography, river flow and tidal mixing are important factors that influence the rate and extent of the mixing of fresh and salt water........Obviously all of these causes and effects are interlinked and it would be difficult to take account of them all in one classification system". Colombo (1977) suggested that at the most precise level of classification, there may for example, be as many lagoon types as there are lagoons. Classification schemes are sensitive to the objective of the designer, and such biases must be noted.

Existing physical classification schemes for transitional fluvio-marine environments, based on mode of formation, salinity structure, circulation and geomorphology, are discussed below.

8.3.2. Global/regional classifications

An empirical classification based on salinity structure proposed by Pritchard (1955) and expanded by Cameron & Pritchard (1963) and later authors (for example Pritchard & Carter, 1971; Schubel 1971), divides estuaries into four main types:

a) "highly stratified salt wedge";
b) "highly stratified fjord type";
c) "partially mixed"; and
d) "vertically homogeneous".

While it is based simply on salinity structure (Fig.8.3), this factor controls other processes, for example, ratio of river water to marine water, turbulence etc, which are implied but not stated explicitly in the classification. *Highly stratified salt wedge* estuaries are those with a large ratio of river flow to tidal flow and virtually no upward mixing of the salinity intrusion into the overlying freshwater. *Highly stratified fjords* differ from salt wedge estuaries as they occupy glaciated valleys and the lower, isohaline layer is very deep. In *partially mixed estuaries* the saline intrusion is mixed progressively with river water by turbulence and river flow is low compared to the tidal prism. Complete mixing of fresh and salt water occurs in *vertically homogeneous estuaries* and, while there may be lateral or longitudinal variations, salinity remains almost constant from top to bottom of the water column .

A complex classification scheme for estuaries was devised by Hansen & Rattray (1966). It involves the use of two dimensionless parameters. The *stratification parameter* is defined as the ratio of surface to bottom salinity divided by the mean cross-sectional salinity. The *circulation parameter* is the ratio of the mean fresh water flow, plus the flow of water mixed into it by diffusion, to the river flow. The variables are then plotted on a bivariate chart which enables comparison between estuaries (Fig.8.4). The classification is thus based solely on measurement of observed variables.

While geomorphologists recognise physical variations between estuaries, few formal schemes have been proposed on the basis of geomorphology. "Estuarine systems" are variously termed, coastal lagoons, embayments, estuaries, coastal lakes, river-mouths and so on (Bird, 1968).

Pritchard (1952) proposed a fourfold division of estuaries into:

a) drowned river valleys or coastal plain estuaries;
b) fjords;
c) bar-built estuaries; and
d) "the rest".

Drowned river valleys formed during Holocene flooding of incised river valleys in which sedimentation did not keep pace with rising sea level. *Bar-built estuaries* also formed in drowned river valleys but sedimentation has kept pace with inundation and a characteristic bar forms across their mouths. *Fjords*

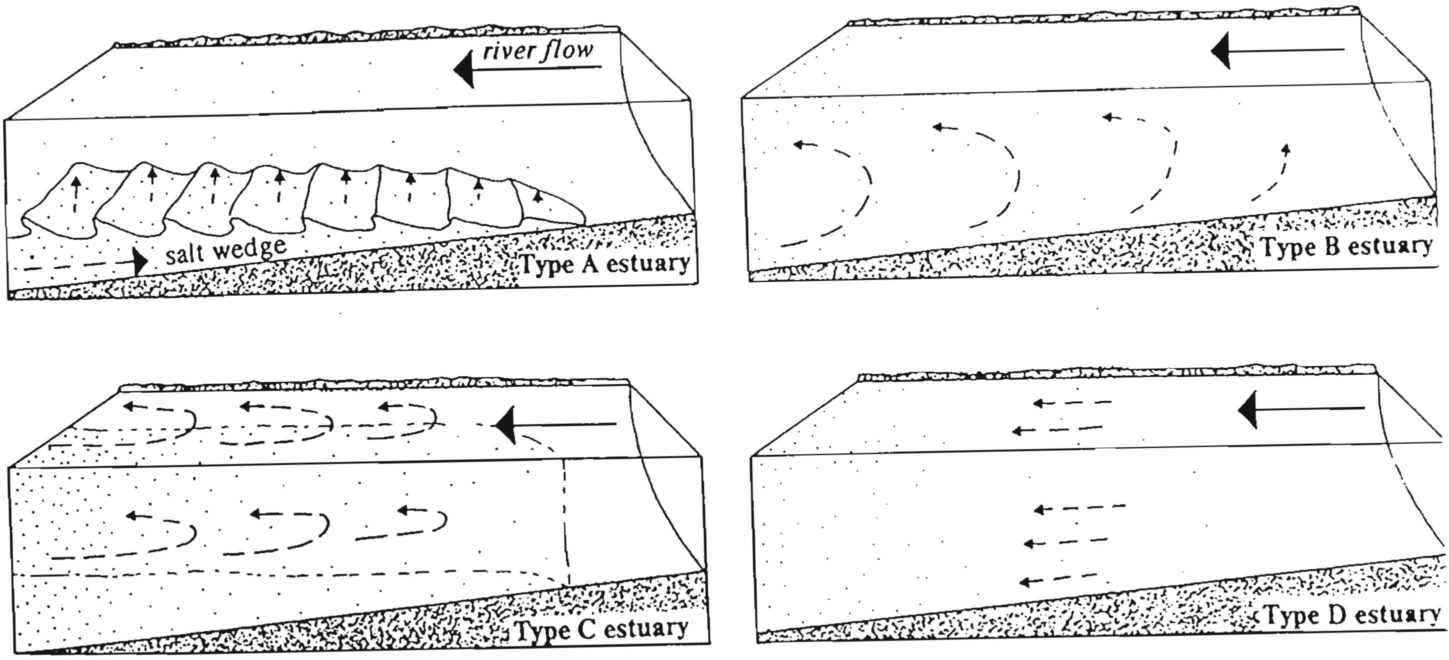


Figure 8.3. Examples of estuaries classified on salinity structure (originally after Pritchard, 1955)

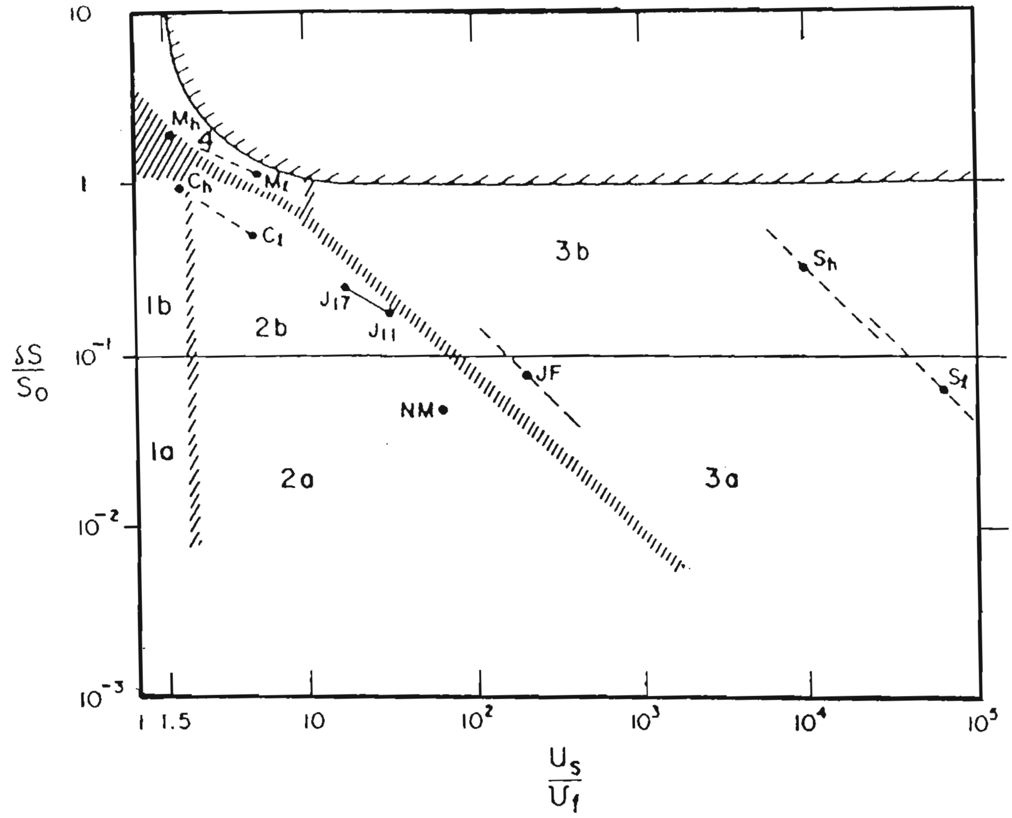


Figure 8.4. Stratification/circulation diagram for estuary classification with some examples (after Hansen & Rattray, 1966). Station code: M, Mississippi River mouth; C, Colombia River estuary; J, James River estuary; NM, Narrows of the Mersey estuary; JF, Strait of Juan de Fuca; S, Silver Bay. Subscripts h and l refer to high and low river discharge; numbers indicate distance (in miles) from mouth of the James River estuary.

occur only in areas which were covered by Pleistocene ice sheets. They are generally very deep and have a sill across their seaward end, deposited by retreating glaciers. The category termed "*the rest*" includes all those estuaries which do not fit into any of the other groupings and include estuaries formed by tectonism, landslides, volcanic eruptions and so on.

McDowell & O'Connor (1977), recognising that estuarine hydrodynamics are essentially governed by tidal action and river flow within a given boundary, indicated that the boundary shape of each system is determined by the geomorphology of the land and the properties of all alluvial materials that form the bed and banks of the channels. Thus the geomorphological framework of an estuary basin is essentially a fixed boundary but the channels, as modified by flow, are variable boundaries in which gradual changes take place due to accumulation and redistribution of sediments. This established a genetic basis for classification of estuaries, and indeed other river-mouth types, but was not explored further by the authors.

Warme *et al.* (1977) compared the sedimentology of a temperate and tropical lagoon and concluded that variations in morphology could be explained by the following:

a) climate (temperate vs tropical);
b) stream runoff;
c) estuary orientation with the inlet (perpendicular or parallel); and
d) vegetation (salt marsh vs mangrove).

In recognising these factors they laid the basis for future classification but did not pursue this further. However, it is unlikely that all these factors are independent. For example, climate probably controls both vegetation and runoff, while coastal geology almost certainly controls the estuary orientation. Thus the controlling factors could not be regarded as genetic.

Lankford's (1977), study of Mexican coastal lagoons, is one of the most comprehensive regional geomorphological classification schemes. The basis of his genetic classification was that, by relating the original geomorphological characteristics to geological history, coastal oceanography and climate, the major types of modern lagoon environmental systems could be grouped subjectively. The classification identified five main groups (Fig.8.5):

a) those formed by differential erosion;
b) those formed by differential terrigenous sedimentation;
c) barred inner shelf environments;
d) Organic-systems; and
e)Tectonic/volcanic.

Each main class was subdivided into two or more sub-classes and the classification made allowance for the fact that several factors affect lagoon morphology.

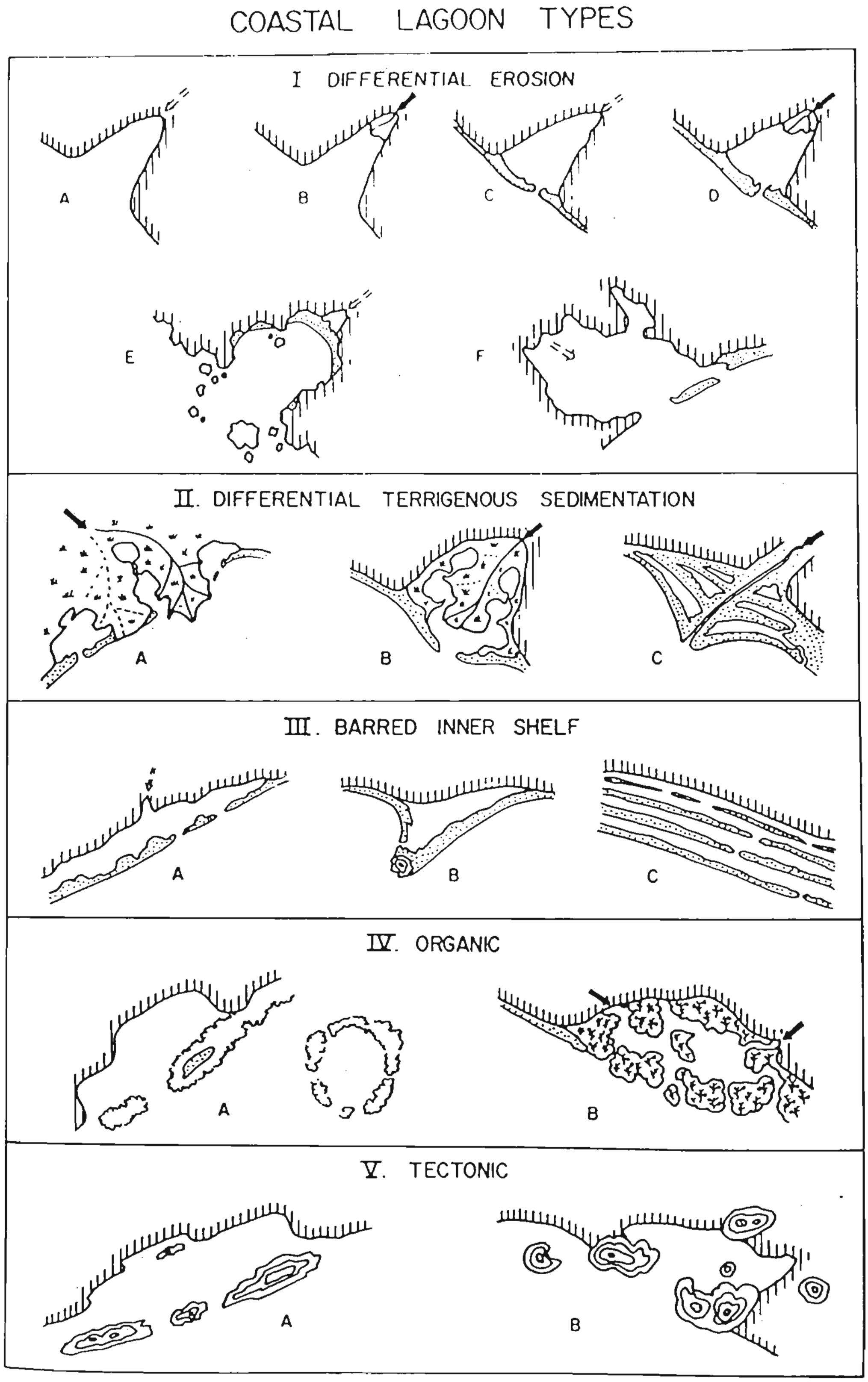


Figure 8.5. Lankford's (1976) classification of Mexican coastal lagoons, showing main morphotypes. Most Natal river-mouths would fall in Group 1.

In a study of New South Wales estuaries, Roy (1984) contended that morphological diversity was a function of:

a) inherited factors of a geological nature (bedrock topography, coastal morphology etc);
b) contemporary process-related factors (tidal currents, river discharge etc).

He divided NSW estuaries into into three basic types corresponding to the entrance conditions (Fig.8.6). These were:

a) drowned river valleys (open mouths, no tidal attenuation);
b) barrier estuaries (open mouths, tidal attenuation); and
c) saline coastal lakes (ephemeral inlets, non-tidal) .

Roy (1984) also identified contemporary estuaries at various stages of infilling which were controlled by variation in sediment supply and established distinct evolutionary sequences for each of the three types identified, based on extensive drilling investigations.

Hayes (1975, 1979) classified estuaries according to tidal range and described distinctive morphologies for each of micro- (2-4 m), meso- (2-4 m) and macrotidal (>4 m) environments. The variation in morphology is summarised in Figure 8.7.

Galloway's (1975) classification of deltas identified variations according to sediment input, wave energy flux and tidal energy flux (Fig 8.8). Three end members were identified and other deltas could subjectively be placed on the continuums between. At the wave-dominated apex, was the São Francisco delta of Brazil, which was stunted in its seaward growth by the wave energy. If the larger river-mouths of Natal are regarded as deltas in terms of this scheme all are even more wave-dominated and consequently entirely channel confined. Only the Tugela is associated with a prograding coastline. The channel-confined deposit in the Orange river-mouth was also seen as this extreme delta type by Van Heerden (1986).

Zaitlin & Shultz (1990) presented a classification of sedimentary models for estuaries, based on the relative effects of wave, river and tidal influences, similar to the delta classification of Galloway (1975).

Coleman & Wright (1975) added a degree of objectivity to delta classification by using multivariate statistics to differentiate between deltas, using a range of variables which controlled their morphology. Through factor analysis they reduced over 400 parameters to the following twelve basic controls on delta morphology:

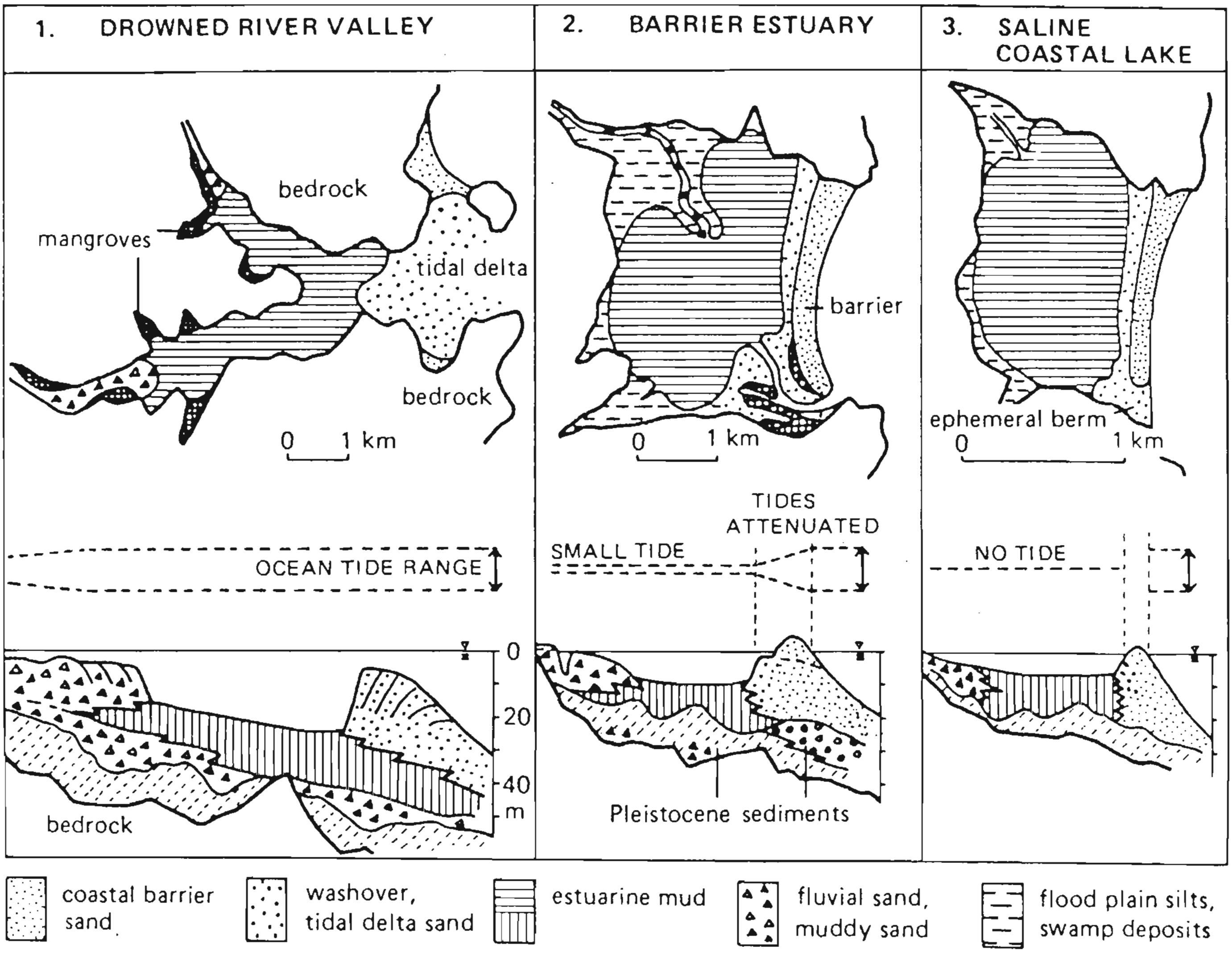


Figure 8. 6. Classification of three main estuary types in New South Wales (after Roy, 1984).

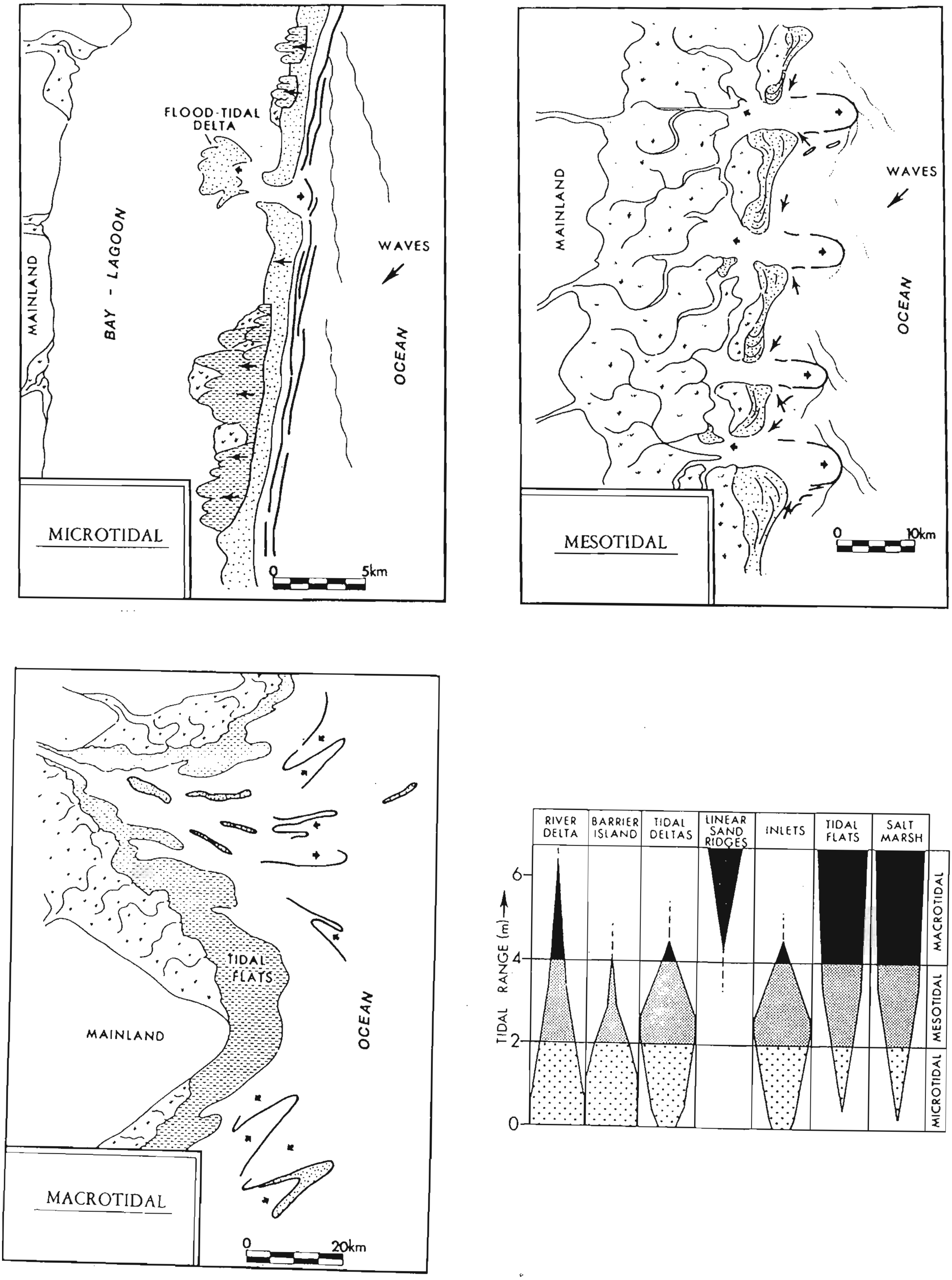


Figure 8.7. Classification of coastal plain estuaries according to tidal range showing distinctive characteristics (after Hayes, 1979). A summary diagram is shown in the lower right-hand corner.

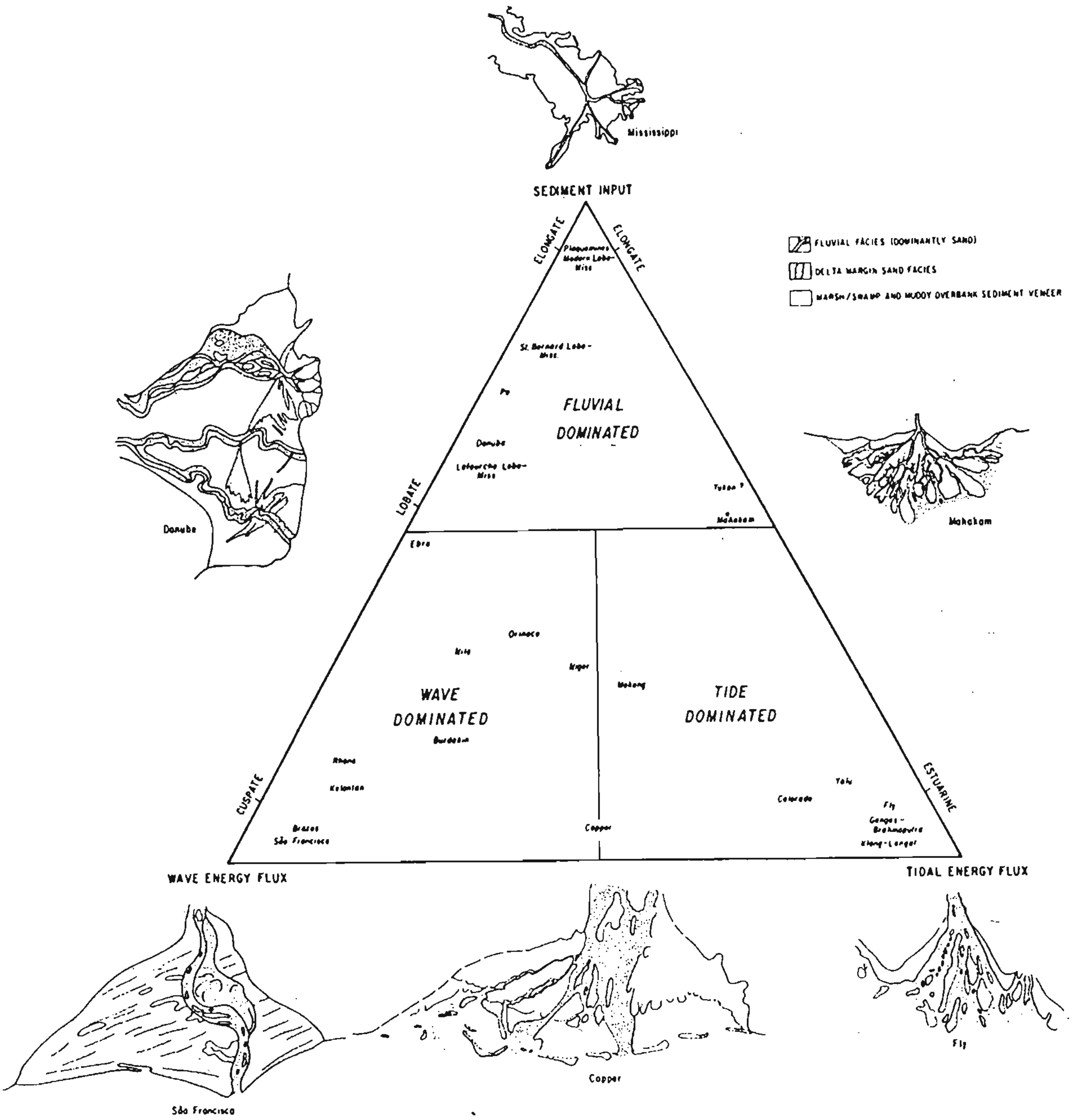


Figure 8.8. Triangular classification of deltaic depositional systems (after Galloway, 1975). This type of classification relates delta morphology to the relative importance of sediment input, wave energy and tidal energy.

a) climate;
b) water discharge;
c) river-mouth processes;
d) tide;
e) nearshore currents;
f) tectonics of receiving basin; and
g) relief of drainage basin;
h) sediment yield;
i) nearshore wave power;
j) winds;
k) shelf slope;
l) receiving-basin morphology.

The range of variation observed was explained in terms of these variables. Delta processes were linked to the controlling variables, as was facies architecture, particularly sand body distribution. As deltas are only one type of river-mouth, with high sediment supply, the same controls may apply to other transitional fluvio-marine zones.

Boyd *et al.*, (1990) outlined the preliminary basis of a classification scheme which incorporates all transitional fluvio-marine environments including deltas, estuaries, embayments, and barrier-lagoons. Their proposed classification is based on the relative importance of waves, tidal currents and river currents which are plotted on a ternary diagram, similar to Galloway's delta classification. A fourth axis, (time) may be added to represent either transgressive or regressive conditions.

8.3.3. Discussion

The information presented above illustrates a selection of the means used to classify transitional fluvio-marine environments. Each was devised for a specific purpose and has its own application. No existing scheme integrates the various river-mouth environments into a coherent classification with a strong genetic basis. Therefore before any classification is applied careful definition of the range of environments is necessary. This may prove problematical as some enigmatic environments may warrant possible definition as a delta, estuary and lagoon, depending on the criteria used.

In a regional context, most of the schemes outlined are too broadly based to be applicable in Natal. In Roy's (1984) scheme, which recognised genetic controls, all Natal river-mouths would fall in the barrier estuary or saline coastal lake class, but, unlike NSW, the Natal examples are at a mature stage of development and thus inferences on the evolutionary succession could only be implied from borehole evidence which is largely lacking at present. The differentiation between barred and non-barred estuaries in NSW corresponds to the depth of the incised valley: in deeper valleys barriers do not become emergent due to the steep nearshore slope, and submerged deltas remain. Shallower bedrock channels have gentler nearshore slopes and so barriers are formed by the upward growth of submerged shoals. In Natal, even the deepest bedrock channels are filled and have a barrier across their mouths.

In the Natal context, all river-mouths would probably fall into Pritchard's (1952) bar-built estuary category: this scheme clearly could not differentiate between the range of observed morphologies. Similarly, most of Natal's river-mouths would also fall in Lankford's Group 1 lagoons, which although sub-divided into 6 minor classes, does not recognise the range of variation in Natal river-mouths.

It would also be possible to place the mouths of large Natal rivers in Galloway's (1975) delta classification as wave-dominated deltas, where wave energy prevents seaward progradation and limits the delta to the river valley. However this would not differentiate between the morphologies observed. It also serves to highlight the difficulties and arbitrary nature of rigid compartmentalisation when the same feature could be termed a delta, estuary or lagoon depending on the context.

While each of these schemes has its merits in particular applications they are generally too broad in scope to be applicable in the Natal situation. While the numerous small river-mouths in the study area could be simply termed bar-built estuaries, they display considerable morphological variation and cannot be accommodated in a single class in a regional context. Factors which are important in the study area, include the period during which the estuary is open to the sea, size of the catchment, sediment yield, and surrounding geology which are not considered in existing schemes. An additional factor to be taken into account is that many of Natal's so-called estuaries do not fit into any of the definitions of estuaries assumed in each of the above classifications, particularly those where salinity structure is involved. Neither do they display typical delta or lagoon morphology.

In contrast to other authors who defined morphology empirically in terms of observed variables, McDowell & O'Connor (1977), Roy (1984) and Coleman & Wright (1975) recognised morphological variability as a function of broadly similar, inherent genetic factors. River-mouth morphology is thus determined by the limits imposed by a geological framework, within which variation occurs in response to variation in the rates and nature of inputs and/or processes. This is, in essence, the approach which is applied to classification of Natal's river-mouths in this chapter.

8.4. EXISTING CLASSIFICATIONS OF SOUTH AFRICAN RIVER-MOUTHS

8.4.1. Introduction

Numerous studies have been carried out on various aspects of South African river-mouths. Geomorphological and sedimentological research is comparatively recent and has been concentrated in the southeastern Cape (Reddering & Esterhuysen, 1981 *et seq.*) and Natal (Cooper, 1987 *et seq.*, Cooper & Mason, 1986 *et seq*; Cooper *et al.*, 1990, Grobbler, 1987). A few site-specific sedimentological studies have been undertaken in the southern Cape (Van Heerden, 1985; Willis, 1985), western Cape (van Heerden, 1986; Bremner *et al.*, 1990) and Zululand (van Heerden & Swart, 1986; Wright, 1990).

Few attempts have been made to compare South African river-mouths to those elsewhere in the world, nor to classify the broad spectrum of estuary types in South Africa in general and in Natal in particular. Those classification schemes which have been applied are outlined below.

8.4.2. South African river-mouth classifications

Begg (1984a) divided the "estuaries" of Natal into four groups which he termed lagoons, estuaries, embayments and river-mouths. The basis of his classification was in the biological function performed by each estuary. *Estuaries* (eg. Mgeni, Mzimkulu and Mtamvuna) included those which had a near-permanent mouth which enabled tidal exchange to occur and which permitted the recruitment of juvenile marine fish into them. In this respect they fulfilled a nursery function and so were termed estuaries. *Lagoons* (eg. Mhlanga, Mdloti, uMgababa and the mouths of most small rivers on the Natal coast) are closed from the sea for most of the year by a barrier and only breached occasionally. Begg found them to be dominated by freshwater fauna and suggested that their nursery function for marine fish was limited. *River-mouths* in Begg's classification are those systems in which the bed level in the lower river course was above sea level so that even though a mouth was present, fresh water passed directly into the sea and no tidal exchange occurred. Their fauna is typical of freshwater river-channel environments (eg, Mzumbe, Mvoti). In his discussion, Begg went on to suggest that the river-mouth was an end point in an evolutionary trend and that estuaries on the Natal coast would ultimately become river-mouths due to continued sedimentation. *Embayments* were those areas which were filled with sea water and in which freshwater influence was minimal. Durban Bay was the only example.

While it was the first comprehensive study of Natal's river-mouths and successfully differentiated river-mouths on their biological communities, Begg's interpretation of the causes of this classification is geomorphologically unsound for several reasons. For example, he did not recognise the role played by floodplain geomorphology in controlling channel migration or channel morphology in the lower reaches of rivers and the effect of bedrock outcrops in determining mouth morphology. Such factors have been shown (Chapter 6) to control the apparently elevated bed level in the Mvoti, its lack of tidal exchange and its apparently unusual ichthyofauna. Thus one could not simply view the Mvoti as one end of an evolutionary lineage: the Mgeni for example, could never resemble the Mvoti as its narrow floodplain promotes braid bar coalescence, island formation and channel incision and hence permits tidal exchange and biological interaction with the ocean, in spite of the fact that the Mgeni is at an equally advanced (mature) stage of development as the Mvoti.

Day (1981) classified South African estuaries on the basis of hydrodynamic and salinity characteristics. His classification recognized "normal estuaries", "hypersaline estuaries" and "closed or blind estuaries". *Normal estuaries* were in turn sub-divided into the salt wedge, highly stratified, partially mixed and vertically stratified estuaries of Cameron & Pritchard's (1963) scheme. *Hypersaline estuaries* were defined as those with a negative salinity gradient and *closed* or *blind estuaries* included those which are separated from the sea by a continuous sandbar for most of the year. (Day equated blind estuaries with Begg's (1978) lagoons and rejected the term 'lagoon' in this context because of its frequent use elsewhere for coastal water bodies with no river-water input). His classification was therefore a combination of existing global schemes with local adaptation. It, however, failed to take into account variations in climate, coastal hydrodynamics, productivity and sediment supply around the South African coast, and is therefore of little use in classifying estuaries according to their controlling variables.

The method used by Ramm (1990) in an application of his Community Degradation Index (Ramm, 1988) to Natal estuaries, was based on empirical physical parameters and involved the selection of eight measurable variables (catchment area, elevation of the source, river length, average bottom salinity, estuarine area, median annual runoff, % of year mouth closed and estuarine length) for each estuary. These data were ordinated using multivariate statistics which clearly grouped the estuaries into 5 classes. Confidence in the method was enhanced by the fact that permanently-open, large estuaries fell into the same grouping while small estuaries formed another set of groups. A shortcoming in this approach is that many of the variables, for example average bottom salinity, are not the basic controls but rather are a dependent variable mediated by one or more controls. Many are also difficult to define, for example estimation of the "estuarine length" of a lagoon is entirely arbitrary. The value of Ramm's (1988) method was demonstrated in his community degradation study but even within the groups identified there were clear differences in morphology and sedimentary processes: detailed investigations of the sedimentary processes in some of Natal's estuaries reveal that systems which appeared similar were, in fact, very different geomorphologically. For example, the Mgeni, Mvoti and Mtamvuna which fall into Ramm's Group 1 estuaries, each experience markedly different sedimentary processes (Chapters 3 to 6). Such differences must be accommodated.

In a discussion of controls on estuarine morphology on the south-eastern Cape coast, Reddering (1988a) discussed differences in morphology of estuaries and outlined a conceptual estuarine classification for the area based on the following characteristics:

a) state of the tidal inlet;
b) volume of the tidal prism;
c) cohesion of the sediment bed;
d) wave climate; and
e) morphology of the adjacent coastline.

This approach enabled the designation of a particular estuary by a code in which each measured parameter was designated by a letter or symbol. Reddering (1988a) suggested that this approach could be extended to include all South African estuaries, if the additional variable of climate was introduced.

While Reddering (1988b) outlined what is a potentially useful regional classification scheme, it is less applicable in Natal than in Cape estuaries for reasons other than climatic variation. For example, in Natal, the catchment size has a direct bearing not only on sediment yield and degree of youthfulness of a system, but also controls the morphology of the drowned bedrock valley. This implies that small catchment systems which one would expect to be youthful (because little sediment is entering them) are, by the same token, likely to have been smaller in the first place and therefore required comparatively less sediment deposition to reach maturity. Furthermore, no account is taken of the lithology in which the estuarine palaeovalley was cut. This is vitally important in that estuaries formed in the resistant Natal Group Sandstone are typically cliff-bound with deep palaeovalleys while valleys cut into the comparatively soft, Pietermaritzburg Shale Formation tend to be broad and shallow. Both exert important controls on subsequent estuarine development and modern estuarine morphology which need to be addressed in any useful classification scheme.

Perry (1985b) outlined a method for classification of Natal's “estuaries” based on historical aerial photographs. She suggested that major floods, riverine vegetation, swamp areas and sandbars at the mouth are the main natural factors influencing the hydraulic behaviour of estuaries. The classification divided estuaries into stable and unstable systems. *Unstable systems* display large temporal variations in sinuosity, large lateral thalweg displacements, and generally show large amounts of change in historical times while *Stable estuaries* show little variation during the period under review. A third group, termed "*apparently stable*" includes those which show a loss in open water area, narrowing channels and general aggradation over time, without the variations in lateral displacement shown by unstable estuaries.

Perry's classification, while using geomorphological data, may be used only to indicate whether or not the morphology of an estuary has changed historically. This is useful but in most instances it is more important to understand the processes and controls on morphology which *cause* changes in morphology. For instance, variations in channel position may be controlled by a variety of factors including bedrock type, alluvial sediment type, valley shape, episodic events or long-term sedimentation trends. It would be expected that meandering channels would naturally show more lateral variation than braided, or bedrock-confined ones. Furthermore, some "unstable estuaries" may be filled with sediment and simply meander across a floodplain while others are "unstable" as a result of continuing sedimentation. Unfortunately Perry made the assumption that stability relates to siltation and that all Natal “estuaries” are part of the same continuum. The classification therefore failed to recognise genetic framework differences between various river-mouths in Natal.

8.4.3. Discussion

Each of the above systems has its merits and particular applications. However, they are unsuitable for the purpose of classifying estuaries according to morphology or sedimentary processes, for use in formulation of environmental management guidelines or construction of sedimentary models .

None of the schemes above allow determination of whether an estuary is dominated by coarse-grained fluvial sedimentation, or if it is likely to change dramatically in the future, or if it is dominated by barrier overwash and undergoing aggradation from a marine source. To fully understand the functioning of groups of river-mouths this information must be documented.

With the exception of that proposed by Reddering (1988a), the classifications currently applied to South African river-mouths are non-genetic and simply measure the resultant morphological, chemical or biological criteria. Use of the aquatic fauna as an environmental “health” indicator, which reflects the range of environmental variables prevailing at any particular time is a useful environmental classification technique (Begg, 1984a; Ramm, 1990; D.E.N.I., 1987). The free-swimming fauna is particularly sensitive to changes and responds more rapidly than the benthos. However, the channel is only part of the geomorphological river-mouth area and it changes temporally as a result of floods, storms, drought, barrier closure and so on. A genetic classification system could eliminate temporal effects and identify the range of variation possible in a particular river-mouth. Such a system would enable other measurements to be placed in correct perspective.

It is clear from the literature that there is no existing global or regional scheme, based on physical parameters and sedimentary processes, which can be applied to river-mouths in Natal. This is primarily because almost all of the existing schemes are too broadly based. For example the parameters which they apply are common to all of Natal's river-mouths and would often result in all of them being placed in a single group. A second problem is that most of the estuaries along the Natal coast do not conform to the commonly accepted concept of an estuary. They are generally dominated by riverine influences, are often closed to the sea for extended periods, and do not display typical estuarine salinity structure. Neither do they qualify as typical deltas because they are mainly channel confined and do not extend seaward of the linear coastline. Terminology for Natal river-mouths is discussed in section 8.9.

8.5. A GENETIC GEOMORPHOLOGICAL CLASSIFICATION

8.5.1. Introduction: The benefit of a genetic system

In general, all drowned river valleys follow a similar evolutionary trend in that they fill with sediment (Davies, 1974). Water depth and surface area decrease with time and hydrological characteristics and biological communities change. This does not necessarily imply that all river-mouths ultimately attain the same morphology because they fill at different rates with different materials, by different processes and within different frameworks. Basin shape and the supply rate and nature of infilling sediment are variable so that much morphogenic variation occurs on the Natal coast.

The question therefore arises "Are all Natal river-mouths part of the same evolutionary continuum?". The general trend is for Natal river-mouth valleys to fill, but, because of the range of morphologies observed in essentially mature river-mouths, the answer is clearly “no”. Both the starting point and nature of subsequent changes are controlled by variables which differ from one river-mouth to another. It is for this reason that a genetic classification system is desirable compared to one based on observed morphology.

Davies (1974, p.7) suggested that in spite of some brave attempts to classify by form it seemed more meaningful to try to isolate the genetic factors involved and to attempt to categorise these. Stoddart (1969a,b) concluded that form of coastal landforms is an ambiguous guide to their origin and pointed to the desirability of identifying genetic *climatic* parameters associated with particular processes. The critical effect of climate on coastal morphology is its influence on the nature and rate of sediment supply to the shore (Davies 1974, p 15). In the study area climate varies little and, if a single climatic parameter-process link does exist, as proposed by Stoddart, it has in Natal, given rise to a variety of forms which must therefore be controlled by additional, non-climatic variables. It is against this background that the present section sets out to classify the river-mouths of the Natal coast.

Geomorphological variation in river-mouths may be interpreted in terms of differences in hinterland topography, catchment size (and hence freshwater runoff), composition of the coast (rocky, sandy or otherwise), and coast-type (headland-bay, stable linear clastic, prograding etc). Resulting geomorphological differences include the presence or absence of a floodplain, tendency to meander, size of tidal deltas, barrier type and marginal vegetation type. Superimposed on these variations are changes which occur after formation of estuaries and may occur in each group. These produce different sedimentary facies and hence different stratigraphic records, however, each is indicative of the same range of coastal conditions but indicates a different range of hinterland conditions.

8.5.2. Constant environmental factors in the study area (Natal river-mouths in global perspective)

Several variables which cause global-scale variation in coastal landforms, may be regarded as constant in the study area. These variables impart a set of common characteristics to Natal river-mouths which classify them collectively on a world scale. Superimposed on these are other locally-important variables which produce the observed range of morphologies. In introducing a genetic classification for Natal river-mouths it is necessary to define their global position so that this does not become simply another regional study with little global focus. In this section the constant factors are identified and Natal river-mouths categorised in a global setting.

The river-mouths in the study area, display some common characteristics which render them different to river-mouths elsewhere in the world, and even elsewhere on the South African coast (see for example, Van Heerden, 1986; Reddering, 1988b, Wright, 1990). The major distinctive characteristics are discussed in this section to set the context in which the classification is to be carried out.

River-mouths on the Natal coast display the following properties.

- They are small in area. Even the largest are small by world standards.
- They are formed in drowned river valleys.
- They are separated from the sea by sandy river-mouth barriers
- They are dominated by fluvially-derived sediment.
- The principal mode of deposition of marine sand in estuaries is barrier overwash, as opposed to flood-tidal currents.
- Ebb-tidal deltas are generally absent.
- Most are in a mature stage of their evolution as a result of high sediment yield.
- Fluvial sediment yield is high.
- Periodic river floods may produce morphological change.

These inherent properties reflect the subtropical climate, steep and narrow hinterland, and strong wave energy. These factors, which influence all of Natal's estuaries, must be excluded from the variables used to differentiate between them.

The subtropical climate which has persisted since the Miocene enhances soil formation on bedrock and soils in excess of 30 m thick have been recorded (Partridge & Maud, 1987). These soils yield large quantities of sediment to rivers. The steep topography of the hinterland enables rapid transportation of this sediment to the coast, which has filled most estuaries to the point where they are in a mature stage of evolution. The fact that the hinterland is comparatively narrow impacts on estuaries by ensuring that river courses are short and are therefore unlikely to join other rivers before reaching the coast. Consequently, catchments and discharge rates are small. This means that river flow is often incapable of maintaining an inlet against wave-induced sediment transport and flood-tidal deltas are generally poorly developed. The prevailing high wave energy tends to transport sand landward to form barriers across river-mouths. These are only breached during sufficient freshwater flow (typically during seasonal or episodic floods) in the smaller rivers. Wave energy also prevents formation of ebb-tidal deltas seaward of river-mouths and those which form during floods are rapidly reworked (Cooper, 1990d).

Begg (1984a, p.159) proposed that sedimentation rates are highest at the head of Natal estuaries and the bayhead delta grows progressively seaward within the estuary to "extend the realm of the river and force the intruding sea out of the semi-enclosed tidal basin until eventually the river reaches the sea through a broad depositional plain and the transformation from estuary to atidal river-mouth is complete". Most Natal river-mouths are already mature and present as filled valleys whose varying fixed boundaries (floodplain limits) are controlled by the surrounding geomorphology and whose channel morphology now relates to discharge from the catchment. Hence, increased sediment supply is no longer a major factor in river-mouth evolution and sediment passes into the sea after only a temporary residence time in the channel or floodplain. Similar assessment was made of the much larger Atchafalaya Bay and the Yangtze River which have high discharge and sediment supply, and the low-discharge rivers of the US southeast coast which drain the deeply weathered Piedmont (Nichols & Biggs, 1985).

Transitional fluvio-marine environments in Natal seldom become truly freshwater river-mouths in the sense envisaged by Begg (1984a,b) as the grade concept prevents aggradation of the bed above the level where water flows to the sea. To do so a river would have to extend its course, separating the upper parts of the estuary from marine influences. This could only happen by delta progradation, a process inoperative under the high wave energy and steeply sloping, current-swept nearshore environment or channel extension on a wide floodplain. Therefore, rivers with sufficient runoff to maintain a mouth will generally experience tidal influence, and the resulting tidal prism will help maintain the mouth. Tidal exchange may be excluded when the outlet channel forms in an area underlain by bedrock at an elevation above high tide.

The world's coasts were classified on the basis of their tectonic setting by Inman & Nordstrom (1971) who identified the entire southeast African coast as an "Afro-trailing edge" coast. Davies (1973) noted that this exerts an important control on fluvial sediment supply to coasts in that rivers which drain toward Afro-trailing edge coasts (eg Congo and Niger) carry relatively small loads (Mitchell & Reading, 1969) because the opposite continental margin is also a trailing edge of low relief. In contrast, on "Amero-trailing edge" coasts, whose opposite continental margin is a collision coast, rivers carry higher sediment loads which are deposited in larger sedimentary plains and wider shelves. Although the Natal coast was classified as an Afro-trailing edge type, the proximity of the Great Escarpment to the coast may render the situation more similar to an Amero-trailing edge with relatively high fluvial sediment loads but no coastal plain due to the steep offshore gradient.

In apparent contradiction to the predicted relatively low fluvial sediment loads, most of sub-Saharan Africa, including Natal, is classified globally as one of the areas of high mechanical erosion with erosion of >50 tons of sediment per km^2 per year (Davies, 1973). Estimates of the annual denudation in the Tugela catchment vary between 250 and 300 m^3/km^2 (Orme, 1974; Rooseboom, 1975), and are significantly higher than any of the major rivers world-wide, for example the Zambesi, Nile and Mississippi (Milliman & Meade, 1983).

Climatic factors are more-or-less constant along the Natal coast. Annual rainfall figures vary little across the hinterland and average between 900 and 1000 mm (Schulze, 1965). A clear indication of the constancy of rainfall is in the strong positive correlation of catchment size with runoff (Fig.8.9). Catchment size as a variable therefore encompasses both rainfall and river discharge. Furthermore, the entire area is a summer rainfall region and experiences similar seasonality throughout. The response to storms also varies little as evidenced by the widespread rainfall and flooding associated with Tropical Cyclone Demoina and the September 1987 cut-off low flood events. All river-mouths are subjected to episodic discharge events, the magnitude of which is controlled by their catchment size.

The topography of the coastal hinterland is steep and overall river gradients vary little, as shown by a plot of river length against source elevation for each of the rivers in the study area (Fig. 8.10). Thus stream velocities are increased throughout the study area. Such steep hinterlands are more normally associated with collision coasts, such as those of the western USA and South America.

So far as the nearshore marine environment is concerned, wave energy along the coast is high and does not vary appreciably (HRU, 1968). On a global scale the area was classified by Davies (1974) as an east-coast swell environment. The continental shelf is very narrow by world standards, even at its widest part (40 km) and this has impacted on river gradients during lowstand periods. Sediment inputs from the hinterland are dispersed on the Agulhas current-swept shelf (Flemming, 1980) and this prevents the formation of submerged deltas.

Coastal wind characteristics are similar throughout the study area (Tinley, 1985) and may disperse fine sand from beaches to promote coastal dune growth. The input of aeolian sediment to river-mouths in the study area is limited, in contrast to others in the eastern Cape (Reddering & Esterhuysen, 1981) and Southern Zululand (Wright, 1990). The coastline is near linear and rocky and sandy beaches are formed along most of its length, in front of or resting on rocky outcrops (Cooper, 1991b). It is not deeply embayed and lacks a coastal plain.

Several of the twelve controls on delta morphology listed by Coleman & Wright (1975) may be regarded as constant in this regional study: They are asterisked in the following list: *climate, *relief of drainage basin, water discharge, sediment yield, *river-mouth processes, *nearshore wave power, *tides, *winds, *nearshore currents, *shelf slope, *tectonics of receiving basin, and receiving-basin morphology.

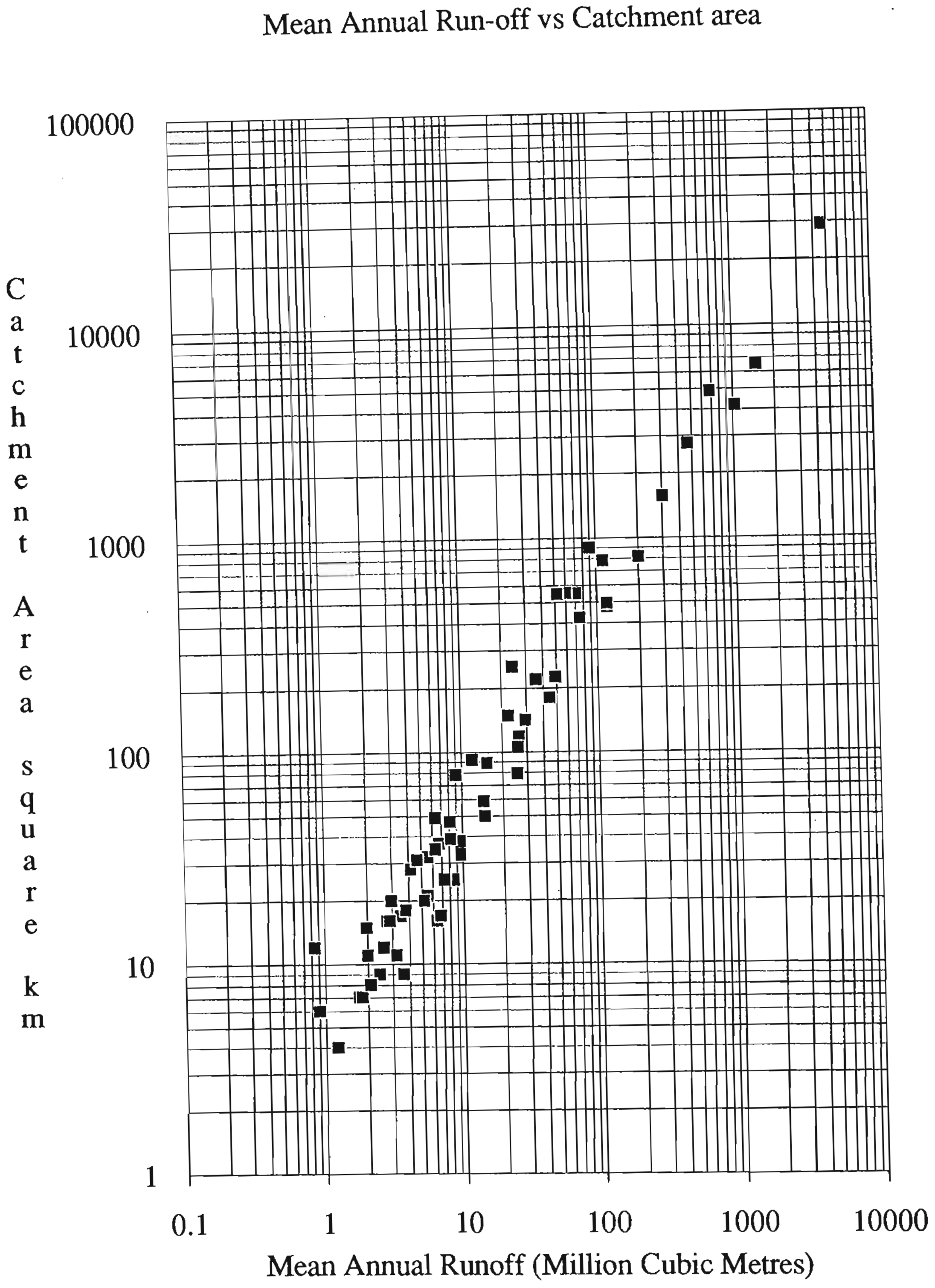


Figure 8.9. Plot of mean annual runoff against catchment area for all rivers in the study area. The linear correlation reflects the constancy of rainfall across the hinterland.

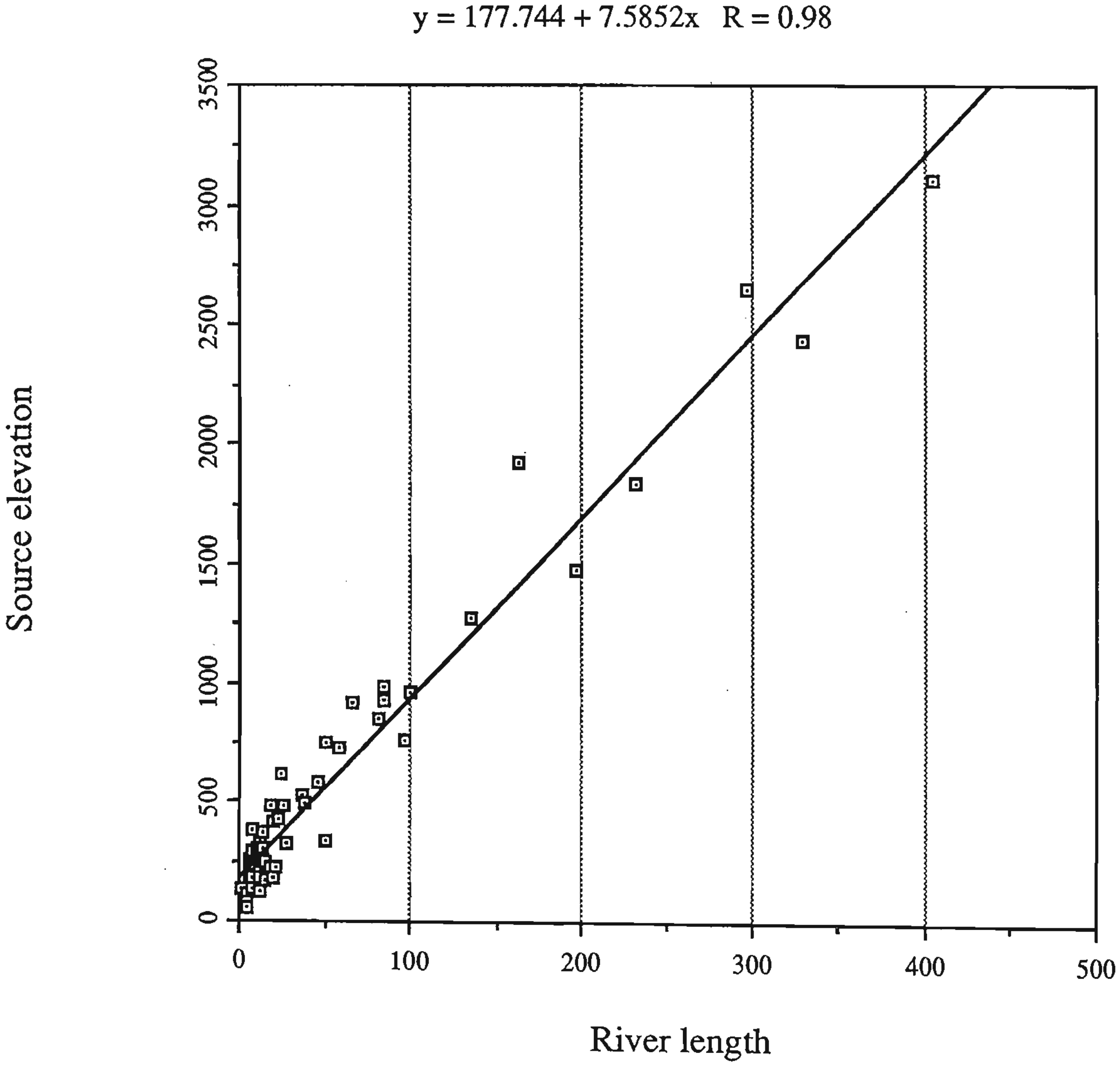


Figure 8.10. A Plot of source elevation against river length for all rivers in the study area shows the low variation in gradient throughout the hinterland.

In summary therefore the factors which influence river-mouth morphology on a global scale but which may be regarded as constant in Natal are as follows:

- Steep river gradient
- High sediment yield
- High wave energy
- Linear rocky coastline
- Lack of tectonism
- 1000 mm annual rainfall
- Subtropical climate
- Episodic river floods
- Shore-parallel winds
- Steep nearshore gradient
- Seasonal rainfall
- Evaporation
- No coastal plain
- Strong nearshore currents

This combination of factors classify the study area on a global scale as no other area could be identified with the same combination of physical parameters as those in Natal. the closest parallel to be drawn is probably with south-east Australia (Roy & Thom, 1981), although that coast is much more embayed than Natal.

These factors give Natal river-mouths several characteristics which may be used to categorise them on a world scale. They are dominated by fluvial rather than marine sedimentation and overwash is the dominant mechanism by which marine sediment enters. When present, flood-tidal deltas are relatively small. All have a sandy river-mouth barrier with a permanent or ephemeral outlet. The humid climate ensures that outlets do not close for years at a time as in the southern Cape (Branch *et al.*, 1985). They are small and mainly confined to the narrow drowned valley (ria) in which they formed, although coastwise extension may occur with suitable nearshore conditions. Sediment entering the sea is rapidly dispersed by wave action and coastal currents; ebb-tidal deltas are not preserved.

8.5.3. Hypothesis

Having eliminated the constant factors in morphology which classify the study area globally, the classification scheme which is outlined below is based on the hypothesis, propounded and discussed at three recent conferences (Cooper 1990a,b,c), that morphological variation among Natal's river-mouths can be explained by four independent variables, on which all other variables depend. The basis of this argument is in the variation observed between the four case studies in this thesis and the other river-mouths discussed in the previous chapter. A diagram summarising the hypothesis is depicted below (Fig.8.11). In essence it states that, given that several environmental factors may be regarded as constant, the morphology of Natal river-mouths can be defined by (a) the size and shape of the initial basin (incised bedrock valley), and (b) the type and volume of sediment supplied to it. These are argued to depend on the catchment size, catchment geology, river-mouth geology and coastal topography.

The rationale behind this hypothesis is as follows. Catchment size controls the discharge and hence the amount of incision which can be accomplished by a river at low sea-level. In combination with the resistance of the surrounding geology this will determine the size and shape of the bedrock valley in which estuaries form under ensuing transgressions. The catchment geology will control the type of sediment carried by the river and the catchment size and discharge will establish the capacity of the river to carry such sediment to the coast. The grainsize of the sediment supplied will affect both channel morphology

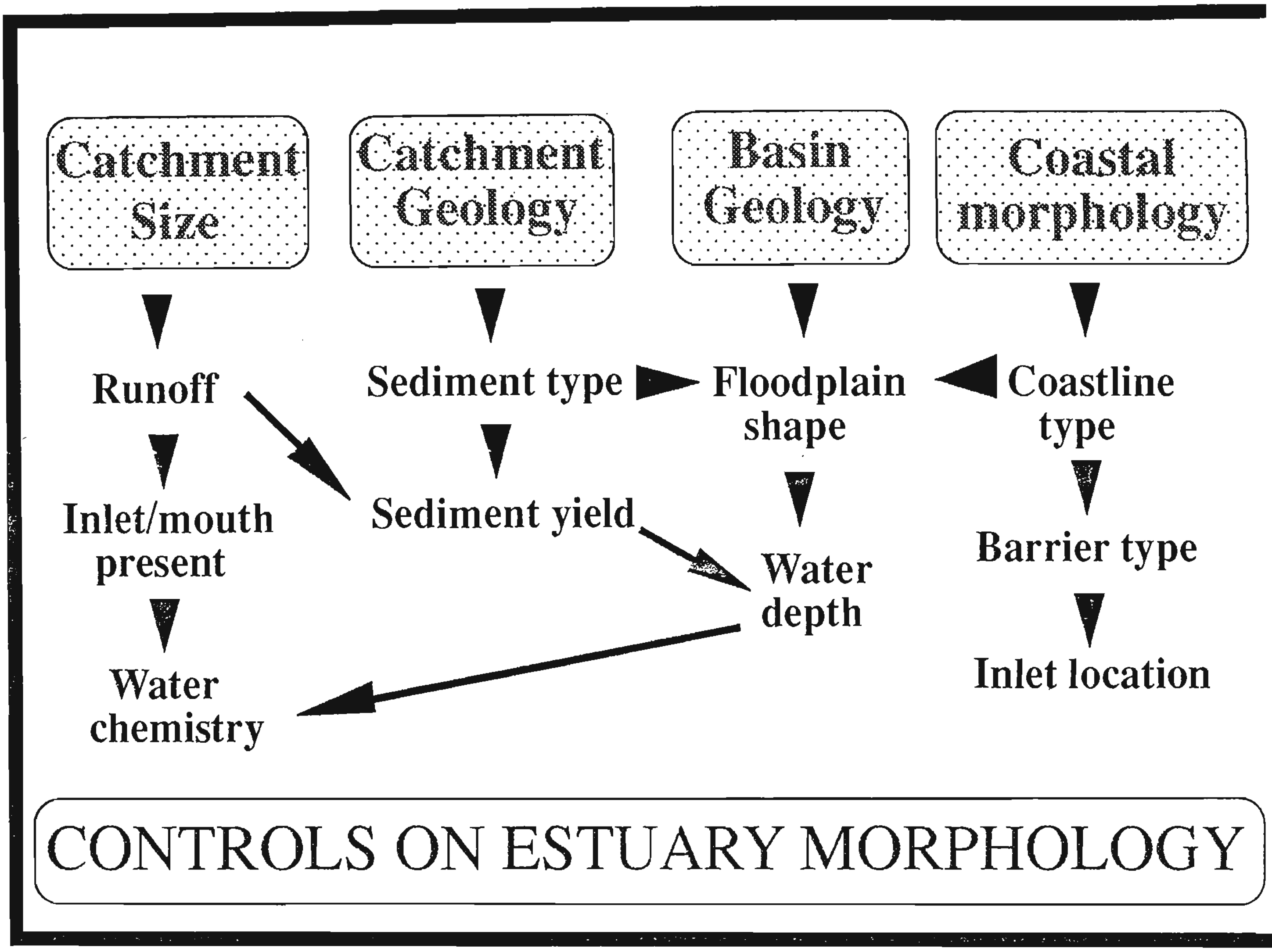


Figure 8.11. Diagram showing hypothesised relationships between four controlling variables and river-mouth morphology in the study area.

and sedimentary processes within the river-mouth while the floodplain width, determined by the river-mouth geology sets the boundaries within which channel migration may occur. The coastal morphology determines whether or not an estuary can be diverted in a coastwise direction (parallel to the coast) behind a barrier in equilibrium with the dominant wave fronts and the barrier length combined with discharge (catchment size) and barrier permeability determines how frequently an outlet forms.

In the following sections an attempt is made to quantify each factor and to use the combined, enumerated variables into a classification which is reflected in and can be interpreted in terms of the range of observed morphology.

8.6. CONTROLLING FACTORS

8.6.1. Introduction

In this section the factors which control variation in river-mouth morphology in the study area are discussed and assessed in two sections:

a) factors which control the size of the receiving basin;
b) factors which control the sedimentary inputs.

Some of the factors impact on both groups.

8.6.2. Factors controlling shape and size of receiving basin

8.6.2.1. Catchment size. One of the most important factors in determining the size of the incised bedrock valley is catchment size. This is linked to amount of freshwater discharge (Fig. 8.9) and hence to the degree of downcutting which could be accomplished by a river during lowstands of sea-level.

8.6.2.2. Coastal geology. The size and shape of the buried bedrock channel is expected to be largely a function of the coastal geology. Softer lithologies, such as shales, would be expected to produce broader, shallower valleys than hard, erosion-resistant lithologies such as sandstones and granitoid rocks (Table 8.1).

Lithology	River	Depth to bedrock (m)	Channel width (m)	Catchment area (km^2)
Ecca Shale	LittleManzimtoti	11	100	18
Ecca Shale	uMgababa	15	360	37
Ecca Shale	Mgeni	>52	420	4863
Vryheid Fm.	Mdloti	30	620	474
Dwyka Tillite	Mtwalume	25	520	553
Granitoids	Mvutshini	12	30	21

Table 8.1. Depth and width of selected bedrock channels incised in varying lithologies. Data on depth to bedrock from Orme (1974).

In the latter group, the resistance of the lithology would prevent lateral erosion during valley incision, and the incised river channel would be forced to exploit vertical weaknesses in the rock such as joints or faults to produce a deeper, narrower bedrock channel. This is well illustrated by the Mtamvuna (Chapter 4).

The uMgababa bedrock valley which is cut into Ecca Shales exhibits marked lateral erosion, accomplished by a relatively small-catchment river. Data on bedrock valleys cut into various lithologies are given in Table 8.1.

8.6.2.3. ***Coastal morphology.*** Several types of coastal morphology occur in Natal (Cooper 1989, 1990a,b). These include beachridge plain, eroding sand cliffs, headland-bay complexes, large-scale coastal planforms and rocky coastal sectors. In terms of river-mouth barrier morphology, the headland-bay, large-scale coastal planforms, and prograding beachridge coasts are most important in determining whether and by how much, a river-mouth is diverted in a shore-parallel direction when it reaches the coast. All river-mouths in the study area are sites of sand accumulation because of the shelter afforded from longshore drift and the ability of the waves to produce an equilibrium planform within the adjacent headlands. If a barrier is located in the mouth of a river valley between steep valley sides the channel will not be diverted in a coast-parallel direction (eg. Mtamvuna, Zolwane) but if it is located some distance seaward of the valley sides in a headland-bay cell (eg. Mzinto, Little Manzimtoti) or a large-scale coastal planform (eg. Mhlanga, Mgeni), the potential exists for coast-parallel river extension. If a river-mouth course is extended at the coast, the frequency of outlet formation is affected by both a longer barrier and enhanced turbulence when an outlet forms across rocky outcrops, marginal to the incised bedrock valley. In areas north of the Tugela River where the coastline is progradational, coastwise extension of river courses is at a maximum and river-mouths may extend over several kilometres behind a prograding beachridge plain.

Sandbar position is also controlled by nearshore wave refraction patterns. For example, the Mtamvuna river-mouth barrier is situated in a river valley where longshore drift cannot remove it and thus its plan form assumes equilibrium with the approaching wave fronts in the lower river valley. The barrier of the Mhlanga river-mouth is situated seaward of its river valley because wave refraction in the Durban Bight permits its maintenance offshore. An additional control on barrier location is that exerted by a change in bedrock gradient as noted by Evans *et al.* (1985) who demonstrated that slight changes on bedrock slope enabled stabilisation of barrier islands in a particular location offshore. This is probably less important in Natal due to high wave energy, than it is in the low-energy Gulf of Mexico, but nonetheless, the position of the Mhlanga barrier some distance seaward of the mainland shore and the presence of bedrock on the floor of the lagoon suggests a bedrock influence.

In a river-mouth with a long coast-parallel extension, not only is the course extended, thereby decreasing the river gradient, but also the number of localities where a river can breach the barrier is increased. This is of fundamental importance to river-mouth processes, particularly during floods when, if a straighter course can be taken, part of the floodplain may remain unaffected by the increased flow. In river-mouths where the barrier is short, the gradient is decreased during low flows by a sinuous channel on the floodplain. Floods may then erode the barrier completely and effect more scouring. In addition, a long barrier, backed by open water, will accommodate more seaward percolation through the barrier and render conditions for outlet formation less frequent than in other rivers of equivalent size but shorter barriers.

8.6.3. Controls on sediment inputs

8.6.3.1. Catchment area. Through exerting a dominant control on discharge, the catchment size determines both the capacity of a river to transport sediment, and the grainsize of the transported sediment. It also controls the magnitude and duration of floods which could be experienced. The discharge regime largely determines the bedload/suspended load ratio which in turn exerts a strong control on river-mouth morphology (Coleman & Wright, 1975; Friedman & Sanders, 1978): rivers with high suspended loads tend to meander (Allen, 1965), while those with high bedload are braided (Tanner, 1968).

As shown in the preceding chapters, small rivers such as the Mhlanga experience lesser peak floods than large rivers. The morphological response to high discharge events is therefore maximised in large-catchment rivers. The catchment areas of Natal rivers range from 4 km^2 to 29 000 km^2 (Table 1.2, Chapter 1) and the entire area is dominated by six large rivers (Fig.8.12). Clearly the magnitude of peak discharge events and morphological responses differ accordingly.

Coleman & Wright (1975) found that sediment yield was directly correlated with the size of deltaic plains. In Natal, the size of the river-mouth area is limited by the bedrock valley margins and high wave energy at the coast. Thus sediment storage capacity is limited and this relationship does not hold in the study area.

8.6.3.2. Sediment type. The nature of the sediment in the hinterland is determined by the material being weathered and eroded. This reflects the underlying lithologies and their associated soils. In general, fine-grained lithologies yield fine-grained sediment.

As in alluvial rivers, the sediment type deposited in the river-mouth controls channel morphology. Braided channels with unconsolidated margins tend to form in sandy substrates as the banks constantly collapse (Leopold *et al.*, 1964; Ingle-Smith & Stopp, 1978). Bank cohesion occurs either through presence of a muddy component or by the binding effects of riparian vegetation. The subtropical Natal climate promotes rapid vegetation colonisation and rivers which deposit sandy overbank sediment after floods generally have braided channels only until the banks are stabilised by new vegetation growth and suspension settling from lower river flows, after which they become narrow and sinuous, as in the Mvoti. A lack of muddy sediment may however, inhibit or slow down vegetal growth in certain rivers.

Only confined fluvial flow, wave flux and tidal currents are capable of transporting appreciable quantities of sand (Galloway, 1975) and the restricted valleys in which Natal rivers flow may therefore promote sand transport.

8.6.4. Discussion

Based on the preceding sections it can be argued that the controls identified do indeed exert a control on river-mouth morphology, and so an attempt is made to implement a classification using enumerated values for these variables. The application of such a numerical assessment removes much of the subjectivity involved in geomorphological classification.

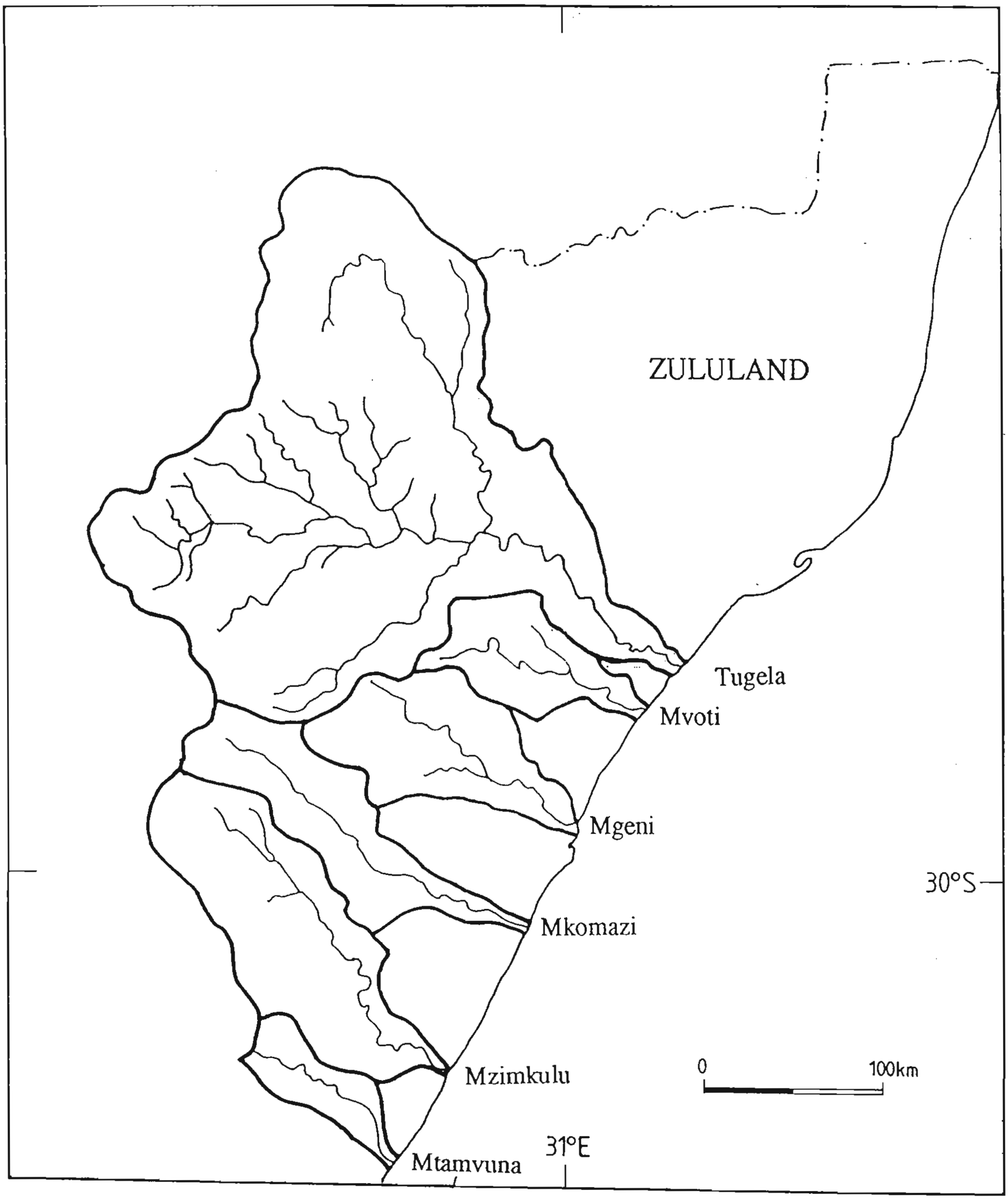


Figure 8.12. The six largest-catchment rivers in the study area dominate drainage in the interior but only account for about 10% of the river-mouths at the coast.

8.7. EXPERIMENTAL APPROACH TO A NUMERICAL/QUANTITATIVE GENETIC CLASSIFICATION

8.7.1 Measurement and analysis

The objective in this section is to quantify each of the controlling variables and, ultimately incorporate them into both conceptual and numerical classifications. Although the hypothesis states only four initial variables, the quantification of each of these involves numerous measurements. The catchment geology, for example, comprises numerous lithologies and the basin geology cannot simply be assigned a numerical value. In order to quantify the genetic controls some numerical assessment must be made.

When dealing with such a large array of data and multiplicity of variables it is frequently necessary to reduce them to a smaller number of variables which are more easily comprehensible although perhaps less easily interpreted (Gauch, 1982). This may be done using a variety of established statistical techniques. Carter *et al.*, (1984) for example, used a clustering technique when dealing with the multiplicity of controls on barrier morphology and outlet formation in south eastern Ireland in order to group similar forms and Coleman & Wright (1975) used multivariate statistical analysis to assess variation in delta morphology.

Detrended correspondence analysis (DECORANA; Hill, 1979a) is a commonly applied procedure when dealing with large numbers of, generally biological, data (Gauch, 1982). It has also been successfully used in other applications using physical data (Ramm, 1990). A complementary two-way species analysis (TWINSPAN; Hill, 1979b), essentially a hierarchical classification procedure, may be carried out using the same data and a quantitative assessment can be made of the validity of the clusters suggested visually by the DECORANA output data. Effective use was made of DECORANA by Begg (1984a) in his biological classification of Natal river-mouths but he found the TWINSPAN application of little use. Use can also be made of various clustering techniques (Wilkinson, 1987) which provide alternative means of grouping data. When the number of variables can be reduced to three or four they can be plotted against each other using the computer application Macspin ® which enables the data to be viewed in three dimensions and rotated on the computer screen for ease of comparison. After experiments with all three available techniques, the best results were obtained using cluster analysis, either from the program SYSTAT or TWINSPAN. Because SYSTAT is more user-friendly on the available computer hardware, it was employed in the analysis and classification.

8.7.2. Catchment sediment type

In order to assess differences in the nature of the incoming fluvial sediment, the area of each catchment underlain by various lithologic units was measured from 1: 250 000 geological maps using a planimeter. The areas were calculated as percentages of the whole catchment and tabulated. Sixteen mapped units were identified initially and the data were tabulated into a 16 x 66 matrix for statistical analysis.

For the first iteration all 16 mapped lithological units were included in the hope that the combined result would give an indication of the range of sediment inputs. The results, however, proved to be of little use in dividing the river-mouths on catchment sediment type, as the cluster analysis dendrogram indicated the main source of variation between the various rivers to be the presence of rare outliers of particular rocks which occurred only in a few catchments. Consequently those rivers which contained these rocks were differentiated from the rest, which formed a single cluster.

To avoid this problem, the catchment lithologies were grouped, according to similar characteristics, into six classes which are listed below.

1.Sandstones. This group comprised mainly the Natal Group Sandstone, and some Proterozoic quartzites which were encountered in the upper reaches of the larger rivers. The latter never amounted to more than 2% of the total in any catchment and so they were combined with the NGS.

2.Tillite. The Dwyka Tillite was put into a class of its own, as it is a glacial diamict which weathers to produce sediment both from its muddy matrix and included sand and pebbles.

3. Shales. In this class the major component was the Ecca Group which is composed predominantly of shales. The Vryheid Formation does contain frequent sandstones which produce sandy soils (Beater, 1970), but because the sandstones tend to be relatively resistant to weathering the dominant sediment derived from the formation is mud from the intervening shales. In addition, in some instances the Ecca was undifferentiated on the geological maps and so it was impossible to include the Vryheid Formation as a separate unit. The mudstones of the Beaufort Group were also included in the shale grouping, as were rare volcanics from the Pongola System, both of which weather to a muddy soil (Van der Eyk *et al.*, 1969; Beater, 1970).

4. Dolerite/basalt. The abundance of dolerite in the catchments varied greatly and, although it does produce a muddy sediment upon weathering, it was isolated because of its resistance and the indurating effect it has on the rocks which it intrudes. Basalt, which occurred only in small areas in the upper reaches of the larger rivers, was grouped with dolerite, because it also weathers to a muddy sediment.

5. Metamorphics. The rocks of the Natal Structural and Metamorphic Province were grouped on the grounds that most are coarse-grained granitoids which tend to produce gravelly or medium to coarse-grained sandy sediment (Beater, 1970), with only subordinate mud.

6. Alluvium. All the unconsolidated sediments in the catchments were grouped together, as most are sandy. These include alluvium in the river catchments and the Berea-type red sand at the coast. Only in a few instances was muddy alluvium recorded, and then in small amounts.

The revised data were used in a second iteration and the results plotted and tabulated. The dendrogram showed a clear split at the first level, based on the presence or absence of shales in the catchment but at the next level, little further separation was achieved due to the close coincidence of shale-containing catchments with those containing dolerite. This impacted severely on the results and caused splits in the dendrogram on unusual factors. A cluster analysis of the input variables (Fig 8.13) revealed that shale and dolerite were the most similar variables and so, to determine the relationship between shale and dolerite in the catchments they were plotted against one another and a best-fit line drawn. The regression (Fig.8.14) gave an r^2 value of 0.56 for a sample size of 34 (the remaining 32 samples lacked either lithology). Given the sample size, the result indicates that the correlation is highly significant (Simpson *et al.*, 1963). The shales in all catchments can therefore be regarded as suffering similar degrees of induration due to dolerite intrusion. The two lithologies both weather to produce muddy soils (Van der Eyk *et al.*, 1969; Beater,

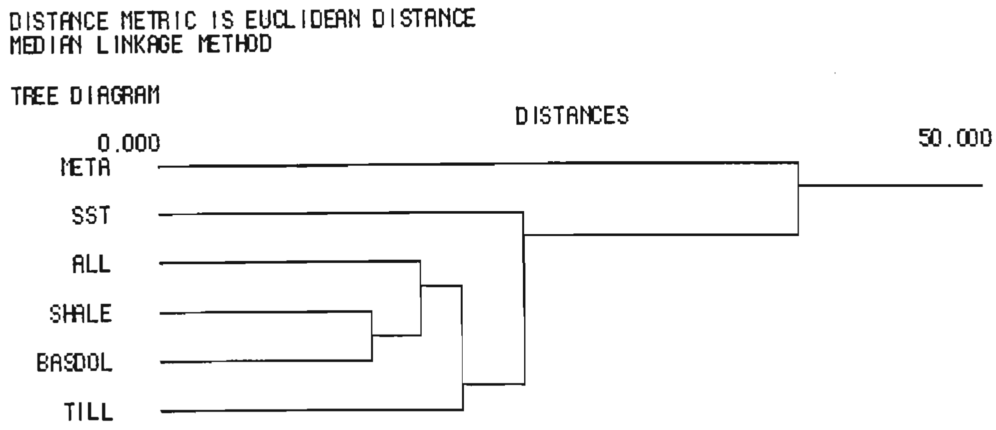


Figure 8.13. Dendrogram of input variables on second iteration of catchment geology clustering. Shale and basalt plus dolerite (BASDOL) showed the highest similarity. META is rocks of the Proterozoic basement, SST is sandstones, mainly Natal Group Sandstone, ALL is alluvium and TILL is Dwyka Tillite.

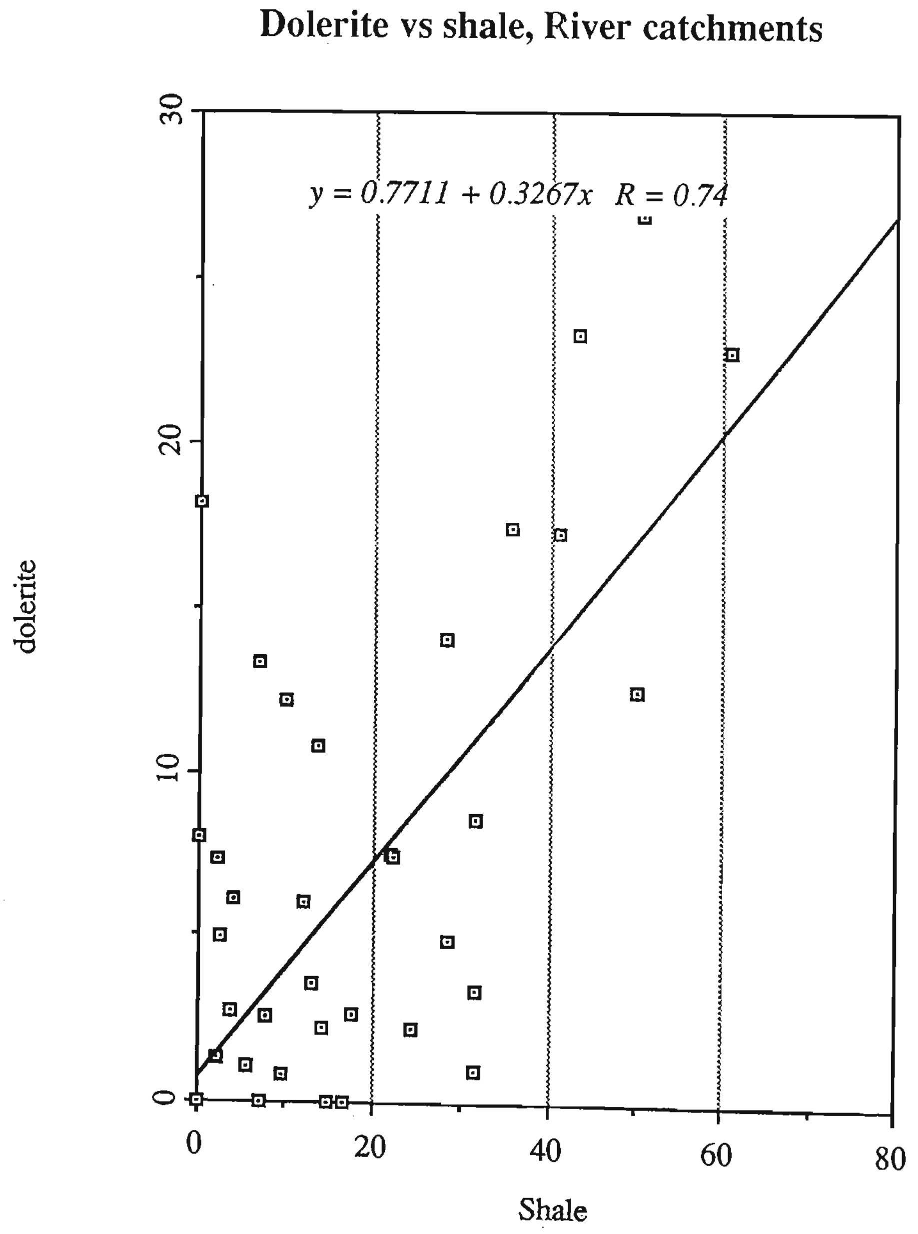


Figure 8.14. A regression of dolerite plus basalt against shale for all river catchments, shows a strong correlation.

1970), although at different rates. Because of their close relationship and similarity of intrusion density in the shale outcrop in the various catchments, shale and dolerite were grouped together.

Alluvium is typically confined to short, wide sections along river courses as the narrow valleys of Natal rivers generally lack much sediment storage capacity (Le Roux, 1990). Only at the coast where some rivers flow through an alluvial plain is alluvium present in significant quantities and here it is more likely to feature as a control on channel morphology rather than as a sediment source. In addition, alluvium is derived from the catchment itself and so reflects the nature of the catchment geology. The Berea Red Sand which was grouped with alluvium as an unconsolidated lithology also contributes little to river sediment as it occurs in a narrow coast-parallel strip and is rarely eroded by the river channel. Thus it was excluded from the catchment geology and the other variables recalculated to 100% of the remaining catchment.

Tillite proved to more similar to the Ecca shales and dolerite, than to sandstone and metamorphic lithologies, but a separation based on dolerite occurred in the dendrogram. Weathered tillite produces mainly fine sandy soils with subordinate silt and clay (Beater, 1970) and so it differs from the mud-yielding shales and dolerite.

Natal Group Sandstone is particularly resistant to weathering and erosion but when it does weather it produces typically fine-grained sandy sediment (Maud, 1988) or sandy loams with 10 to 15% clay from the breakdown of constituent feldspars (Beater, 1970). It thus differs from the metamorphic granitoid lithologies which are frequently the source of medium-grained sand to gravel-sized sediment. The two could therefore not be grouped together. However, the close similarity in grainsize of soils of the Dwyka Tillite and Natal Group Sandstone, both of which produce fine-grained sandy soils, meant that they could be grouped in terms of their sediment-yielding characteristics in a subsequent ordination.

These three variables: (a) mud-yielding rocks (shale+dolerite), (b) fine-sand yielding rocks (sandstone+tillite) and (c) medium to coarse-grained sand-yielding rocks (granitoid metamorphics) were plotted on a ternary diagram (Fig.8.15) using the computer application MacSpin®.

The plot shown in Figure 8.15 represents the variation in grainsize of the potential sediment supply from each catchment. The sediment fractions actually transported by the river and whether, or for how long, they are deposited in a river-mouth or carried into the sea, depends on several other factors, including the river discharge characteristics and morphology of the receiving basin at the river-mouth. These will be discussed subsequently.

Those river-mouths which lie along the Granitoid metamorphics - Sandstone/Tillite axis would be expected to have a fluvial sediment supply dominated by sand. The beds too should be sandy. In cases where there is insufficient flow to transport sandy sediment the channels should also be relatively deep and, because of low mud supply, their waters should be comparatively clear. It is not to say that mud will be completely absent but it will be present in smaller quantities than in other estuaries of equivalent size and basin

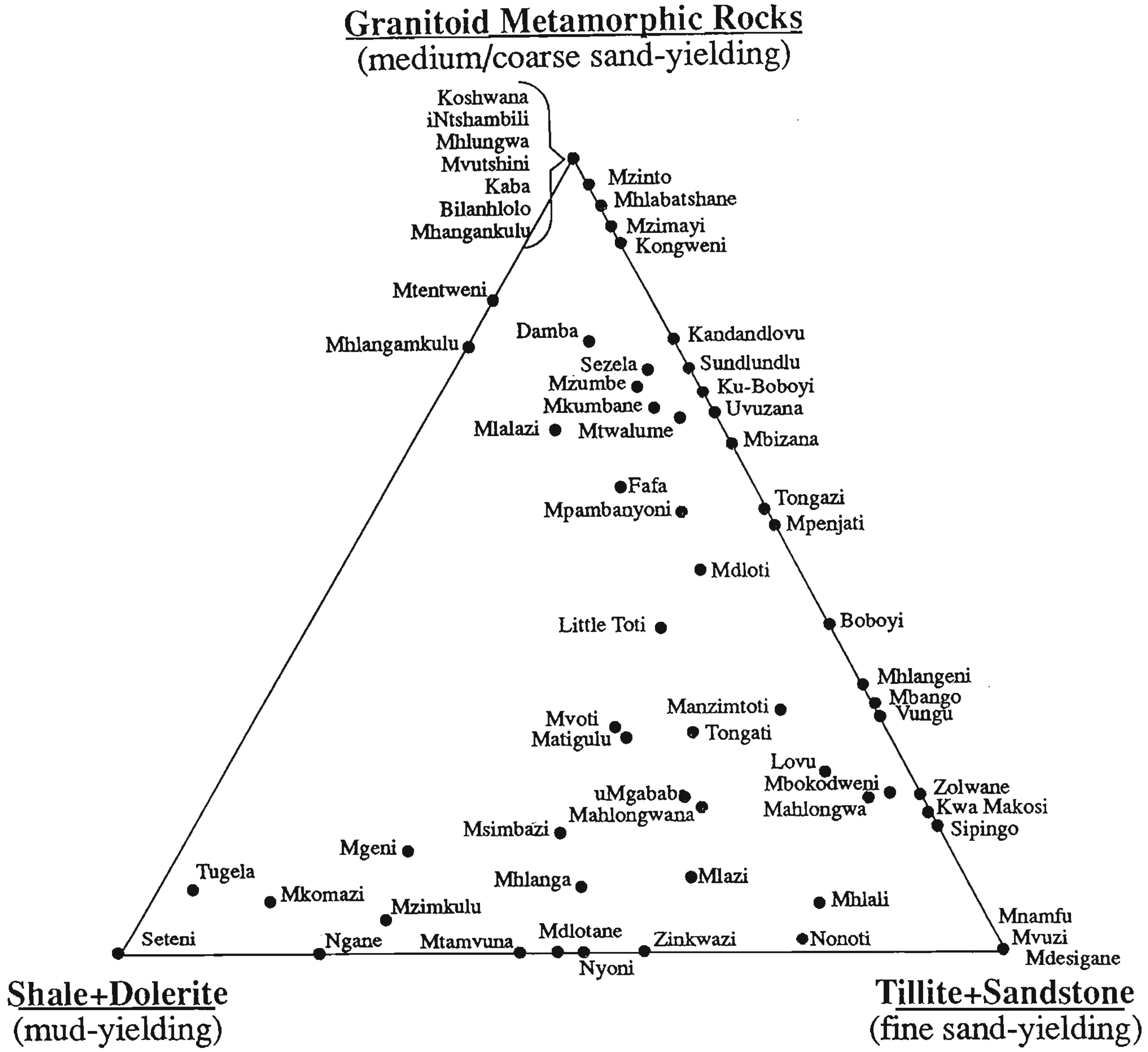


Figure 8.15 Triangular diagram showing the relative proportions of three groups of lithologies in the river catchments. Each group of lithologies has similar sediment-yielding properties in terms of grainszie and weathering rates.

morphology. Along the same axis, river-mouths toward the the metamorphic apex should have coarser-grained sediment within their channels. Water in these river-mouths is generally clear, a fact remarked upon by Begg (1984b). Begg (1984b) found that bottom sediment in the Bilanhlolo river-mouth (situated at the granitoid apex) comprised muddy sand throughout its length and rocks were exposed along the southern bank and on the floor of the lagoon in the upper reaches. The muddy sand described by Begg is consistent with the sandy nature of the lagoon predicted from its catchment geology, because in his faunal investigations Begg (1984a), was most concerned with the topmost layer, which in such systems would be expected to be muddy. Mud only accumulates from suspension settling and organic inputs from marginal vegetation when the outlet is closed. It has only a temporary residence time in the river-mouth, being transported seaward when the barrier breaches.

Observations and sediment sampling in the Zotsha river-mouth which lies midway along the axis showed it to be clear and dominated by sandy sediment throughout its length (NECRU, 1990). In several of the smaller lagoons along this axis, the bottom was characterised by mud. This probably reflects the inability of the river flow to transport coarser-grained material. Nonetheless almost all of the river-mouths which plot along this axis were noteable for their water clarity (Begg, 1984b).

A few estuaries plotted on the Sandstone/Tillite - Shale/Dolerite axis. These would be expected to contain more fine-grained than coarse-grained sand and should be more muddy and turbid as they approach the Shale/Dolerite apex. Those near the Sandstone/Tillite apex should contain greater proportions of fine sand compared to mud while those toward the shale apex should be mud-dominated. The Mtamvuna river-mouth (Chapter 3), which is mud-dominated, lies on this axis and is dominated by mud and fine sand. The erosion-resistance of both the sandstone and tillite have also resulted in the Mtamvuna river-mouth being deep, through a low sediment input. The lack of a floodplain has prevented the accumulation of fine sediment in overbank areas.

The Seteni River, which lies at the mud-yielding Shale/Dolerite apex has a catchment entirely composed of dolerite. It is typified by high water turbidity (Begg, 1984b, p. 41) and the bottom sediments comprise “soft silt” surrounded by muddy sand. The preferential retention of sand on the margins may reflect the constricted nature of the channel and floodplain. The catchment of the Ngane River is also dominated by mud-yielding lithologies and its channel sediments were reported by Begg (1984a) to be composed of silt.

Apart from those rivers which plot at the apices, only two catchments, those of the Mtentweni and Mhlangamkulu Rivers, which lie adjacent to one another in space, occur on the Shale/Dolerite - Metamorphic axis. Those river-mouths are closer to the metamorphic than the shale axis and are expected to have mainly coarse-grained sand in the channel lag deposits, although mud would accumulate during periods of insufficient energy to transport coarse sand. Begg (1984b) noted the “distinctly coarse sand” which occurred near the headwaters of the Mtentweni and the silt which was deposited in the deeper portions. The water was clear, which may reflect the fact that the catchment contains only a small proportion of shales.

River-mouths which lie off the axes should exhibit a range of grainsizes according to the mixture of lithologies in their catchments. The extent to which each is represented in the sediments of the river-mouth will depend on the magnitude and regularity of discharge: large rivers with constant high flows would be expected to continuously transport suspended sediment through their channels and only retain coarse-grained sediment within the estuary basin. If they have sufficiently wide floodplains or backwaters which are protected from scour during high flood discharges muddy sediment could accumulate there and be preserved in the sedimentary record. Sampling of both the channel and floodplain sediment in the Mdloti river-mouth (Grobbler *et al.*, 1987) showed the separation of muddy sediment (which occurred on the floodplain) and sand which dominated the channels. Grobbler (1987) also found that sediment samples from 0,5 m below the surface contained less mud than samples collected at the sediment surface, and attributed this to preferential retention of sand.

These three variables (Shale/Dolerite, Sandstone, and Granitoid metamorphics) can therefore be argued to differentiate between the range of sediment inputs experienced by Natal river-mouths and can therefore be incorporated into a genetic classification.

8.7.3. Basin size & shape

The morphology of the receiving basin (basically the drowned incised bedrock channel at the coast) controls the extent to which a river-mouth can store sediments, and in which form they are stored (floodplain or channel sediments). As noted by McDowell & O'Connor (1977) the basin sets the limits within which other variables operate. Coleman & Wright (1975) also found the receiving basin morphology to exert a strong control on the morphology of deltas, but noted that no method has been developed for quantifying the geometry of receiving basins. In the scheme which they presented of receiving basin morphologies, all Natal river-mouths would fall in one group.

In the hypothesis presented it was argued that the morphology of the receiving basin was a function of the lithology in which it was cut and the size of the inflowing river. On the basis of reconnaissance-level studies on the bedrock channels, Orme (1974) suggested that the depth of incision and size of the bedrock channel could be positively correlated with catchment size. This is true in only general terms as the catchment areas span four orders of magnitude whereas the depth of incision in bedrock valleys varies only between 10 and 60 m. The distance to the shelf break and elevation of the river source would also play a role in the depth of incision at lowered sea-levels. In addition, many of the bedrock channels depicted by Orme (1974) show a broad channel, commonly with a base at about -15 m MSL, into which a deeper, narrower channel is incised (Fig.8.16). The broad channel probably formed during a Pleistocene sea-level stillstand (Orme 1974, 1975) when lateral erosion predominated, and the deeper channel formed during vertical erosion associated with regressive conditions during glacial lowstands.

Incision of South African rivers may have begun as early as the Oligocene when sea-level fell to as low as 400 m below present (Dingle, 1971; Rogers, 1977). The incised channels were drowned and re-incised several times during the remaining Late Tertiary and Pleistocene (McCarthy, 1967; King, 1972). Thus the bedrock channel is a composite feature whose volume and morphology is affected by different processes.

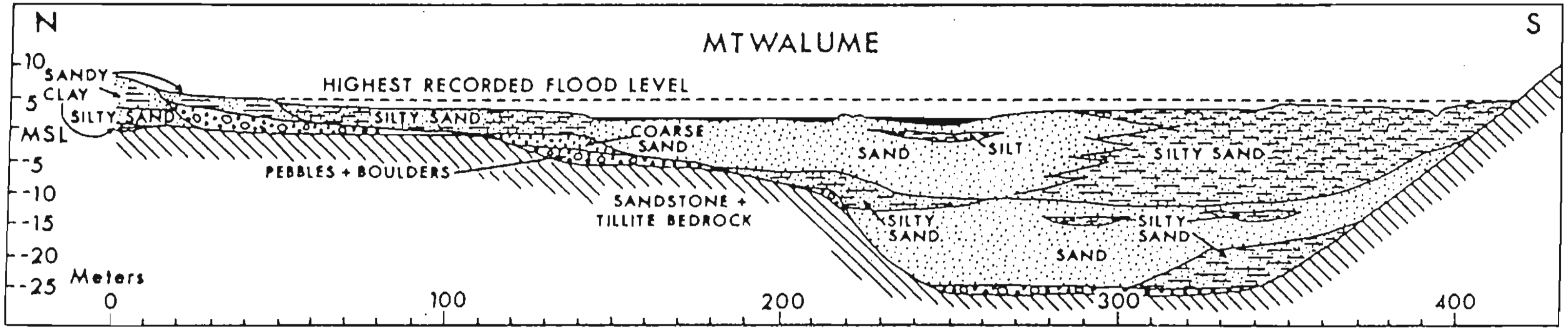


Figure 8.16. Cross-section of the Mtwalume bedrock channel (after Orme, 1974). Note the deep bedrock channel incised into a broader, shallower bedrock channel.

It is, however, likely that softer lithologies would undergo more marine erosion than harder ones and this, combined with a similar response to fluvial erosion, would be lithology-controlled. As the bedrock valleys are essentially filled with sediment their storage volume is now negligible, with the exception of the Mtamvuna. Consequently the main control which they exert is in limiting river channel size and lateral movement.

Floodplain width controls the ability of a river-mouth channel to migrate or split into distributary channels. In general, floodplains formed in resistant lithologies (NGS and granitoid metamorphics) are laterally restricted, compared to those in softer lithologies of the Ecca Group. The relationship is variable but lithology-type is generally reflected in floodplain width. The extent to which a river-mouth channel floodplain occupies the floodplain depends on discharge (a function of catchment size), nature of the bank materials (a function of the catchment geology) and height of the river-mouth barrier (related to wave refraction and barrier grainsize and sediment supply).

This multiplicity of controls on morphology of the receiving basin causes difficulties in assignment of a simple numerical value. The floodplain area of each river-mouth was calculated from the 1:10 000 orthophoto maps. In the hope of distinguishing the range in morphologies from short and wide to long and narrow floodplains, the axial length of the floodplain was also measured. The limit of the floodplain was marked by a distinct break in slope which, in the smaller river-mouths, approximated the five metre contour. In the larger rivers the 10 m contour was closer to the floodplain margin. In the Isipingo, Mlazi and Mbokodweni problems in defining the floodplain arose from human interference through canalisation, water diversion, embankment construction and buildings These three, together with the rivers north of the Tugela, occur in unconsolidated alluvial plains and have virtually unconfined floodplains due to the low surrounding gradient.

With the exception of river-mouths located in Quaternary unconsolidated sediments, it was possible to correlate the log of the floodplain area with the log of the catchment area with significant to highly significant correlation coefficients for each lithology. However, an equally good correlation was obtained when all the lithologies were grouped (Fig.8.17), and no significant differentiation in floodplain size occurred, based on lithology. It is however the floodplain shape, and more specifically the width rather than the size which influences river-mouth morphology, and so the axial length of each floodplain was calculated. This, divided by the floodplain area, gave a value for the average floodplain width. Wider floodplains enable overbank storage of sediments and the nature of those sediments exert a control on the nature of the river channel. Narrow bedrock channels restrict or prevent floodplain formation while broad floodplains may form in wide bedrock valleys.

For each given lithology, although broad generalisations could be made, no significant correlation was found between floodplain width and catchment size which suggested that variations in the degree of induration and subtle variations in lithology and topography masked simple lithological control. Nonetheless, when all the river-mouth floodplain widths were compared a general trend could be discerned for the wider valleys to occur in Alluvium and in both the Vryheid and Pietermaritzburg Formations.

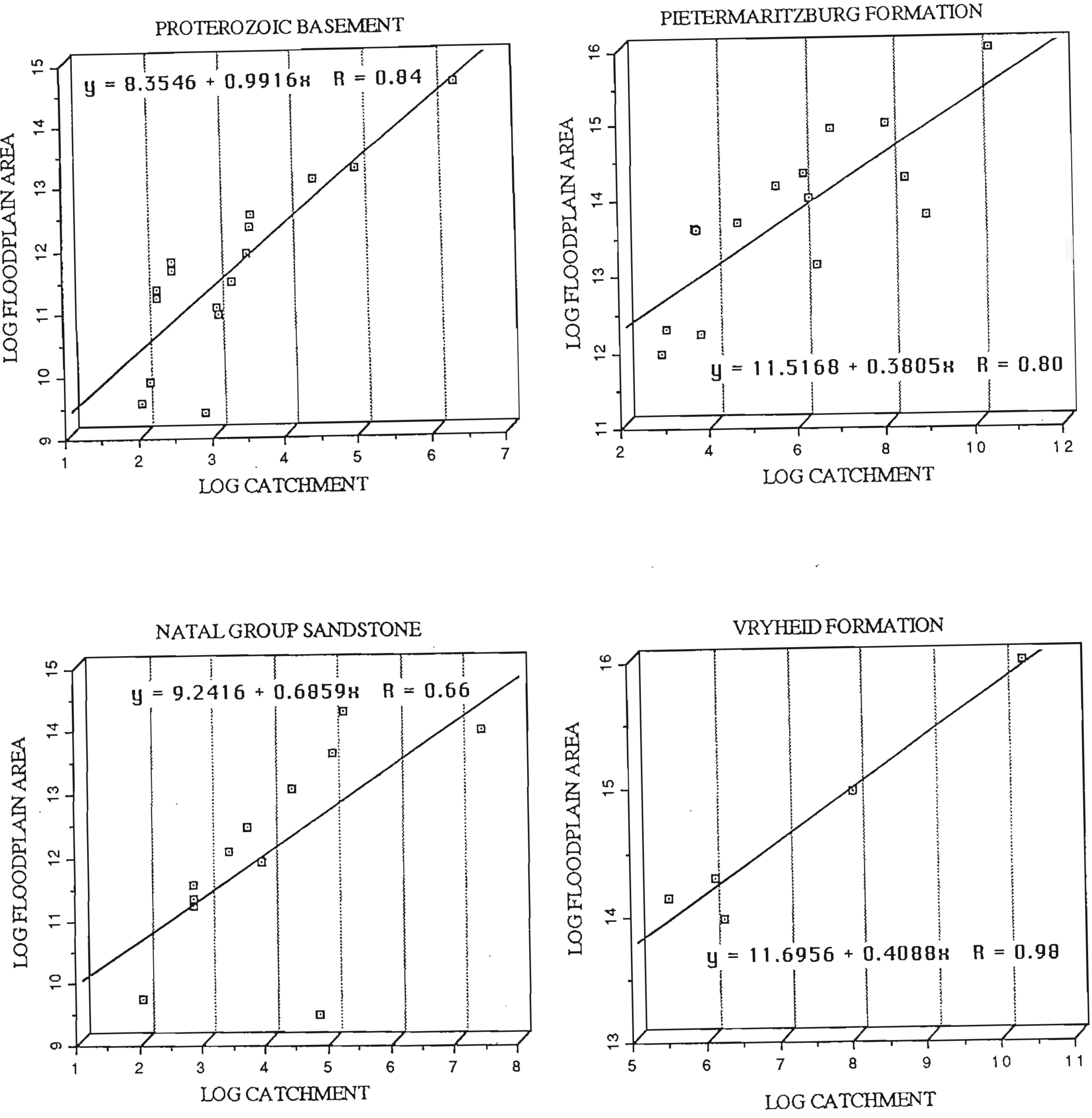
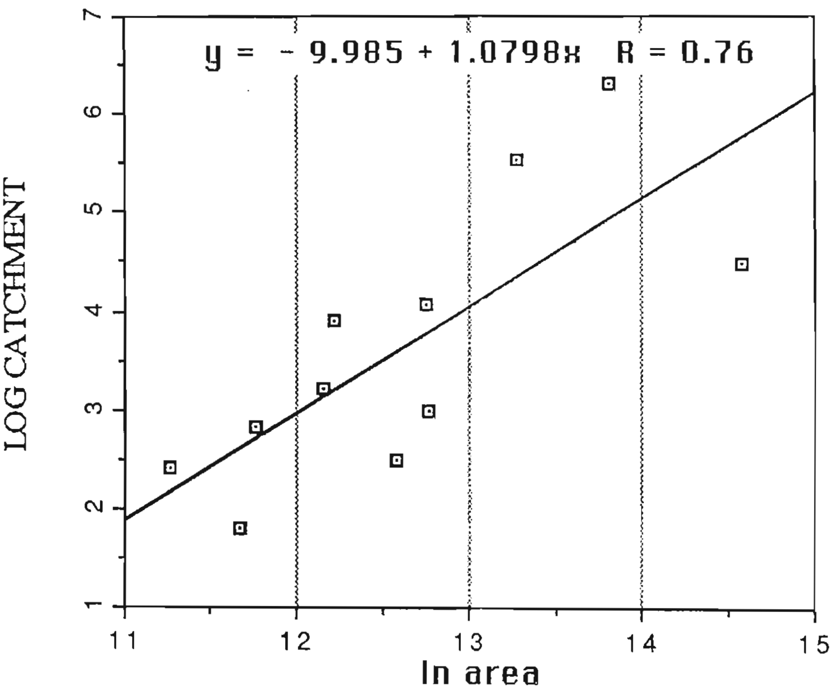


Figure 8.17. Logarithmic plots of catchment area against floodplain area for river-mouths cut in each coastal lithology (A-E) and for all river-mouths (F) (continued overleaf).

DWYKA TILLITE



ALL LITHOLOGIES

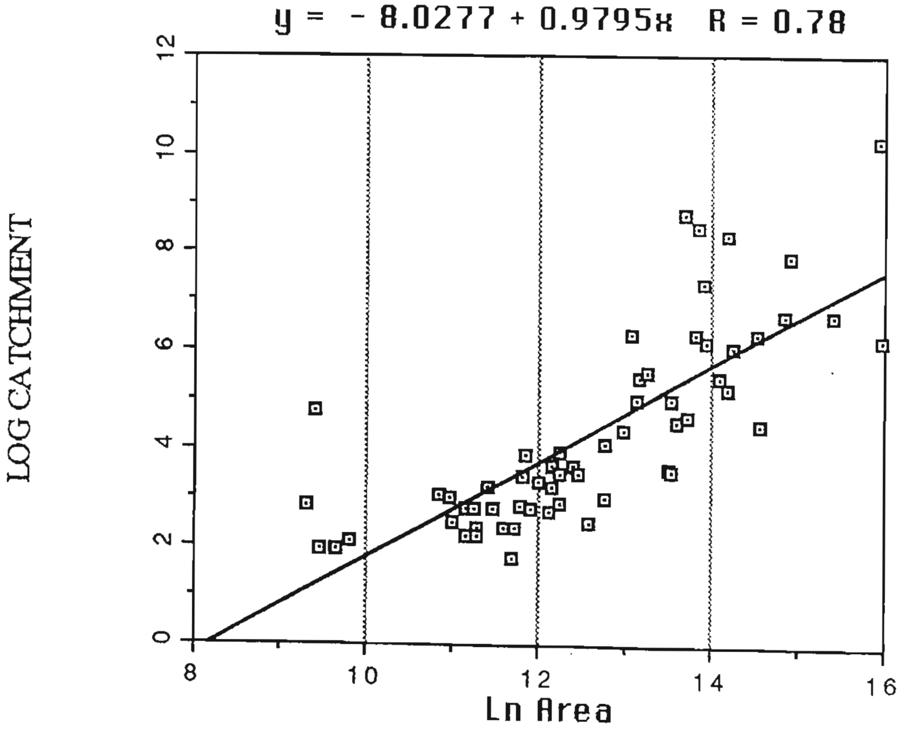


Figure 8.17 (continued). Logarithmic plots of catchment area against floodplain area for river-mouths cut in each coastal lithology (A-E) and for all river-mouths (F).

Moderately broad valleys are cut in Dwyka Tillite while laterally restricted valleys form in metamorphic rocks and Natal Group Sandstones (Table 8.2). Apparent anomalies in this list do occur, for example, the iNtshambili and Koshwana which occur in resistant lithologies have large mean floodplain widths. This is because, in both instances they are joined at the coast by a small tributary which increases the floodplain area without increasing the axial length. The Mzumbe has an unusually wide floodplain considering it is located in metamorphic rocks, but the mean floodplain width is increased by a large low-lying area north of the main river course, located behind a 40 m-high dune. The area may represent a coastal terrace and so is unrelated to incision by the river. Nonetheless it forms part of the modern floodplain and so increases its width. The Mpenjati which is wider than most river channels cut into metamorphic lithologies, is probably underlain at the coast by Cretaceous siltstone (Begg, 1978) which increases the average floodplain width.

Because of the various anomalies and masking effect of other variables the average floodplain width was considered to reflect the surrounding geology as affected by minor variations in topography and degree of induration or facies variation. Although it is not in itself genetic, it is seen as a composite reflector of genetic controls and is therefore incorporated into the classification as a variable which controls river-mouth morphology. Because the floodplain area was related to catchment size and catchment size is incorporated in the classification, the floodplain area is not.

8.7.4. Coastal morphology

The coastal morphology exerts an important control on the morphology of the receiving basin, particularly in the siting of the barrier and as a variable it should be incorporated into the classification. Barriers vary in size and shape, largely in accordance with coastal morphology. In areas where the coastline is rocky, sandy beaches are restricted to small embayments, many of which occur in river valleys.

The length of the river-mouth barrier should reflect to a large degree the nature of the adjacent coastline. Short barriers are generally confined to the lower reaches of a valley while longer barriers are associated with larger scale coastal planforms. Particularly long barriers are associated with prograding beachridges which progressively elongate the river course parallel to the coast.

Many barriers, particularly between Durban and Port Shepstone, have been impacted by embankment construction for railway lines. This effectively shortens the river-mouth barrier and reduces its permeability. The pristine length was used in the classification as the intention to assess the pristine morphology of the river-mouths and subsequently assess the effects of human impacts at a later stage.

A vital control on river-mouths is the flength of time for which the outlet is open. This largely depends on catchment size. A plot of the percentage of the year for which the mouth is closed against catchment size (Fig.8.18) shows a wide gap between river-mouths which are closed for over 50% of the year and those which are closed for less than 30% of the year. Several small-catchment rivers maintain outlets for most of the year while a few large-catchment rivers have no outlet for long periods. The reasons for these anomalies must be sought in other parameters. To clarify this on the plot, the largest-catchment rivers

FLOODPLAIN AREA (sq. m)	LOG CATCHMENT AREA	AV. FLOODPLAIN WIDTH	MOUTH GEOLOGY	RIVER-MOUTH
11000	2.83	31.43	BASEMENT	TONGAZI
13000	1.95	43.33	BASEMENT	MVUTSHINI
10000	1.39	60.00	BASEMENT	KU-BOBOYI
15333	1.95	69.70	NATAL GROUP	ZOLWANE
201920	3.91	80.77	DWYKA	MTENTWENI
51000	3.04	85.00	BASEMENT	BILANHLOLO
18000	2.08	90.00	BASEMENT	UVUZANA
12000	4.77	100.00	NATAL GROUP	VUNGU
77720	2.40	103.63	DWYKA	MHLANGAMKULU
79500	2.20	106.00	BASEMENT	MHLANGANKULU
75000	2.77	107.14	NATAL GROUP	MNAMFU
88640	3.22	110.80	BASEMENT	DAMBA
188880	3.66	111.11	SHALE	MANZIMTOTI
68000	2.77	113.33	NATAL GROUP	MFAZAZANA
57330	3.00	114.66	BASEMENT	KONGWENI
117040	1.79	130.04	DWYKA	MDESIGANE
67920	2.20	135.84	BASEMENT	KANDANDLOVU
433360	4.36	149.43	NATAL GROUP	MDLOTANE
106000	2.40	151.43	BASEMENT	KABA
60000	2.77	153.00	BASEMENT	SANDLUNDLU
120680	2.40	154.72	BASEMENT	KOSHWANA
182680	2.71	158.85	DOLERITE	MAHLONGWANA
94920	2.77	163.66	NATAL GROUP	KWA MAKOSI
147960	2.77	164.40	SHALE	NGANE
579200	5.54	165.49	DWYKA	FAFA
59450	2.48	169.86	DOLERITE	SETENI
129500	2.83	172.67	DWYKA	MBANGO
237000	3.64	182.31	NATAL GROUP	MHLANGENI
189000	3.22	189.00	DWYKA	BOBOYI
135080	3.43	192.97	BASEMENT	MZIMAYI
512000	4.95	196.92	BASEMENT	MBIZANA
137880	3.85	196.97	NATAL GROUP	MZIMAYI (S)
1090000	7.36	201.85	NATAL GROUP	MTAMVUNA
472120	6.30	224.82	SHALE	MPAMBANYONI
1432880	8.34	234.90	SHALE	MKOMAZI
158920	3.33	244.49	NATAL GROUP	MKUMBANE
999600	6.32	249.90	DWYKA	MTWALUME
205242	2.89	256.55	SHALE	LITTLE TOTI
430000	4.37	260.61	BASEMENT	MPENJATI
287160	2.48	261.05	DWYKA	MVUZI
345000	4.08	265.38	DWYKA	ZOTSHA
348960	3.00	268.43	DWYKA	SEZELA
753320	5.00	269.04	NATAL GROUP	MZINTO
527480	5.40	310.28	QUATERNARY	MBOKODWENI
253000	3.50	316.25	BASEMENT	INSHAMBILI
1320440	5.42	330.11	VRYHEID FM.	MHLALI
205080	3.47	341.80	BASEMENT	MHLUNGWA
1549320	6.05	344.29	VRYHEID FM.	TONGATI
1123480	6.16	362.41	VRYHEID FM.	MDLOTI
916880	4.65	366.75	QUATERNARY	MHLANGA
2143640	4.49	396.97	DWYKA	ZINKWASI
1024320	8.49	409.73	QUATERNARY	MGENI
750200	3.56	416.78	SHALE	MSIMBAZI
1482920	5.19	436.15	NATAL GROUP	NONOTI
893440	8.79	446.72	SHALE	MZIMKULU
746200	3.61	533.00	SHALE	MGABABA
8351640	10.28	556.78	VRYHEID FM.	TUGELA
807640	4.52	598.25	SHALE	MAHLONGWA
3015680	7.93	670.15	VRYHEID FM.	MVOTI
2781960	6.67	843.02	SHALE	LOVU
4992440	6.70	860.77	QUATERNARY	MATIGULU
2073560	6.31	1295.98	BASEMENT	MZUMBE
8658720	6.20	2546.68	QUATERNARY	MLALAZI

Table 8.2. Log of catchment area, floodplain widths and areas, and mouth geology of river-mouths in the study area ranked in order of floodplain width. A broad trend exists for narrow floodplains in Proterozoic basement and Natal Group Sandstone with wider floodplains in the Vryheid Formation, Pietermaritzburg Formation (SHALES in table) and Quaternary alluvium. Other factors such as catchment size and topography also play a role in floodplain morphology.

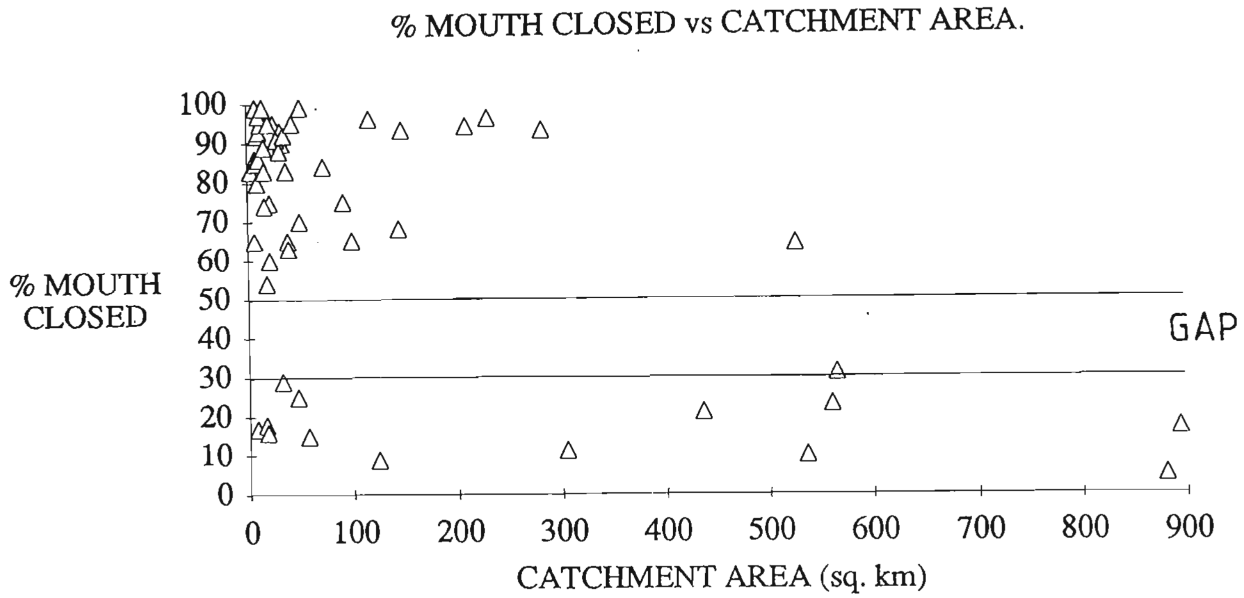


Figure 8.18. Plot of catchment area versus the percent of the year for which an outlet is present. There is a broad gap between those river-mouths whose outlet is closed for less than 30% of the year and those whose outlet is closed for over 50% of the year. There is a broad coincidence between large-catchment rivers and generally open outlets but considerable overlap exists.

were excluded and the data replotted. This made identification of the anomalies easier, a necessity if the reasons for their anomalous outlet characteristics were to be explained. Six river-mouths, the Zotsha, Boboyi, Mhlabatshane, Tongazi, Sandlundlu and Zolwane, maintain open outlets more commonly than others of similar size. Conversely, the Mdloti stands out as one of the larger rivers which is closed for most of the year.

Formation of an outlet through a barrier depends on the relationship of discharge compared to evaporation, seepage through the barrier, evaporation and transpiration (Carter *et al.*, 1984). Maintenance of the outlet occurs as long as discharge exceeds the above factors plus wave energy which works to close the outlet.

As discharge is related to catchment size, and evaporation is linked to climate, which may be regarded as constant along the coast, then seepage through the barrier is the main variable as yet unaccounted for. Seepage per unit barrier length depends largely on grainsize and hence porosity (Carter *et al.*, 1984). In addition, the barrier length controls the flux. The presence of rocks (either bedrock or beachrock) under or within the barrier, may reduce seepage and promote breaching. Barrier length relates to floodplain width except where coast-parallel extension or restriction occurs. Turbulence will tend to maintain an outlet more easily than laminar flow as sand moved into the outlet by wave action can be entrained and removed. The presence of rocks at the base or side of a channel enhances turbulence and assists in outlet preservation. Outlet formation is important to biological diversity in Natal river-mouths, as it enables organisms to move from the sea to the river-mouth and vice-versa at appropriate stages in their life cycles (Wallace & van der Elst, 1975; Whitfield, 1980; Wallace *et al.*, 1984). The frequency of outlet formation also controls the extent to which breaching-related impacts occur, and the extent to which muddy, organic-rich sediment can accumulate in tranquil, back-barrier areas when no outlet is present.

The Mdloti river-mouth is normally closed despite a large discharge because of its large open water area and long barrier which promote evaporation and seepage. Wave refraction at the straight barrier is negligible and little variation in elevation of the barrier crest occurs. Consequently there is little opportunity for river flow to exploit natural weaknesses.

All of the small rivers which have persistent outlets (Zolwane, Tongazi and Sandlundlu), are characterised by narrow, rocky outlet channels. The Zotsha and Boboyi which are slightly larger, form outlets across rocky outcrops at the southern end of their long barriers. It is difficult to assign a numerical value to the extent to which rock is present under a barrier and insufficient data is available to state the volume of sand or flux of water through Natal river-mouth barriers at this stage. The relationships between outlet formation and the controlling variables too have not been quantified. Consequently, in view of the complexity of the variables involved, it was decided to simply include the amount of time the outlet is closed as a variable in the classification, in that it is a consolidating factor which embodies the as-yet unquantified relationship between coastal morphology and outlet formation. As the catchment size and barrier length are also to be used, the other factors in outlet formation will also be incorporated in the classification.

8.7.5. Receiving basin morphology

Assessment of the overall morphology of receiving basins, by combining the coastal morphology and floodplain controls, is attempted in this section. A plot of catchment size, percentage of time the outlet is closed, barrier length and mean floodplain width was made in the hope that it would illustrate the range of variation observed. Because of the wide variation in catchment size, the rivers were divided into 4 groups. This can be justified on the relationship between catchment size and discharge and between discharge and sediment-transporting capacity of a river. The Tugela, whose catchment is an order of magnitude bigger than the next largest river and is as large as all the other rivers combined, was classified alone. The next largest rivers are the Mzimkulu with a catchment area of over 6000 km^2, and several others over 1000 km^2. There is a large gap in the ranked catchment sizes between 254 and 422 and so the lower limit of the next division was made there. This subjective division also separated those catchments with sufficient discharge to effect significant morphological changes during extreme events. All of the rivers in this group were identified by Perry (1989) as having sustained "severe flood damage and/or inundation" during the 1987 flood. There is then a continuum of smaller rivers with few breaks and so an arbitrary split was made at the 50 km^2 catchment interval.

Thus, setting aside the Tugela, the remaining rivers were divided into three groups: large-catchment rivers (422 to 6562 km^2), intermediate-catchment rivers (50 to 254 km^2) and small-catchment rivers (4 to 48 km^2). For each of these groups a plot was made of the three variables, average floodplain width, barrier length and percent of the year the mouth is closed. The results are depicted in Figures 8.19A,B and C.

In all cases, bivariate plots of barrier length versus floodplain width clearly showed three trends. Those river-mouth basins which are elongated at the coast plot on a trend to the left of the diagram where barrier length significantly exceeds the average floodplain width. In the centre of the plot are a number of river-mouths in which the barrier length approximates the average floodplain width. To the right lie those river-mouths which have a barrier shorter than the average floodplain width and which are consequently restricted at the coast.

When the third axis was added (Fig 8.19A,B,C), the central rivers on each plot which displayed little coastwise extension or restriction, were subdivided into those which are normally open and those which are normally closed. This incorporates the numerous variables which control outlet formation and maintenance. This variable was less important in the case of larger rivers which are generally open, but even in this case, the Mdloti was isolated as a normally-closed large-catchment river.

8.7.6. Discussion

In order to test the validity of the results presented the river-mouths identified within each group were compared and the catchment geology of each was also compared. Any range of variation observed within the group should be explained by differences in the nature of the incoming sediment. In the small river-mouths for example, the Mhlangankulu, Mahlongwana, Mhlungwa, Mtentweni, Kongweni and Mkumbane were grouped together as rivers with coastwise extensions. They however lie at different positions on the

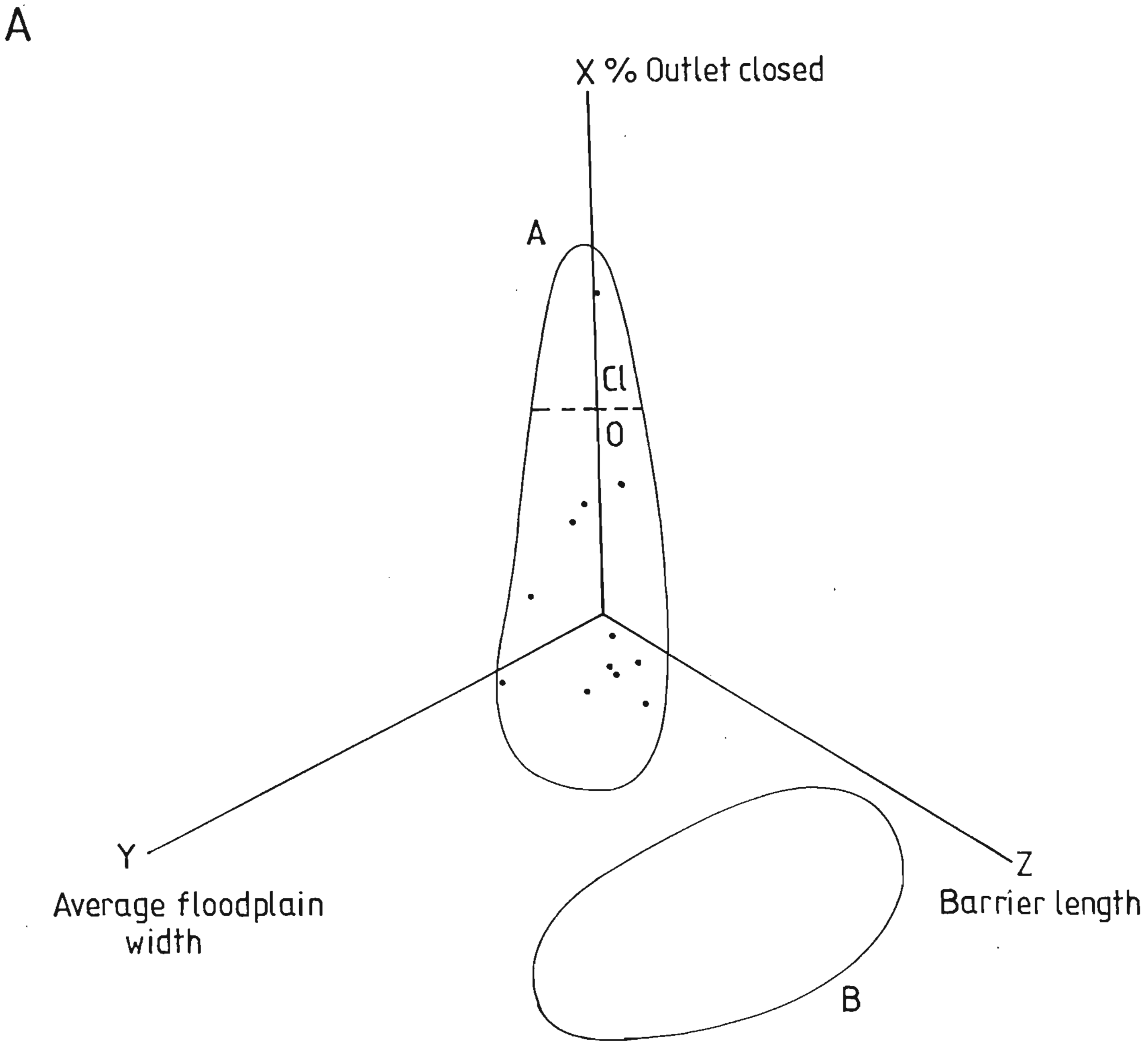
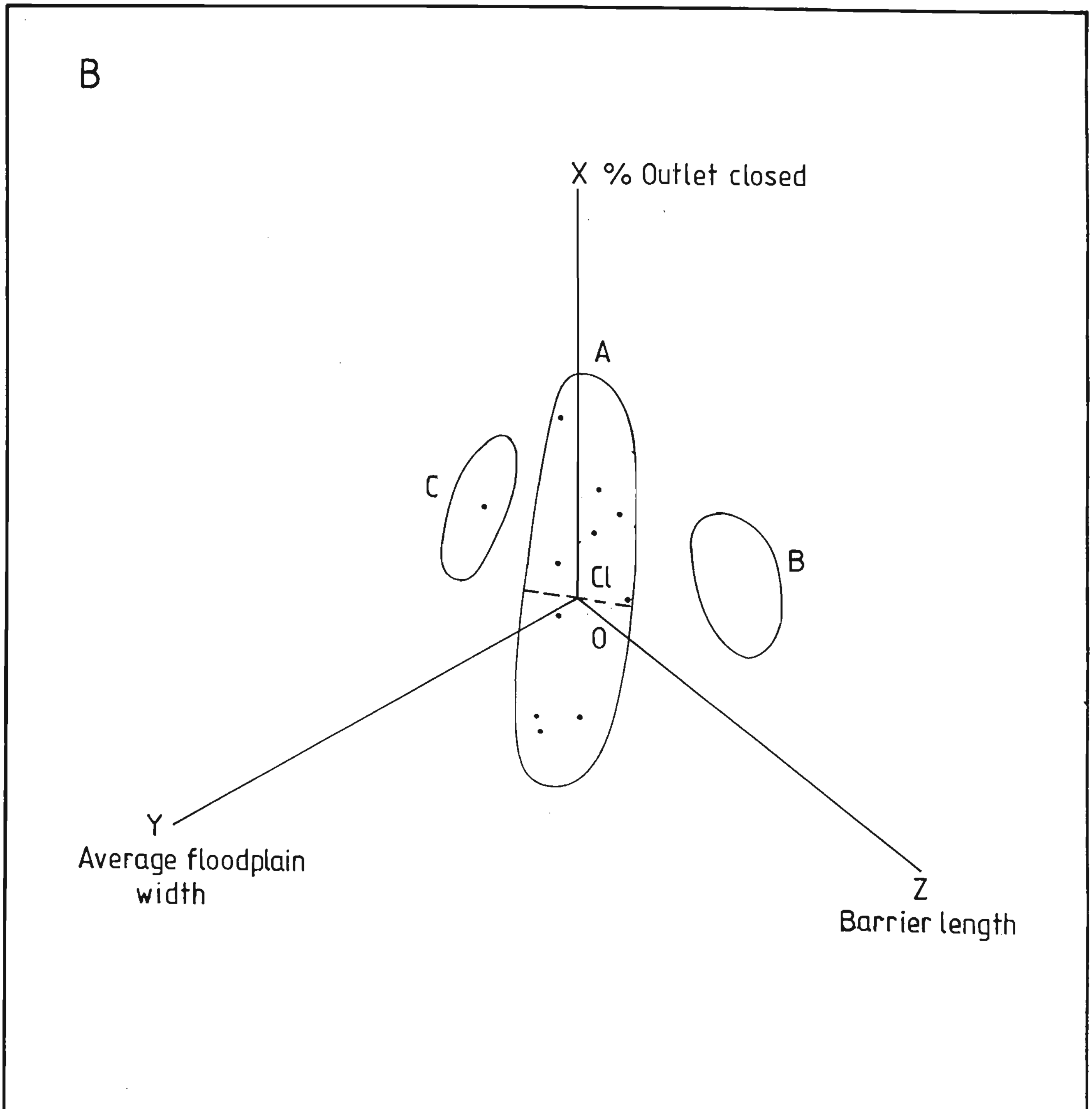


Figure 8.19A-C. Triangular plots of percent of the year the mouth is closed, barrier length and average floodplain width for three group of river-mouths separated arbitarily into large, medium and small catchments for ease of presentation. In each case a number of groupings can be recognised: A, River-mouths in which floodplains and barriers were equal in length; B, River-mouths in which the barrier was longer than the floodplain width; and C, River-mouths with barriers shorter than the average floodplain width. Subdivisions could also be made into open (O) and closed (Cl) versions of each group.


B
X % Outlet closed
A
C
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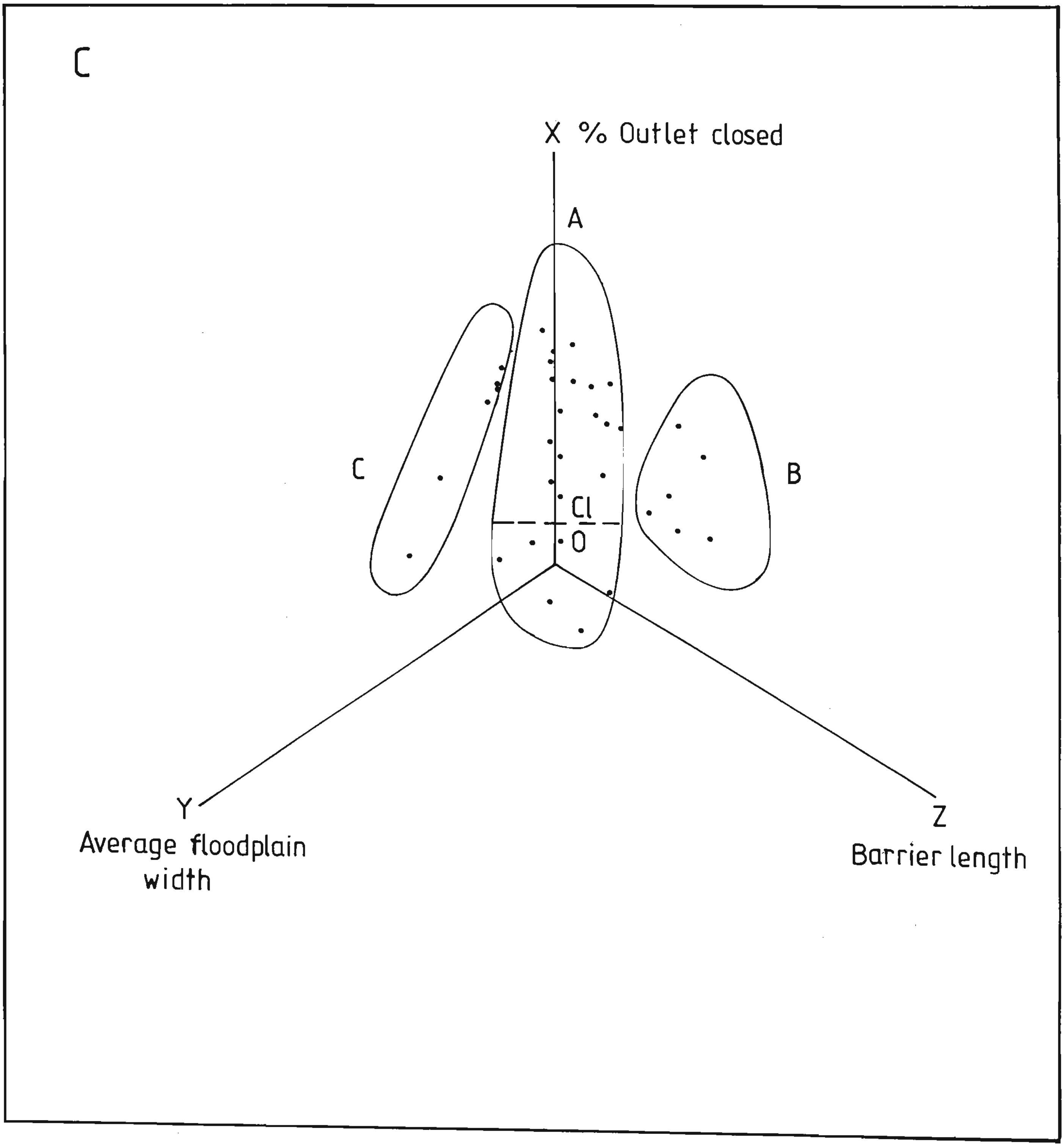
Y
Average floodplain width
Z
Barrier length


C
X % Outlet closed
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C
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Cl
O
Y
Average floodplain width
Z
Barrier length

sedimentary inputs plot. The variation in morphology was best illustrated by comparing the Mahlongwana with the other river-mouths. The Mahlongwana has considerably more mud- and fine-sand-yielding rocks in its catchment. In comparison to other river-mouths in this group it had well-developed vegetation on a central island and its channels were apparently deeper and more turbid. The other river-mouths which are more dominated by granitoid rocks have typically sandy channels. This suggests an unsuitable substrate for vegetal colonisation.

The small river-mouths with coastal restriction were the uMgababa, Msimbazi, Sezela, Mzimayi, Seteni and Koshwana. These river-mouths have broad floodplains, typically surrounded by vegetation.

In the smaller river-mouths which are not impacted so severely by floods, vegetation may overcome the control of sediment grainsize and enable maintenance of stable banks. Hence small river-mouths in this category may have the appearance of being similar morphologically. The Sezela which is dominated by a sand-yielding catchment has a channel pattern superficially similar to the uMgababa and Msimbazi which have more muddy catchments. However, in the Sezela the surrounding floodplain is vegetated by ***Phragmites*** reeds while in the others muddy supratidal flats are vegetated by sedges and the channels are vegetated with *Zostera* (eel grass) (Grobbler *et al.*, 1987). The Mzimayi, and Koshwana too are surrounded by *Phragmites* reeds.

The other small river-mouths, which have neither coastwise extension or restriction, are divided into closed and open. The Tongazi, Zolwane, Boboyi, Sandlundlu, Little Amanzimtoti and Mhlabatshane are normally open. The Zolwane and Tongazi are predominantly rocky channels with little sediment input and they lie toward the Tillite and Sandstone end of the sand-yielding axis. The Boboyi has a similar position in the group because of its open mouth but morphologically it displays coastal constriction. River flow is too low to occupy the entire floodplain and because of its sandy nature the surrounding floodplain is dominated by *Phragmites* reeds rather than a vegetated muddy floodplain. The Little Manzimtoti displays coastwise extension but is classified in this group because of its open condition. The presence of mud in its catchment has enabled formation of vegetated supratidal areas in its floodplain. The Mhlabatshane and Sandlundlu are essentially sandy channels with little colonisation by vegetation, a factor which may be in part ascribed to their open nature and relatively narrow valleys.

The remaining small-catchment rivers are those where the barrier simply encloses the river valley, permitting no channel extension or constriction at the coast. The eighteen river-mouths in this group have a wide range of morphologies which hopefully depend on their catchment geologies. Four of these, the Mdesigane, Mvuzi, Mnamfu and Kwa-Makosi, lie at or near the Tillite/Sandstone apex. The Mdesigane and Mvuzi are characterised by surrounding reedswamps in their floodplains while the Mnamfu and Kwa-Makosi are noteable for the absence of reeds (Begg, 1984a) and presence of grasses and sedges. All, however, have discrete channels which are comparatively deep even when the outlet opens.

At the granitoid apex lie the Kaba, Bilanhlolo, iNtshambili and Mvutshini, all of which have shallow sandy channels characterised by clean sandy bedforms. Small areas of *Phragmites* reeds are encroaching on the channels of the Bilanhlolo and Mvutshini, while the Kaba has a well-developed fringing reedswamp on the channel margin which is still encroaching on the channel area (Begg, 1984a). The absence of reeds in the Ntshambili may be attributed to its narrow, rock-confined channel. In this class there is an indication that some river-mouths are more advanced in their evolution than others, but only by a few years reed growth. A complicating factor arises from the fact that reed growth may be hindered in some instances by high water levels during the closed phase which render the water too deep for reed growth. This could be linked to barrier height which, if above the equilibrium long profile gradient of the river, would inhibit reed growth indefinitely by promoting deep water.

At the shale+dolerite apex lies the Seteni, whose narrow floodplain has inhibited vegetation growth. Nonetheless, Begg (1984a) noted encroachment of reeds between 1978 and 1984. the channel is relatively deep and characterised by muddy sediments.

River-mouths which lie within the triangle vary in their channel characteristics according to the amount of mud- and fine-sand-yielding lithologies in their catchments. These lead to more restricted and deeper channels compared to the sandy channels of the granitoid-dominated catchment rivers.

In the intermediate catchment-size category of river-mouths four were in the permanently open category, the Vungu, Zotsha, Mahlongwa and Nonoti. The Vungu is in a class of its own, being essentially a coastal plunge pool at the base of a waterfall. The others are typified by vegetated floodplains with laterally-restricted channels. Reedswamps occur on the channel margins except in the Mhlali. Tidal exchange through the outlet (Begg, 1984a) cannot be argued to inhibit their growth as they are present in the Mahlongwa which also experiences tidal exchange. The Mhlali floodplain is vegetated with grasses and sedges. The Zotsha channel is shallower and more sandy than the other river-mouths, a fact attributable to its mainly sand-yielding catchment.

The Mhlanga and Nonoti are the only river-mouths in this category which experience coastwise extension behind sandy barriers. The Mhlanga has much more mud-yielding rocks in its catchment which may be responsible for the sinuous channel pattern there, compared to the more sandy Nonoti whose channel is straighter.

The only intermediate-sized river-mouth which is constricted at the coast is the Zinkwasi. There a wide floodplain is occupied by a *Phragmites* swamp but a clearly-visible flood channel is located at the northern side of the reedswamp.

Fourteen rivers are in the large catchment-river category. None of these were restricted at the coast as a result of the high discharge and erosive power of the outflowing water. The Mdloti and Mtwalume were categorised together, due to being frequently closed and having wide floodplains. Both have similar catchment geology and lie closest to the granitoid apex which gives them both sandy channels.

In the larger rivers the effect of floodplain width is more important, as this strongly influences the response of the river-mouth during floods. Wider floodplains experience less vertical erosion during floods than narrow ones and provide sites for overbank deposition. The Lovu, Mzumbe and Mvoti have wide valleys while the Tongati, Mpambanyoni, and Mtamvuna are narrow. The Tugela, Mzimkulu, Mgeni and Mkomazi are of intermediate width, but their catchments are much bigger than the other rivers in this group, suggesting that they belong in a class by themselves. The Matigulu, Mlalazi, and Mgeni are extended parallel to the coast.

8.8. DISCUSSION

The results outlined above demonstrate the roles played by the various factors in river-mouth morphology both on the sedimentary inputs and the receiving basin. They have been shown to exert controls on river-mouth morphology. In order to fully classify these river-mouths it is necessary to combine the two groups of controlling factors (receiving basin morphology and sedimentary inputs) into a single classification. Two possibilities exist. One is to recognise four groupings for each of the three catchment-size classes (twelve groups) and then to superimpose on this an arbitrary subdivision into catchments dominated by various sedimentary inputs. At its simplest level this would involve three options: shale-dominated, Tillite and Sandstone-dominated or Granitoid-dominated catchment categories. Such a classification would result in thirty-six classes. The second possibility is to tabulate all the data together and use multivariate statistics to classify them into groups of river-mouths which are morphologically similar.

For only sixty three river-mouths a classification into thirty six classes is clearly unacceptable as too much scatter would be produced. Furthermore, it was found with reference to delta morphological classification, (Coleman & Wright, 1975) that not all permutations of variables necessarily occur in nature. Coleman & Wright (1975) found multivariate statistical methods gave an acceptable classification of delta morphology and it was decided to adopt a similar approach here.

The seven variables used in the classification are as follows:

- percentage of year mouth closed
- average floodplain width
- percentage of catchment underlain by granitoid rocks
- percentage of catchment underlain by Dwyka Tillite/Natal Group Sandstone
- percentage of catchment underlain by shales
- barrier length
- catchment size

The tabulated data is contained in Table 8.3.

Labels	Tillite +sst	shale +doleri	Metamorphics	Catchment	Av.F.Plain.w	total barrier	% mouth closed
MTAMVUNA	46	54	0	1570	202	630	2
ZOLWANE	80	0	20	7	70	25	17
SANDLUNDLU	29	0	71	16	153	140	18
KU-BOBOYI	33	0	67	4	60	60	83
TONGAZI	44	0	56	17	31	50	16
KANDANDLOVU	25	0	75	9	136	140	80
MPENJATI	45	0	55	79	261	390	65
KABA	0	0	100	11	151	140	92
MHLANGANKULU	0	0	100	9	106	350	93
MBIZANA	37	0	64	141	197	500	68
MVUTSHINI	0	0	100	7	43	80	86
BILANHLOLO	0	0	100	21	85	110	75
UVUZANA	33	0	67	8	90	80	85
KONGWENI	11	0	89	20	115	360	60
VUNGU	72	0	28	118	100	100	9
MHLANGENI	68	0	32	38	182	170	65
ZOTSHA	70	0	30	59	265	510	15
BOBOYI	60	0	40	25	189	70	29
MBANGO	71	0	29	17	173	300	95
MZIMKULU	28	67	5	6562	447	1100	3
MTENTWENI	0	20	80	50	161	350	70
MHLANGAMKULU	0	25	75	11	104	80	97
DAMBA	15	10	75	25	111	220	95
KOSHWANA	0	0	100	11	155	40	86
INSHAMBILI	0	0	100	33	316	320	90
MZUMBE	23	8	70	549	1296	1100	10
MHLABATSHANE	7	0	93	47	197	250	25
MHLUNGWA	0	0	100	32	223	450	93
MFAZAZANA	33	0	67	16	113	150	89
KWA MAKOSI	81	0	19	16	118	200	83
MNAMFU	100	0	0	16	107	180	89
MTWALUME	26	6	67	553	250	950	31
MVUZI	100	0	0	12	200	300	99
FAFA	27	15	58	254	220	500	96
MDESIGANE	100	0	0	6	130	140	65
SEZELA	32	0	68	20	268	120	95
MKUMBANE	24	8	68	28	244	550	91
MZINTO	5	0	95	149	220	600	93
MZIMAYI	11	0	89	31	193	70	88
MPAMBANYONI	36	10	55	546	225	280	23
MAHLONGWA	74	7	20	92	598	930	75
MAHLONGWANA	58	25	17	15	159	450	99
MKOMAZI	15	78	7	4183	235	1100	1
NGANE	23	77	0	16	164	150	74
MGABABA	55	27	18	37	533	220	83
MSIMBAZI	42	42	15	35	417	170	92
LOVU	68	10	22	785	843	650	17
LITTLE TOTI	40	20	40	18	257	370	54
MANZIMTOTI	59	12	29	39	111	210	63
MBOKODWENI	77	4	20	221	310	650	99
MGENI	27	61	13	4863	410	1600	0
MHLANGA	50	44	6	105	367	900	96
MDLOTI	42	11	47	474	362	900	64
TONGATI	51	22	27	422	344	320	21
MHLALI	76	19	6	226	330	450	11
SETENI	0	100	0	12	170	50	83
MVOTI	42	30	28	2773	670	1150	2
MDLOTANE	49	51	0	78	149	200	95
NONOTI	77	23	0	180	200	950	94
ZINKWASI	60	40	0	89	351	250	84
TUGELA	6	87	9	29000	557	1450	5
MATIGULU	44	29	27	814	861	4800	5
MLALAZI	17	19	64	492	2547	4800	5

Table 8.3 Data used in the cluster analysis.

8.9. CLASSIFICATION RESULTS

8.9.1. Cluster analysis

A hierarchical cluster analysis of the seven tabulated variables was carried out, using the computer program SYSTAT on an Apple Macintosh computer. Cluster analysis is a multivariate procedure for detecting natural groupings in data and in one respect resembles discriminant analysis, in which the researcher seeks to classify a set of objects into subgroups (Wilkinson, 1987). Unlike discriminant analysis, however, neither the identity nor the number of subgroups in the set is necessarily known. Hierarchical clustering partitions a set of samples into a group of nested sets and the output is in the form of a dendrogram (Johnson, 1967). In the computerised analysis, a distance matrix is first computed among all cases using all the numerical variables in the tabulated data. Distances are computed as normalised Euclidean distances. The distance of one object or cluster to another can be calculated by a variety of methods (linkages). In the analysis performed here, the best results were obtained using the median linkage method which uses the median of all distances between pairs of objects in different clusters to see how far apart they are (Gower, 1967).

8.9.2. River-mouth groupings

The resultant dendrogram from the cluster analysis is shown in Figure 8.20. Considerable variation was evident between the larger catchment rivers which were distinguished from the rest at high levels in the analysis. At lower levels (higher degrees of similarity) several distinct clusters emerged among small-catchment river-mouths. These are identified and labelled in Figure 8.20. By cross-reference to Table 8.3 the general attributes of each cluster were identified and listed below. For ease of reference these are divided into three sections: groups 1-5, groups 6-9 and outliers. Illustrations of typocal river-mouths are all drawn to the same scale to facilitate comparison.

8.9.2.1.Groups 1-5

Group 1. This group consists of twenty-four small-catchment river-mouths: the Zolwane, Tongazi, Mvutshini, Mhlangamkulu, Ku-Boboyi, Uvuzana, Bilanhlolo, Koshwana, Mzimayi, Boboyi, Mdlotane, Mhlangeni, Mdesigane, Mnamfu, Kwa-Makosi, Manzimtoti, Kandandlovu, Mfazazana, Kaba, Sandlundlu, Damba, Ngane, Sezela and Seteni. While they all have small catchments they can clearly be subdivided into two subgroups (Fig.8.20). At successive splits in the dendrogram, the Seteni and Sezela emerge as outliers within Group 1, and are apparently most different from the rest of the group, probably as a result of shale and dolerite-rich catchments. The remaining two subgroups, designated 1A and 1B are discussed below. River-mouths in Group 1 which were documented by Orme (1974) have shallow bedrock valleys, generally less than 15 m below sea-level.

Group 1A. (Zolwane, Tongazi, Mvutshini, Mhlangamkulu, Ku-Boboyi, Uvuzana, Bilanhlolo, Koshwana, Mzimayi and Boboyi). These ten river-mouths appear to have been grouped on the basis of having small catchments (<30 km^2), narrow floodplains, barriers shorter than 100 m, predominantly sand-yielding catchments and being generally closed. The main source of variation within the group is in floodplain width and outlet presence/absence.

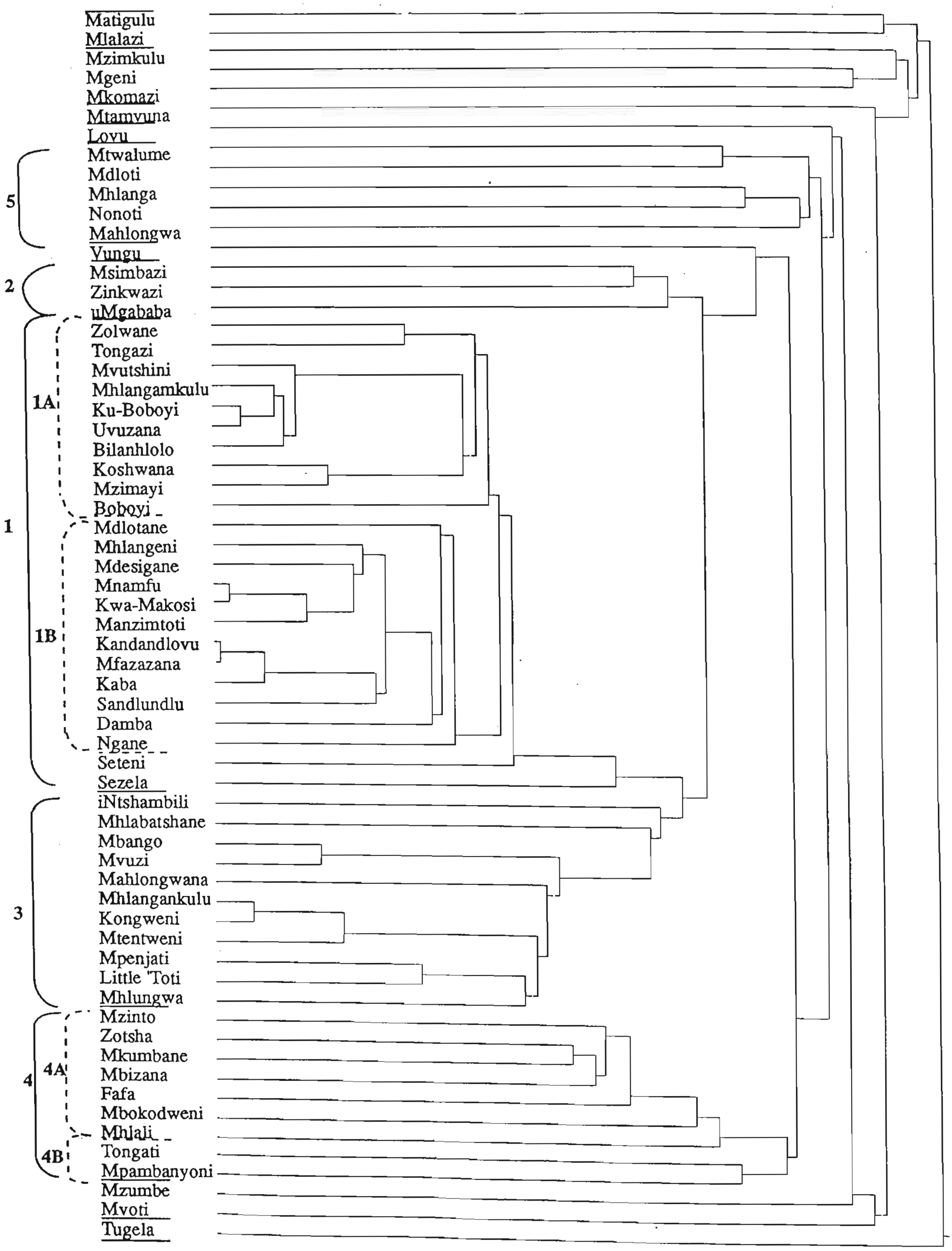


Figure 8.20. Dendrogram of river-mouths based on seven variables listed in Table 8.3. Numbered groups are discussed in text. For groups 6 to 8 see Figure 8.21.

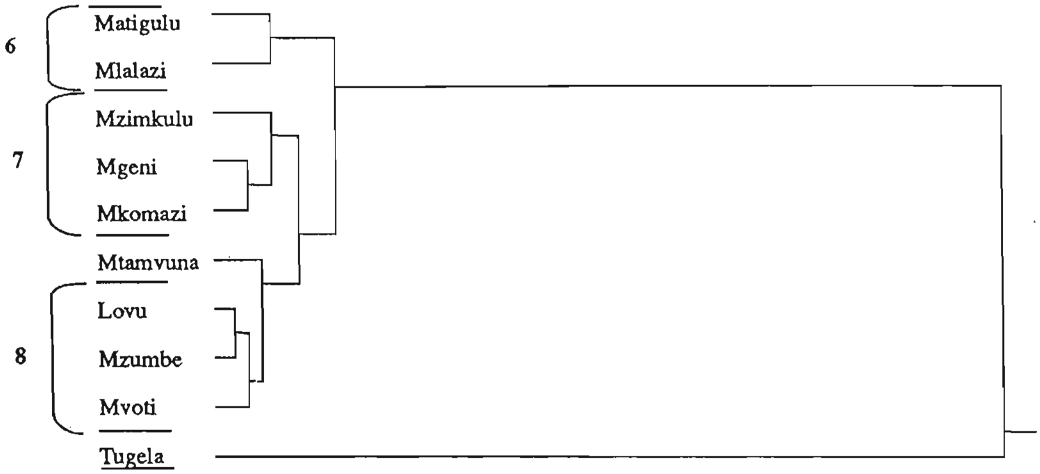


Figure 8.21. Dendrogram of large river-mouths extracted from Figure 8.20, showing relationships between large river-mouths. Three groups are recognised and the Mtamvuna and Tugela emerge as outliers.

Morphological response to these variables is reflected in elongate, generally bedrock valleys, which are mostly occupied by open water and lack extensive floodplain development. A selection of river valleys in this group are shown in Figure 8.22. Those which have insufficient discharge from the catchment to fill the entire valley have only narrow floodplains, and hence the channels are small and generally fringed by *Phragmites* reeds. Several of these small river-mouths (Zolwane, Tongazi and Boboyi) maintain outlets for long periods. This probably results from short barriers and the presence of bedrock in the outlet position of the Zolwane and Tongazi. The reed-filled floodplain and consequently restricted channel, of the Boboyi, compared to the broad shallow channel of the Bilanhlolo, for example, may assist in outlet maintenance. This suggests that the Boboyi is at a more advanced evolutionary stage than the Bilanhlolo. Begg (1984b) noted that the floodplain of the Mzimayi was rapidly colonised by reeds in the period 1978-1984, which further suggests that this is a typical evolutionary trend for this group of river-mouths. The more restricted channel in mature river-mouths of this group may then permit more frequent outlet formation. A similar evolutionary trend was noted in small Australian estuaries (Roy, 1984) .

Group 1B. This group comprises the Mdlotane, Mhlangeni, Mdesigane, Mnamfu, Kwa-Makosi, Manzimtoti, Kandandlovu, Mfazazana, Kaba, Sandlundlu, Damba and Ngane river-mouths. These twelve river-mouths appear to have been grouped on the basis of having small catchments (<40 km^2), floodplains between 100 and 200 m wide, barriers between 150 and 200 m long, predominantly sand-yielding catchments (except the Mdlotane and Ngane, which lie at the outside edges of the group) and being generally closed. This group differs from 1A mainly in having larger and wider floodplains in relation to their catchment size, consequently the channels occupy only part of the river valley. Their typically longer barriers enable limited coastwise extension in most cases (Fig.8.23) and thus evaporation and seepage cope with freshwater discharge and outlet formation is infrequent. The Sandlundlu is an exception which is frequently open, probably as a result of rocks at the outlet position. Comparison of the Sandlundlu and Kandandlovu which are virtually identical in input variables, shows that the Sandlundlu has a broad sandy channel which is frequently open to the sea, while the Kandandlovu has a narrow channel surrounded by a *Phragmites* reedswamp. This suggests an evolutionary trend in which the Kandandlovu is more advanced. It is however, unable to maintain an outlet despite its channel-restricted flow because of its wider barrier compared to those in group 1A. The Sandlundlu may be hindered from achieving this evolutionary step because of its open mouth: high salinity impedes growth of *Phragmites* (Benfield, 1984).

Group 2. This group lies to the left of Group 1 in the dendrogram and is separated from it distinctly. It contains only three river-mouths, the Msimbazi , uMgababa, and Zinkwasi. They are characterised by mainly shale and tillite/sandstone in their small catchments (35-90 km^2), and have particularly wide floodplains (>350 m). They typically lack outlets and when they breach, drain rapidly, exposing the river bed (Grobbler, 1987). In addition, river-mouth barriers are markedly narrower than floodplains. This restricts the water bodies at the coast and diminishes the input of marine sand through barrier overwash.

The large, wide, floodplains are elevated to such an extent that grasses have colonised them (Fig 8.24) in an apparent evolutionary succession to the pioneering *Phragmites* reeds which fringe some of the channels. Narrow dendritic channels are cut in the cohesive sediment of the floodplain, marginal to the main water

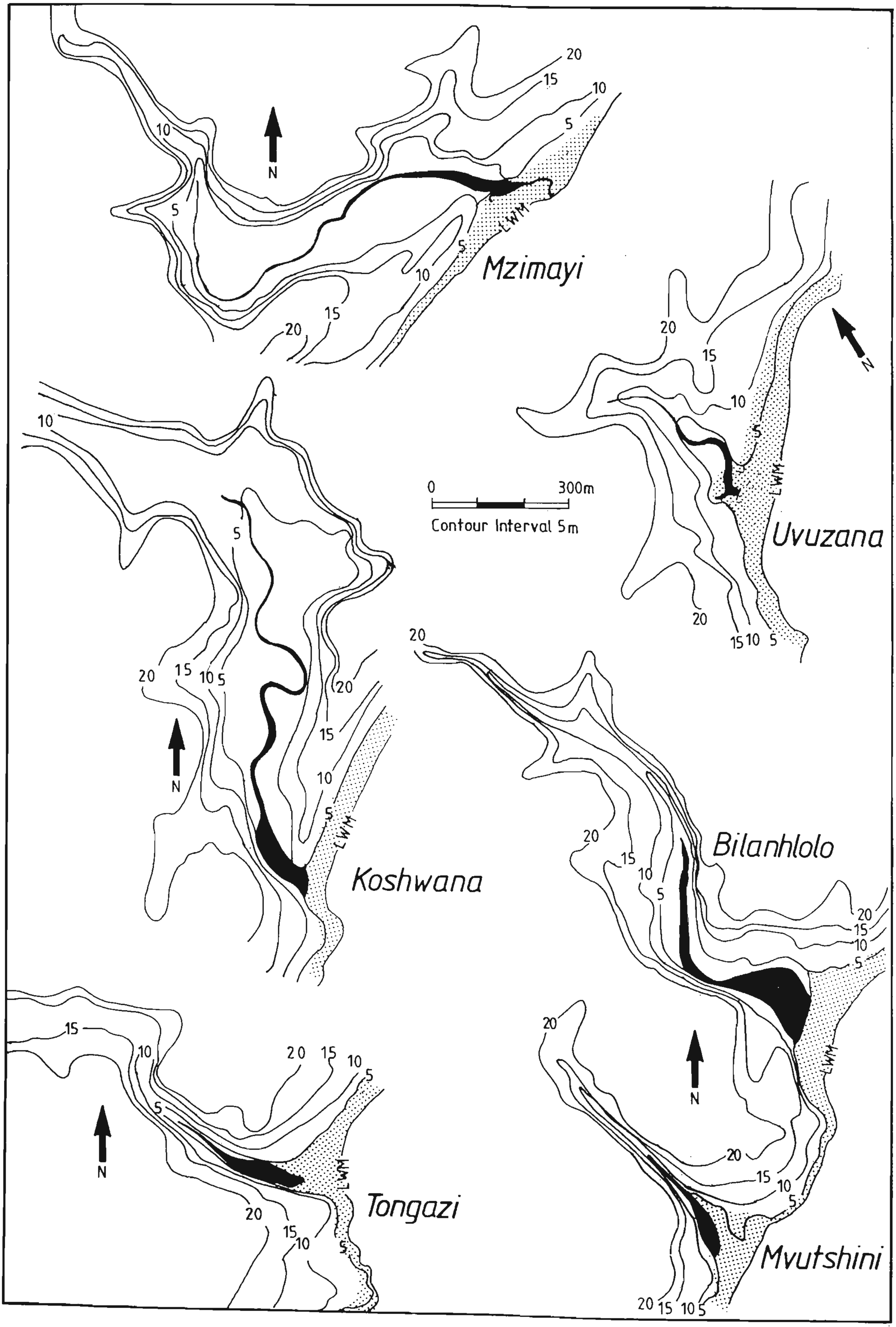


Figure 8.22. Topography of several river-mouths in Group 1A. Water area shaded black. These rivermouths are narrow and have short barriers.

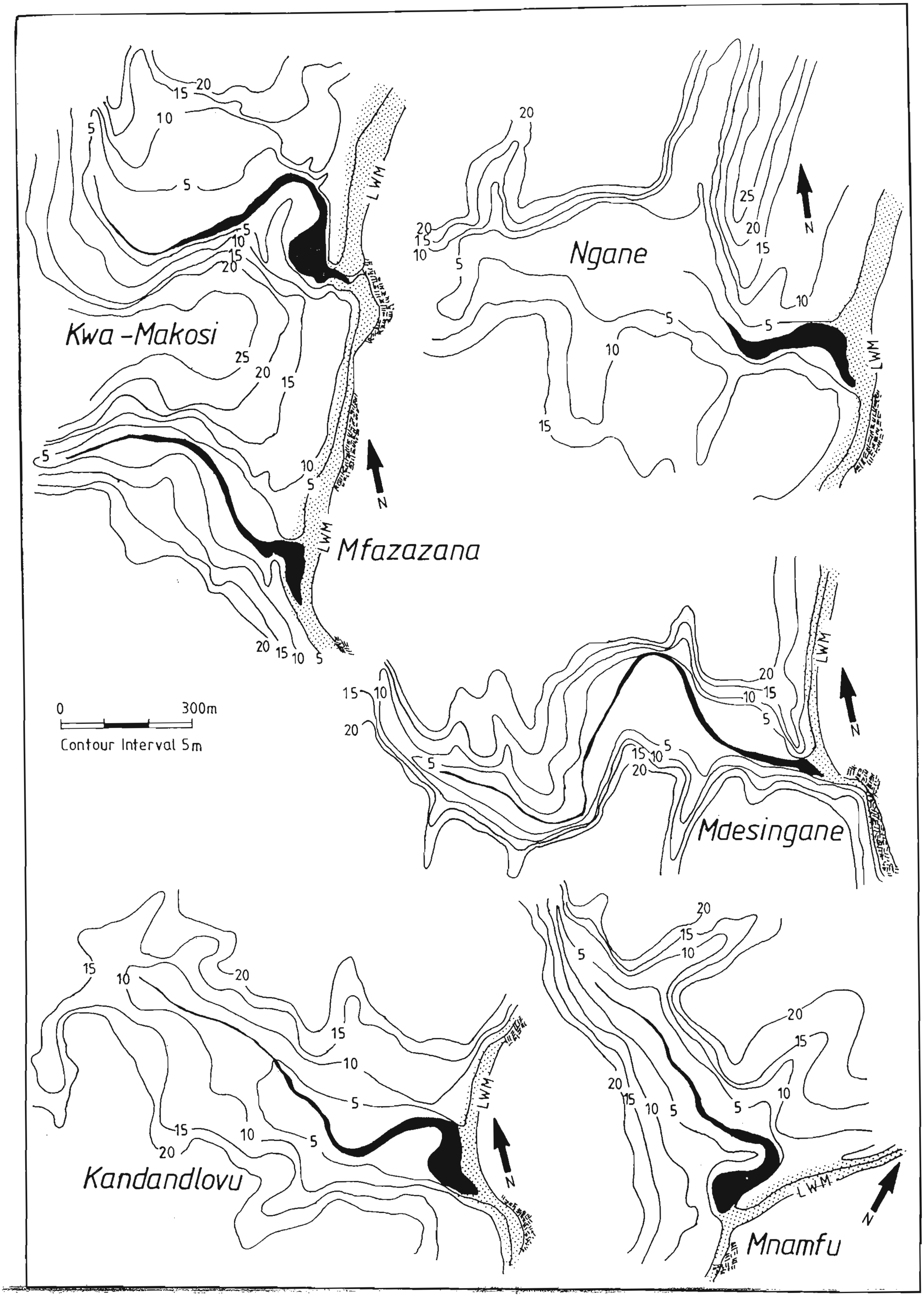


Figure 8.23. Topography of several river-mouths in Group 1B. These have narrow valleys but are typically elongated at the coast behind a barrier (same scale as Figure 8.22).

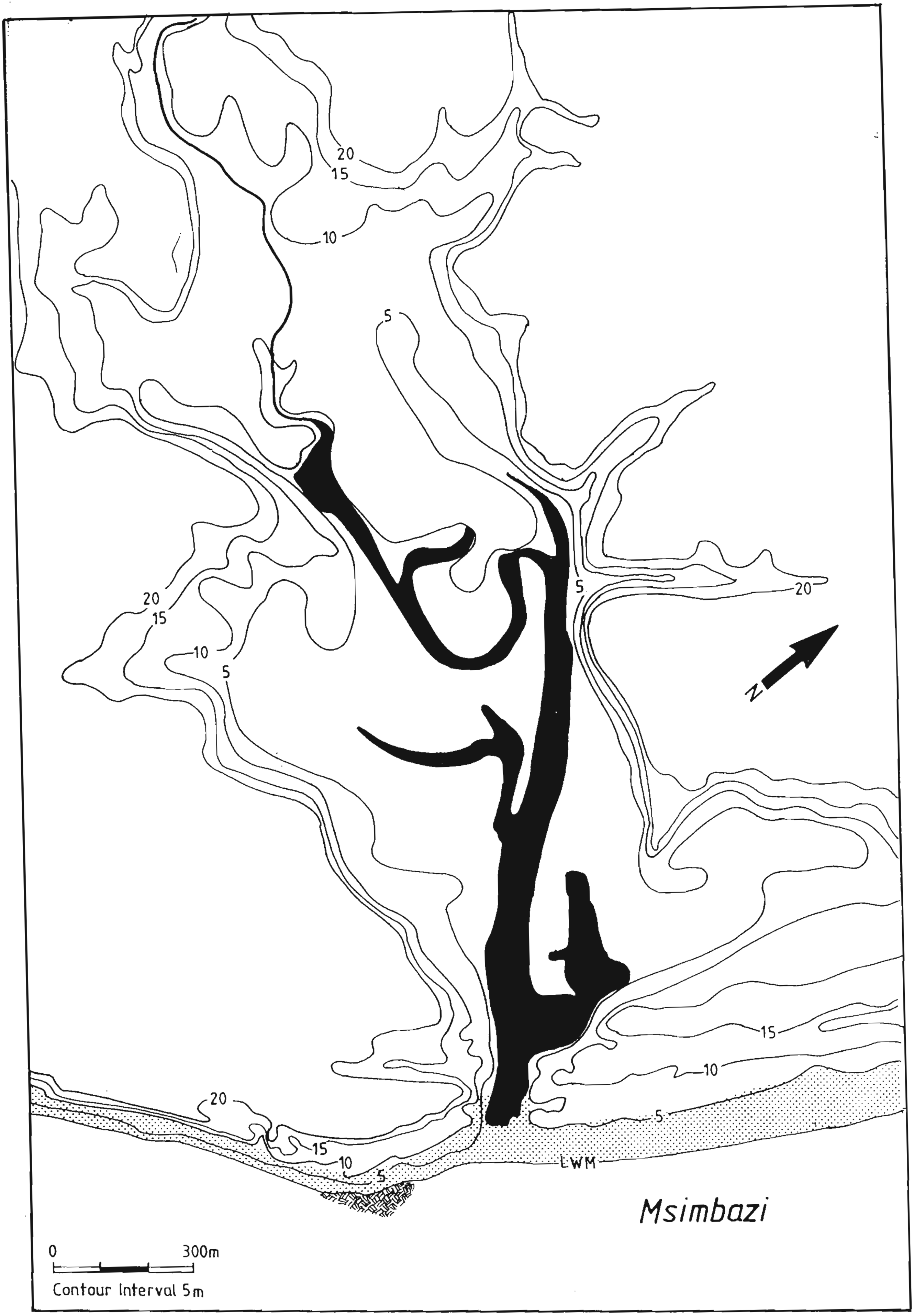


Figure 8.24. The Msimbazi river-mouth is classified in Group 2. It has a wide floodplain and relatively short barrier. (same scale as Figure 8.22).

body. The resultant highly irregular shoreline provides a range of sheltered habitats for the aquatic fauna. The Zinkwasi which has a larger catchment and freshwater discharge than the other two, exhibits a wider channel which occupies much of the valley, particularly in the lower reaches (Fig. 8.25). In the uMgababa, mud characterises the floodplain and backwaters while the main channels are typically sandy (Grobbler, 1987). Mud accumulates in the channels temporarily but is removed following breaching or floods (Grobbler 1987; Cooper *et al.*, 1988). Despite having comparatively short barriers these river-mouths are generally closed, which suggests that their large water areas on the wide floodplains, promote evaporation as a major factor in coping with freshwater discharge. Their closed state has given such stability to these river-mouths that aquatic plants have been able to colonise the channel beds (*Chaetomorpha* in the Msimbazi, *Zostera* in the uMgababa and *Lamprothamnium* in the Zinkwasi, Begg 1984a). Dense bioturbation by the burrowing prawn *Callianassa* has occurred in all three river-mouths. The loss of 7 Ha of open water area in the Zinkwasi through *Phragmites* encroachment (NRIO, 1981b) since 1937, suggests that the Zinkwasi is at an earlier stage of evolution than the two others but an elevated former channel area has been colonised by grass, behind a fringe of *Phragmites*.

The wide floodplains of these river-mouths may enable preservation of earlier alluvial deposits as channels may incise the floodplain without necessarily eroding it. Shells of estuarine molluscs in the muddy floodplain deposits of the uMgababa (Grobbler *et al.*, 1987) may relate to the Late Holocene highstand, but radiocarbon dating and incontrovertible evidence of molluscs being *in situ* are generally necessary to confirm this (Reddering, 1987). Nonetheless the molluscs recovered do not inhabit the uMgababa at present and they were recovered from above present water level which suggests that the floodplain is, in part, an emergent feature which has been incised during a latest Holocene fall in relative sea-level. The implication is that such relict deposits are preferentially preserved in river-mouths of this type, compared to restricted valleys from which they would be eroded during uplift or regression. Cross-sections of the Msimbazi and uMgababa (Orme, 1974) show infilling sequences comprising clay, silt and fine sand with medium to coarse-grained sand confined to channel bases. This illustrates the ability of these river-mouths to preserve fine-grained sediment (as floodplain and backwater deposits) in the stratigraphic record, despite the removal of mud from modern channels during fluvial floods and the preservation of predominantly sandy channel deposits. The bedrock valleys of the Msimbazi and uMgababa are comparatively shallow (-15 m MSL) but very wide (Orme, 1974).

Group 3. This group lies to the right of Group 1 and splits from it at the same level as Group 2. The eleven river-mouths included in it are the iNtshambili, Mhlabatshane, Mbango, Mvuzi, Mahlongwana, Mhlangankulu, Kongweni, Mtentweni, Mpenjati, Little Manzimtoti and Mhlungwa. Their catchments typically lack shales and are dominated by sand-yielding tillite and sandstone and/or granitoids. The catchment areas range from 20 to 80 km^2 but are typically about 30 km^2. The floodplains range from 150 to 300 m in width. The barriers are typically between 300 and 400 m long and the outlets are generally closed. The main within-group variation arises from the presence of 20 and 25 % shale in the catchments of the Little Manzimtoti and Mahlongwana, and in the variation in catchment size.

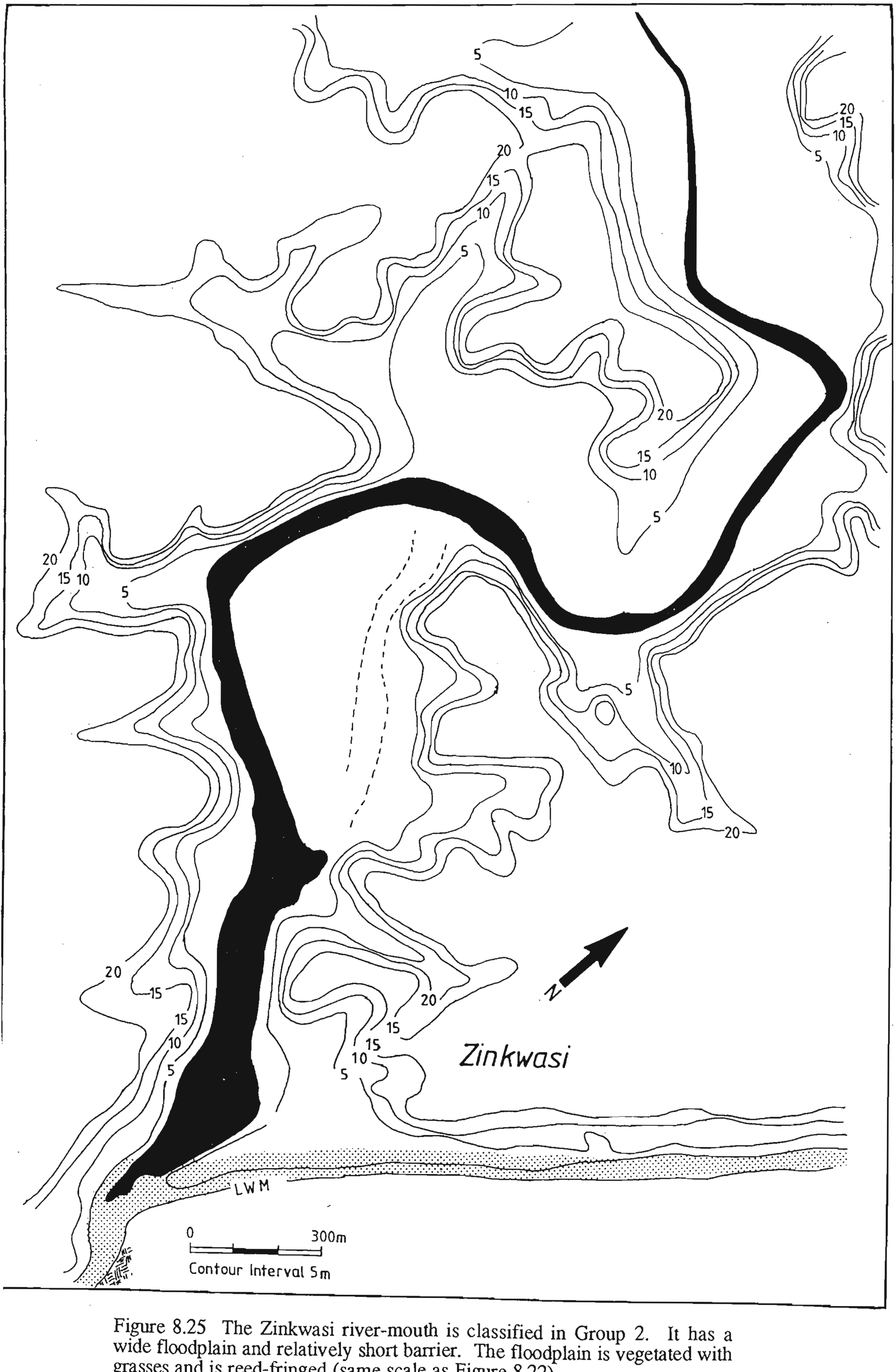


Figure 8.25 The Zinkwasi river-mouth is classified in Group 2. It has a wide floodplain and relatively short barrier. The floodplain is vegetated with grasses and is reed-fringed (same scale as Figure 8.22).

In general the morphology of each of these river-mouths comprises a restricted, elongate floodplain with fringing reedswamp development, and a single, channel through which the discharge passes (Fig.8.27). The river-mouth barriers are comparatively long and coastwise extension is pronounced in all the river-mouths in this group. Outlets consequently form uncommonly, except in the Mhlabatshane which has a particularly short barrier (250 m) in relation to its large catchment (47 km^2) and a prominent rocky outcrop where its outlet forms. The long barriers in these river-mouths allows a potential for outlets to form in several positions and enhances the input of marine sediment through barrier overwash. In some instances, however, for example the Mahlongwana, aeolian sand accretion on the barrier may limit the effective area where outlet formation may occur.

Development of a central island in the Mahlongwana (Fig 8.26) may be attributed to a higher proportion of shales in its 15 km^2 catchment than in other rivers in this group. This yields muddy sediment which stabilises central bars as noted in the Mgeni (Chapter 3). Larger-catchment rivers such as the Mtentweni (50 km^2) have wider channels than the 12 km^2-catchment Mvuzi, for example and have less reedswamp development.

Little sedimentological information exists on these river-mouths although Orme (1974) illustrates a cross-section of sediments in the valley fill of the Little Manzimtoti which comprises 10-14 m of fine-grained fluvial sand and a 0.5 m-thick basal sand and pebble layer overlying the bedrock. The lack of muddy sediment in this cross-section suggests a lack of fine-sediment preservation in river-mouths of this group, due to the restricted nature of the valley in relation to catchment size. The depth to bedrock in the Mahlongwana is 15 m (Orme, 1974). Continuing sediment accumulation in the Mhlangankulu (CSIR, 1990) suggests that it is at a less advanced evolutionary stage than other river-mouths with reed-filled shallows.

The river-mouths in this group are similar to Group 1B but have larger catchments and correspondingly wider floodplains.

Group 4. This group includes nine river-mouths: the Mzinto, Zotsha, Mkumbane, Mbizana, Fafa, Mbokodweni, Mhlali, Tongati, and Mpambanyoni. They have relatively narrow floodplains in relation to their large catchments. Of these, the Tongati and Mpambanyoni are shown as different from the rest in the dendrogram and may warrant subdivision of the group into 4A and 4B, particularly on the basis of the large catchment areas of these rivers. At the same level as groups 2 and 4 are separated, the Vungu is isolated as an outlier.

Group 4A. This group comprises the Mzinto, Zotsha, Mkumbane, Mbizana, Fafa, Mbokodweni and Mhlali river-mouths. They are characterised by a general absence of shale in their catchments. They have relatively long barriers in relation to their catchment size (barriers are 300 to 500 m long) and similarly wide floodplains (300 to 500 m), thus coastwise extension is limited, but if the floodplain is vegetated and the orientation of the inflowing river is suitable, river courses may flow behind a barrier across most of the

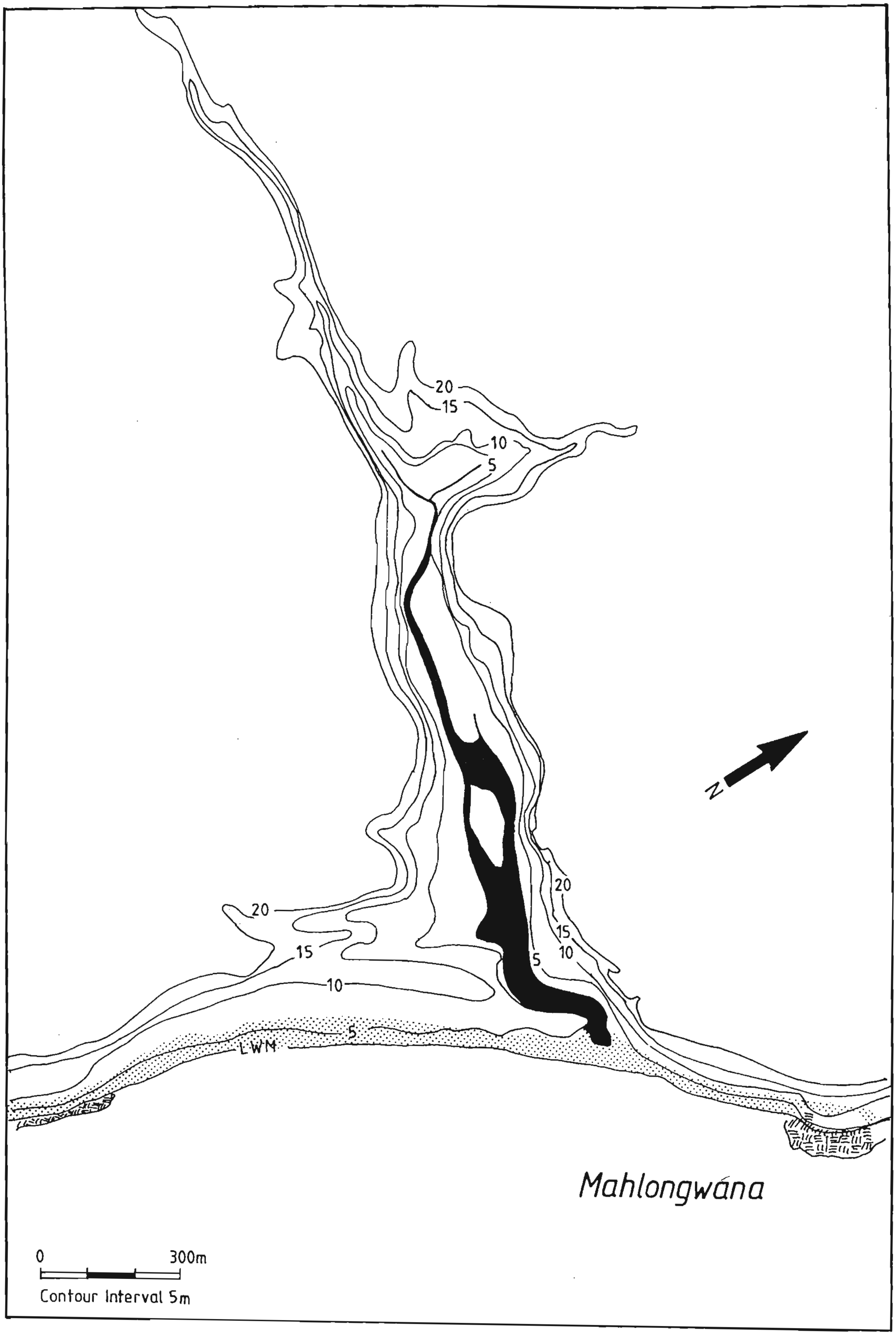


Figure 8.26. The Mahlongwana river-mouth, with its narrow floodplain is classified in group 3. Coast-parallel channel extension behind the barrier is characteristic of this group (same scale as Figure 8.22).

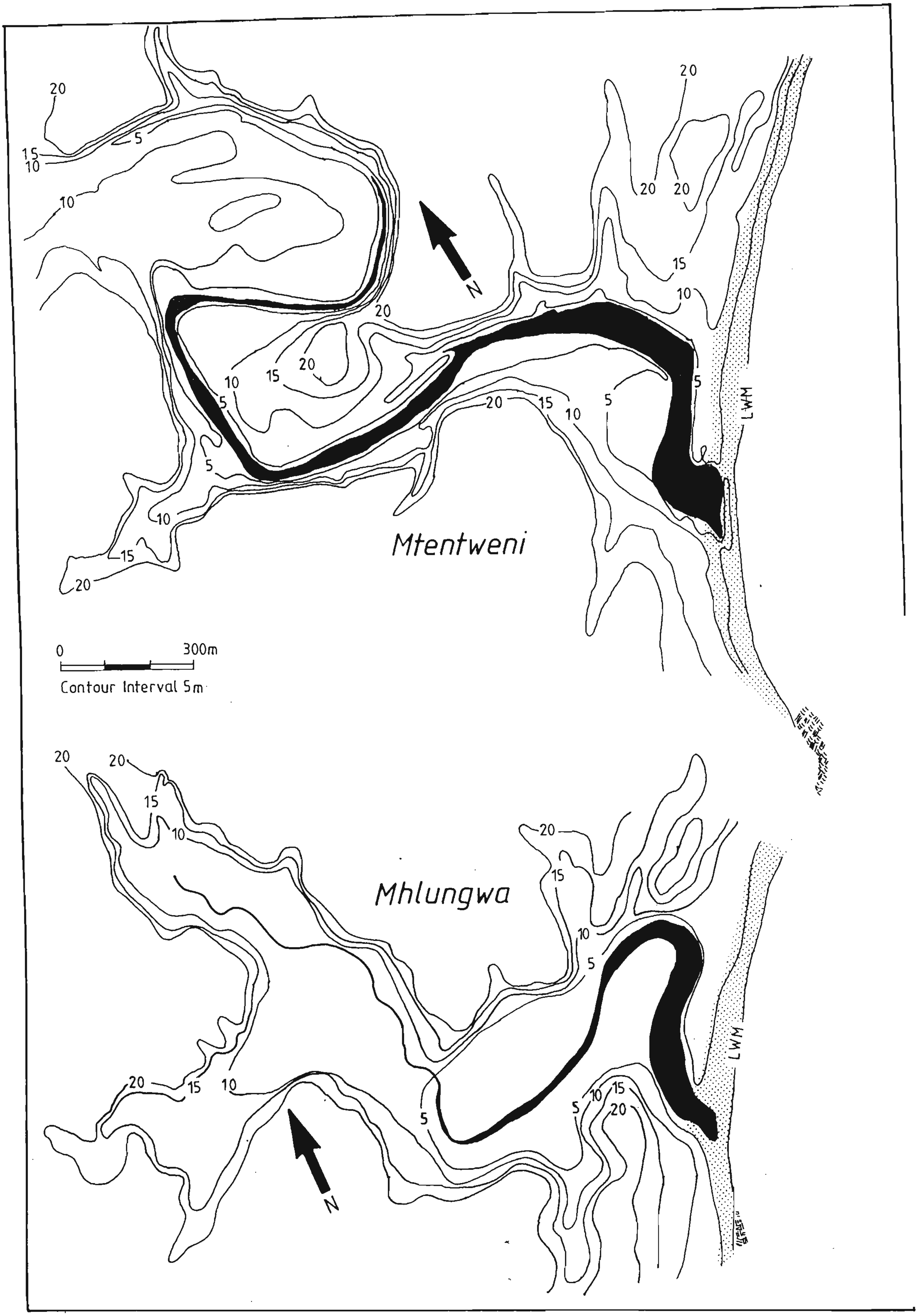


Figure 8.27. Two river-mouths showing typical Group 3 morphology of restricted floodplain and coast-parallel channel extension. Aeolian buildup on these barriers is less marked than on the barrier of the Mahlongwana (same scale as Fi

length of the floodplain at the coast. Outlets are typically absent. Most of the catchment areas are between 100 and 200 km^2 but the Zotsha and Mkumbane are smaller (59 and 28 km^2 respectively).

A wide, vegetated floodplain with a single, sandy-bottomed channel typifies morphology of these river-mouths. Floodplains are confined behind a barrier which only maintains an outlet if located across rocky outcrops, such as at the Zotsha river-mouth. Evidence of an evolutionary sequence in these river-mouths is suggested by comparison of the Zotsha or Mbokodweni (Fig.8.28) which have well-vegetated floodplains and a narrow river channel, with the Fafa or Mbizana (Fig 8.29) where shallow, sandy channels occupy most of the river valley. The latter rivers may be at an earlier stage in their evolution in that vegetation has not yet colonised their floodplains and restricted their channels. Both are, however, subjected to human interference which may have impeded evolutionary progression. To facilitate water sports, the Fafa river-mouth water level is artificially maintained at a high level by a weir at the barrier outlet position. This limits reed encroachment and stabilisation of the floodplain. The Mbizana river-mouth is heavily exploited for building sand, which disturbs rooting of vegetation and prevents sediment accumulation. Its outlet is also manipulated to maintain high water levels for recreational activities.

Breaching of river-mouths in this group at an early evolutionary stage results in exposure of large unvegetated sand banks, while closure of the lagoon causes them to revert to shallowly submerged lagoon floor deposits. This produces rapid changes in environmental conditions. In contrast, the more mature river-mouths of this group still maintain their channel areas, albeit shallower, and only limited areas are exposed subaerially after breaching. The latter, more advanced river-mouths are therefore ecologically more stable as breaching results in fewer changes within the bank-confined channels. This must impact on the aquatic fauna and flora.

Group 4B. This includes only the Tongati and Mpambanyoni which separate from the rest of Group 4 on the basis of much larger catchments (>400km^2). Their barriers are shorter than others in the group and floodplain development in the bedrock valleys is restricted because of the higher discharge which necessitates wider channels. Outlets are normally present.

Morphologically they differ from those in Group 4A in the development of mid-channel bars and/or islands, and undergo major short to medium-term morphological changes as a result of floods (Perry, 1989). The Tongati catchment contains more shales (22%) than the Mpambanyoni (9%) and this may account for the differences in channel pattern. The Tongati develops mid-channel islands during stable (interflood) periods, while the Mpambanyoni is characterised by a shallow braided channel, which probably lacks an adequate mud supply from its catchment for stabilisation. Neither have been studied sedimentologically and assessment of their evolution and physical processes remains largely conjectural. The bedrock valleys of both rivers are in excess of 20 m deep (Orme, 1974) and the valley fill of the Mpambanyoni comprises mostly coarse fluvial sand (Orme, 1974) which probably results from vertical scour in the confined bedrock channel, which prevents preservation of fine-grained sediment in the stratigraphic record.

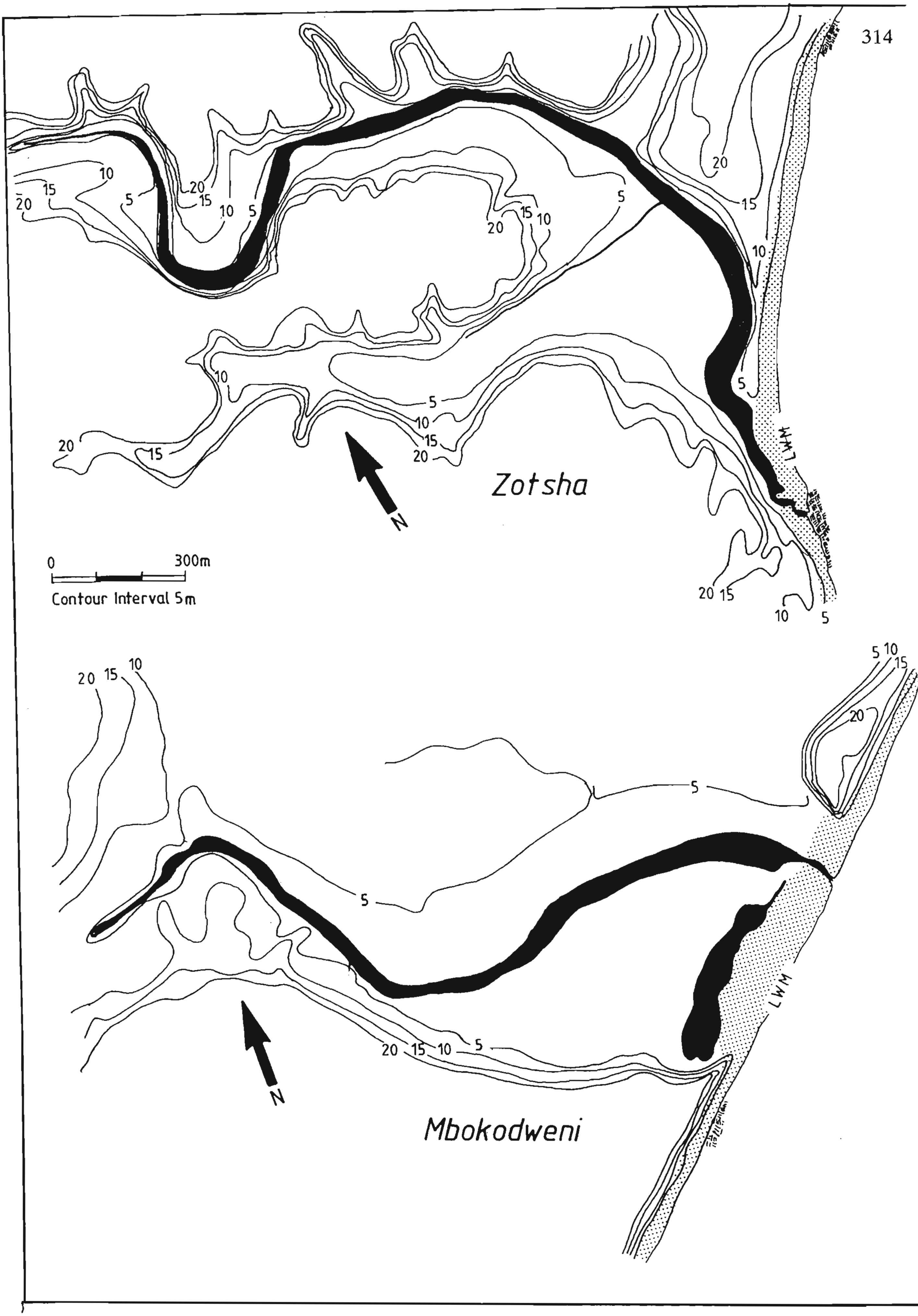


Figure 8.28. Evolutionary progression has led to these Group 4A river-mouths being restricted to only a part of the floodplain. The wide floodplains and elongate barriers are typical of this group (same scale as Figure 8.22).

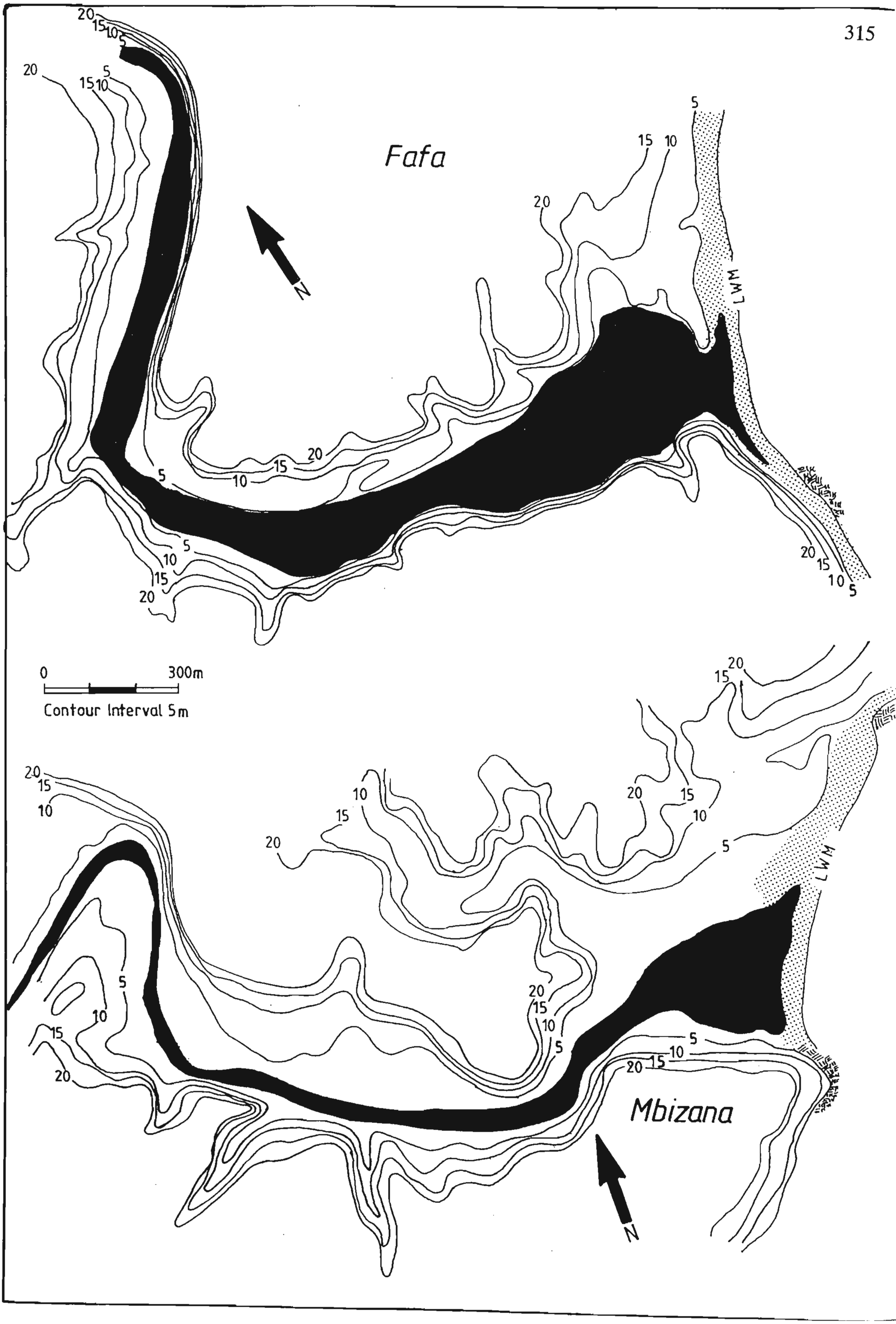


Figure 8.29 The Fafa and Mbizana which also fall in Group 4A are apparently at a less advanced evolutionary stage than the Zotsha or Mbokodweni (Fig. 8.28). They have similarly wide floodplains and long coastal barriers but the channels occupy a large part of the valley. This may be attributed to human interference (same scale as Figure 8.22).

Group 5. This group was identified at a higher level than the previously-described groups in the clustering analysis. It includes the Mtwalume, Mdloti, Mhlanga, Nonoti and Mahlongwa river-mouths. These are characterised by relatively large catchment areas between 100 and 550 km^2, which contain all three geology types (with 44%, the Mhlanga has by far the most shale-rich catchment). They have wide floodplains, averaging about 300 m and barriers which all exceed 900 m in length, indicating significant coastal extension. They are generally closed except the 533 km^2-catchment Mtwalume river-mouth, which is commonly open.

The river-mouths in this group have long coast-parallel sections which facilitate seepage through the barriers and introduction of marine sediment through overwash. In most cases the floodplain has been colonised by vegetation and river flow is contained within a confined channel. River channels commonly take a sinuous to meandering course across the floodplain and then flow behind the barrier. Thus channel elongation is maximised both by sinuosity and back-barrier extension, and although flow is channel-confined, breaching is uncommon. The Mhlanga has been shown above (Chapter 5) to be at a stable stage of development, and so represents an advanced evolutionary stage. The Mahlongwa (Fig 8.30) and Nonoti appear to be at a similar level of development, as was the Mdloti before the flood of 1987 (Fig 8.31). The Mtwalume channel has not advanced to the same degree of confinement and vegetal colonisation of the floodplain and so appears to be at a less advanced stage of development. This may however, have been altered by embankment construction across the floodplain which limits sinuosity of the mature channel and through channel straightening, induces higher stream power at the barrier.

Only the larger river-mouths in this group, the Mdloti (Grobbler, 1987; Cooper *et al.*, 1988) and Mtwalume (Perry, 1989), are markedly affected by floods. In the Mdloti the 1987 flood eroded the confined banks and floodplain to enlarge its channel to cope with the increased discharge. Following the flood, sedimentation caused the channel to shallow and narrow and renewed vegetation growth stabilised the banks. Thus flood impacts cause temporary reversals in the evolutionary trend in large-catchment, mature river-mouths in this group. Ultimately, however, each will attain a similar morphology comprising a sinuous channel, diverted at the coast by an elongate barrier and typically closed from the sea. Sedimentary processes are dominated by cycles of breaching, during which outflowing currents produce distinctive bedforms (see Chapter 3 and Grobbler, 1987) and closure, during which suspension-settling dominates sedimentation.

8.9.2.2.Groups 6-8

The remaining ten river-mouths of the Mlalazi, Matigulu, Mzimkulu, Mgeni, Mkomazi, Mvoti, Lovu, Mzumbe, Mtamvuna and Tugela, were separated from the others at an early stage of the cluster analysis. This list includes all of the largest catchment rivers in the study area, with the exception of the Mtwalume and Mpambanyoni, which are classified at a lower level in the analysis. The large catchments which extend far into the hinterland generally mean that each of these rivers traverse all three lithological types. Despite their small number, appreciable differences in controlling variables produced several groupings and unique outliers among these river-mouths.

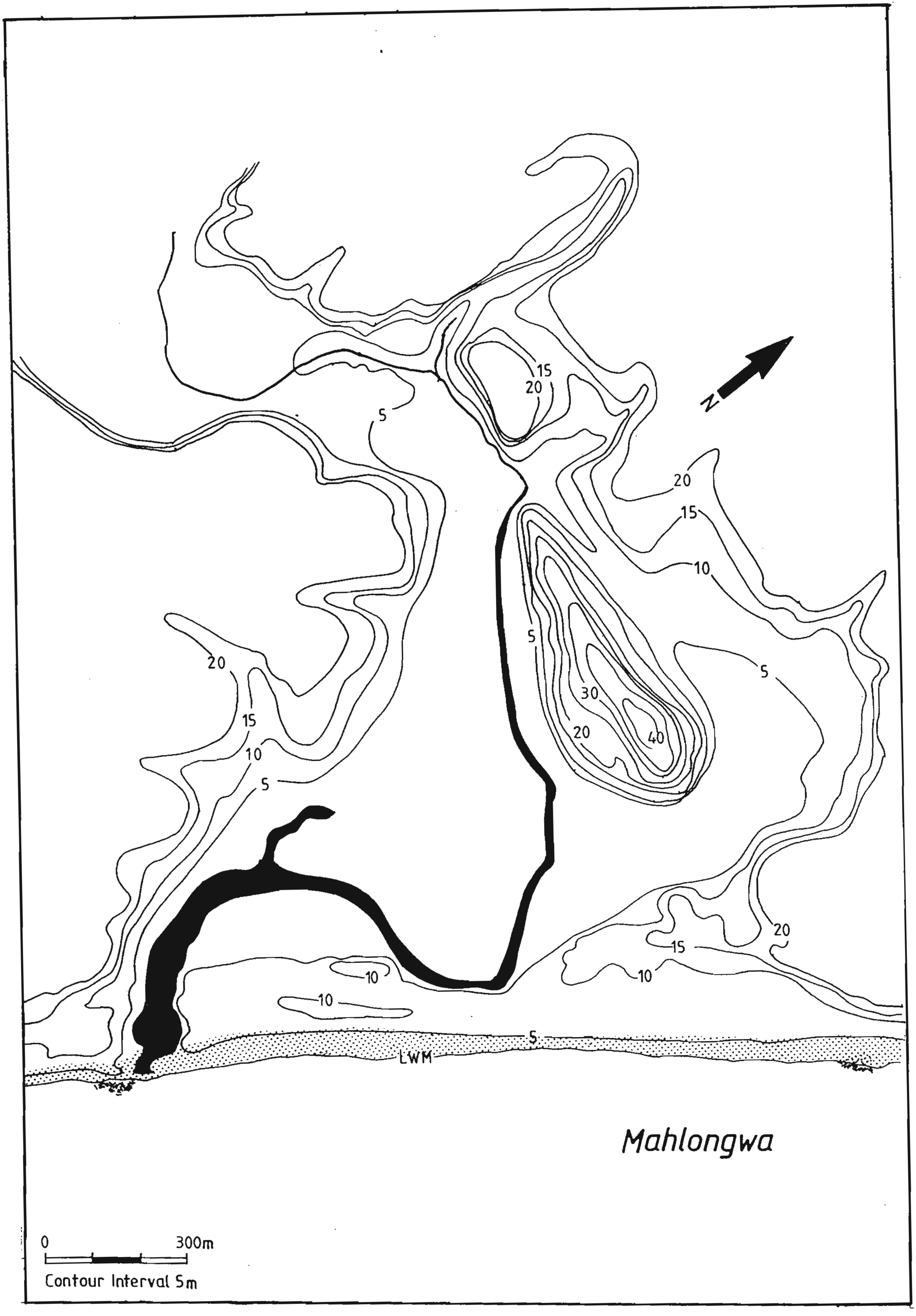


Figure 8.30. The Mahlongwa river-mouth is classified in Group 5 which is characterised by elongate barriers. Aeolian deposition on the barrier has limited potential breaching positions in the Mahlongwa, in contrast to the Mhlanga (Chapter 5) (same scale as Figure 8.22).

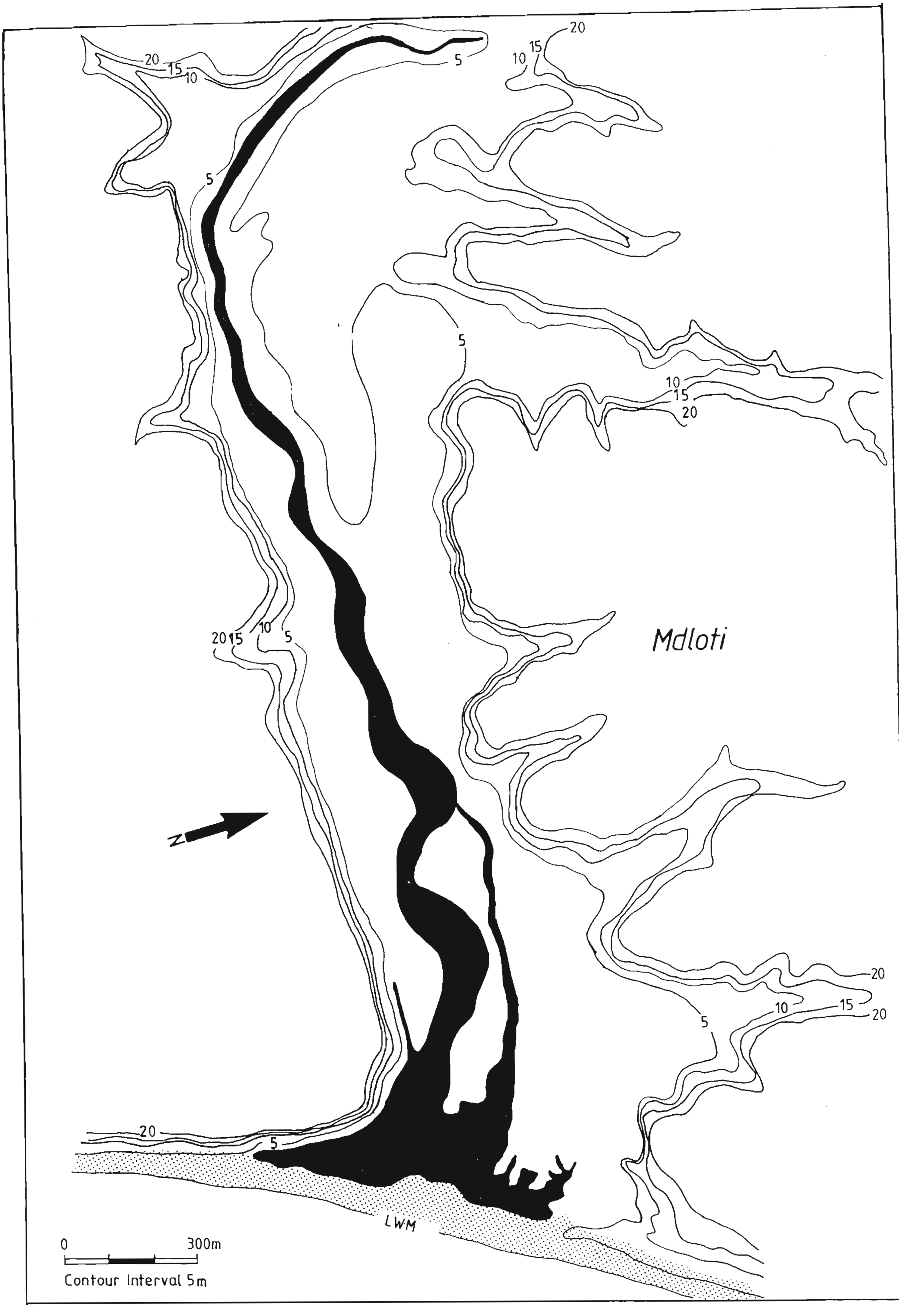


Figure 8.31. The Mdloti river-mouth of Group 5 has a wide floodplain and long barrier. When mature the channel is sinuous and surrounded by a vegetated floodplain. This situation is changed by episodic floods (same scale as Figure 8.22).

The Tugela was separated at the highest level as unique, because of its large catchment. At the next level, the Matigulu and Mlalazi separate as a distinct group. At the next level, the Mzimkulu, Mkomazi and Mgeni are separated from the rest as large-catchment river-mouths with restricted floodplains and wide barriers. The next split isolated the Mtamvuna, from the Mvoti, Lovu and Mzumbe were grouped. The separations identified among these large-catchment rivers are apparently justified in view of the large differences in variables, particularly catchment size, between the rivers. This part of the dendrogram is enlarged in Figure 8.21. It is proposed that they be designated as three groups with the Tugela and Mtamvuna designated as a outliers.

Group 6. This group comprises the Matigulu and Mlalazi whose main diagnostic characteristics are their long barriers and wide floodplains. They have catchments which traverse all three lithological types and their catchments cover 492 and 814 km^2.

Their morphology comprises a relatively wide floodplain and a significant degree of coastwise extension behind a prograding beachridge plain. The two rivers vary in channel morphology, because the Mlalazi is located on a broader section of the coastal plain and its floodplain is wide. The Matigulu flows through a valley cut in Natal Group Sandstone to within 200 m of the coast and its upper reaches are consequently narrow. The wide and long barriers at these river-mouths are distinctive and group them together but the Matigulu barrier is lower and more prone to breaching at a number of localities after floods, than the Mlalazi barrier which is topped with sand dunes and consequently unlikely to breach other than at its normal outlet. Both river-mouths are characterised by normally open outlets and the presence of flood-tidal deltas, but lack of sedimentological investigations in them prevents close assessment of sedimentary processes. Continuing extension of the Mlalazi by coastal progradation may ultimately cause it to close completely. The orientation of the Matigulu barrier does not favour large scale aeolian deposition and consequently it may be breached by floods.

Group 7. This group includes the Mzimkulu, Mkomazi and Mgeni. They are very large-catchment (>4000 km^2) rivers, with floodplains about 400 m wide and barriers over 1000 m long. Their catchments are a mixture of lithologies. Their outlets seldom close due to high discharge.

The floodplains of these rivers are not particularly wide in relation to their large catchments and consequently the river channels occupy a large portion of each floodplain. This controls flood response (Chapter 4) in that appreciable downward rather then lateral scour occurs during floods and deepens the channels. There are, however, appreciable differences between these rivers, despite their common grouping, and this is reflected in the high level at which they were isolated in the dendrogram. The Mzimkulu maintains a single channel without central islands, in contrast to the Mgeni which tends to bifurcate when mature. This appears to be due to bedrock control on the river course as it reaches the river-mouth. In contrast to the other two, the Mgeni channel tends to contain considerable gravel and commonly exhibits braiding after floods, which may be due to the close proximity upstream of deeply weathered granitoid metamorphic lithologies. In addition the Mgeni barrier forms only part of a large-scale coastal planform which in the past permitted considerable lateral variation in outlet position.

No evolutionary trend is evident in these river-mouths, all having reached maturity by filling their bedrock valleys and varying their channel dimensions on the floodplain in response to flow characteristics. It is in this context that apparent shallowing at particular locations in the Mkomazi (CSIR, 1990) and Mzimkulu (Begg 1984b) must be seen. Shallowing by 1 m in the upper reaches of the Mkomazi is documented on the basis of a rare set of channel cross-sections spanning the period from 1875 to present at irregular intervals (CSIR, 1990). The rise in bed level was accompanied by an increase in channel width which indicates the bank materials were more easily eroded by floods than the bed. This may be due to destabilisation of the riparian vegetation.

Tidal exchange through the outlets of these rivers produces estuarine circulation and flood-tidal deposition, although as shown in the case of the Mgeni, flood-tidal deposition increases with evolutionary maturity. Floods temporarily reset the evolutionary sequence by eroding accumulated and stabilised deposits in these river-mouths.

Group 8. In this cluster are the Mvoti, Lovu and Mzumbe which appear to have been grouped on the basis of their large to very large catchment areas, wide floodplains and long barriers. Their catchment geologies include all types but the Mzumbe has appreciably more (70%) granitoid metamorphics in its catchment than the others. The relative amount is reduced in the Mvoti because the large catchment extends inland where the small tributaries drain Karoo mudrocks.

The floodplains of these river-mouths are wide even in relation to their large catchments and this exerts a strong control on sedimentary processes as illustrated by the Mvoti (Chapter 6). Overbank deposition and lateral scour is enhanced during floods and channel migration across the floodplain may occur. The floodplains are not sufficiently wide, however, to permit avulsion and channel switching similar to that reported for the Mfolozi River in Zululand (van Heerden & Swart, 1986) and other unconfined delta-top river channels. In addition, the predominantly sandy floodplain deposits probably limit dewatering and subsidence on the floodplain and reduce the sediment storage capacity in relation to more muddy floodplains. Major flood impacts were noted in the Mvoti (Chapter 6), Lovu (Grobbler, 1987) and Mzumbe (Perry, 1989). Downward erosion is minimised during floods by lateral channel expansion and so they differ significantly from the river-mouths of Group 7. Under natural circumstances the rivers are diverted behind the barrier and the consequent coastal extension and reduction in river gradient, limits frequency of outlet formation. Flood response is to erode a channel through the barrier by bypassing the coastwise extension, thus increasing channel gradient and current velocity. Two of these river-mouths have been altered by railway embankment construction, the Lovu in 1940 (Grobbler, 1987) (Fig 8.32) and Mzumbe in 1954 (Begg, 1984b), so the typical flood response cannot occur. Their now-restricted channels therefore probably produce more downward erosion than under natural conditions. This has led to the Lovu being more frequently open than predicted under natural circumstances but, as noted by Begg (1984b) it receives little marine water even when open, as a result of the inefficient meandering outlet channel and elevated bed levels in the river-mouth.

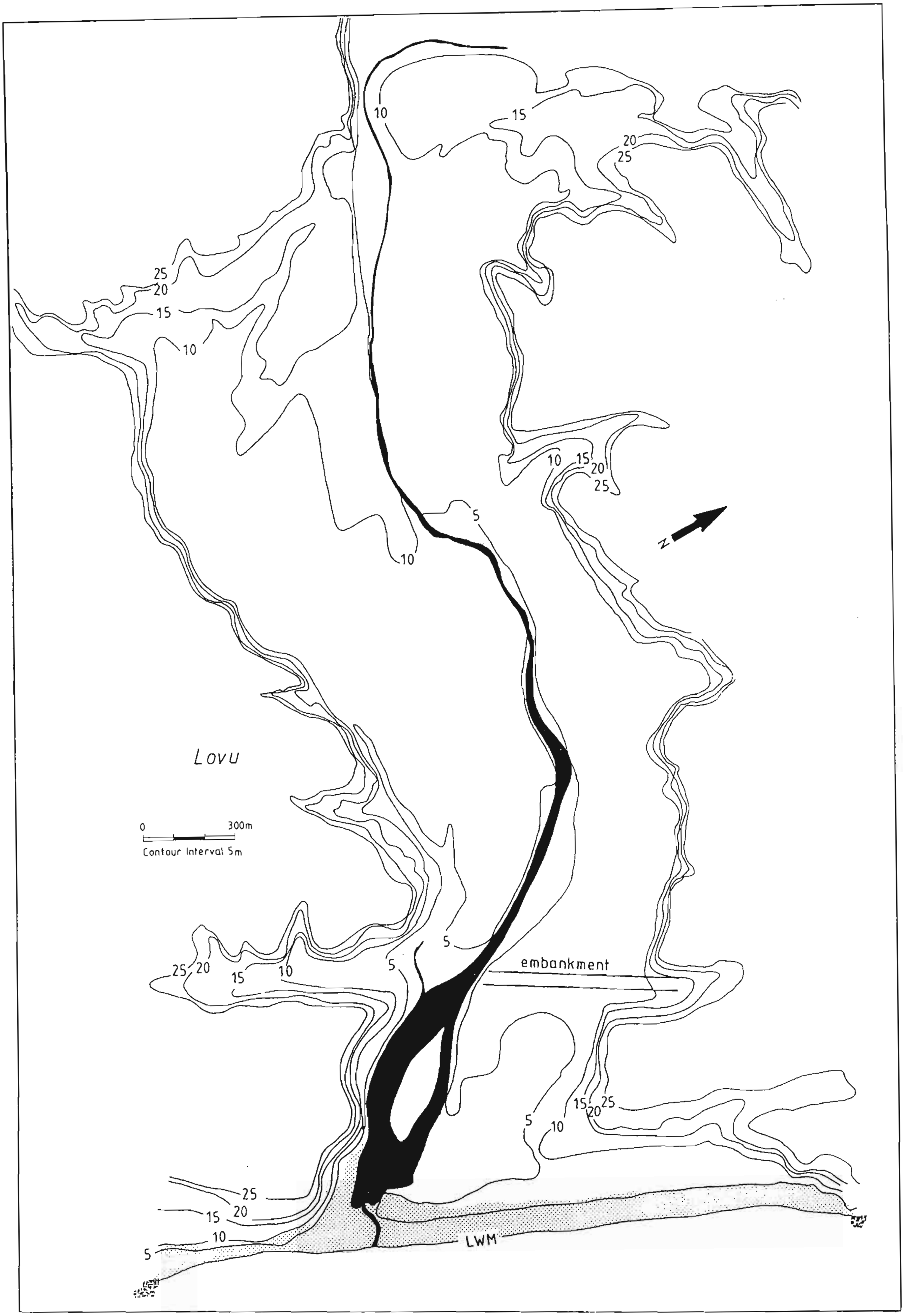


Figure 8.32. The Lovu river-mouth is classified together with the Mzumbe and Mvoti (Chapter 6) on the basis of its large catchment, wide floodplain and elongate barrier. The Lovu has been altered from its natural state by embankment construction (scale reduced compared to previous figures).

8.9.2.3. Outliers. Several river-mouths were identified as unique at various levels in the hierarchical cluster analysis. They are discussed below in terms of morphology and controlling variables.

Tugela. This river-mouth was classified as an outlier on the basis of its catchment area which is an order of magnitude larger than the next biggest-catchment river. Consequently its discharge is much greater and the size of its channel must be correspondingly large. The Tugela fills most of its bedrock valley and has a shallow braided sandy channel. Turbid plumes of suspended sediment occur off its mouth after increased flows, and during severe floods, such as September 1987, its barrier is eroded and an extensive delta is deposited opposite its mouth (Cooper 1990d, CSIR 1990). North of the Tugela is an extensive beachridge plain (Fig 8.33), supplied by sandy sediment derived from the Tugela River. It extends for 45 km north of the river-mouth. The Tugela is evidently full of sediment and has been supplying sandy sediment to its beachridge plain since well before 1937, because at that time several lines of beach ridges were already established. Since then beachridge accumulation has proceeded at nett rates up to 5 m per year (Cooper, 1990a) as a result of the northward transport of Tugela -derived sediment under wave action. Its accumulation may be attributed to more gentle nearshore gradients or a possible reversal in longshore transport direction (Cooper, 1990a).

Irregular beachridge accretion may be linked to episodic flood events (Cooper, 1990d) but further work is necessary to confirm this. Because of the presence of a rocky promontory at the northern side of the Tugela mouth, the beachridge plain (in effect the coarse-grained delta of the Tugela) is actually separated from the river-mouth with which it is associated. If preserved in the sedimentary record, the beachridge plain of the Tugela would probably be mistakenly associated with the river-mouths of the Matigulu or Mlalazi, which flow behind it.

Mtamvuna. This river-mouth was isolated in the cluster analysis on the basis of its large catchment size, narrow floodplain, and lack of granitoid metamorphic rocks in its catchment. As shown in Chapter 4 it is significantly different from any other river-mouth, both in terms of its depth and in the presence of a large flood-tidal delta. This was attributed to low fluvial sediment supply, resulting from the catchment geology. The lack of an extensive floodplain in such a large-catchment river is also unusual, and classifies it as unique among Natal river-mouths which are generally full of sediment and in which river channels traverse an alluvial floodplain. The lack of coarse-grained sediment supply from this, the largest river south of the Mzimkulu, renders the adjacent coast predominantly rocky and its transgressive sandy barrier is confined to the river valley. In the presence of a well-developed flood-tidal delta which is eroded during floods and reformed subsequently, becoming transgressive into the river-mouth in interflood periods, it is similar to estuaries of the Eastern Cape (Reddering & Esterhuysen, 1981, 1987b; Reddering, 1988b) and the St Lucia Estuary in Zululand (Wright, 1990; Wright & Mason, 1990).

Vungu. This unusual river-mouth enters the sea at the base of a 15 m-high waterfall (Fig 8.34). The plunge pool is 40 m deep (Begg 1984b) and is partly confined by a transgressive sandy barrier. A narrow outlet permits intrusion of seawater and the plunge pool commonly exhibits stratification, although this periodically breaks down due to mixing during high river flows (Begg 1984b). The base of the plunge

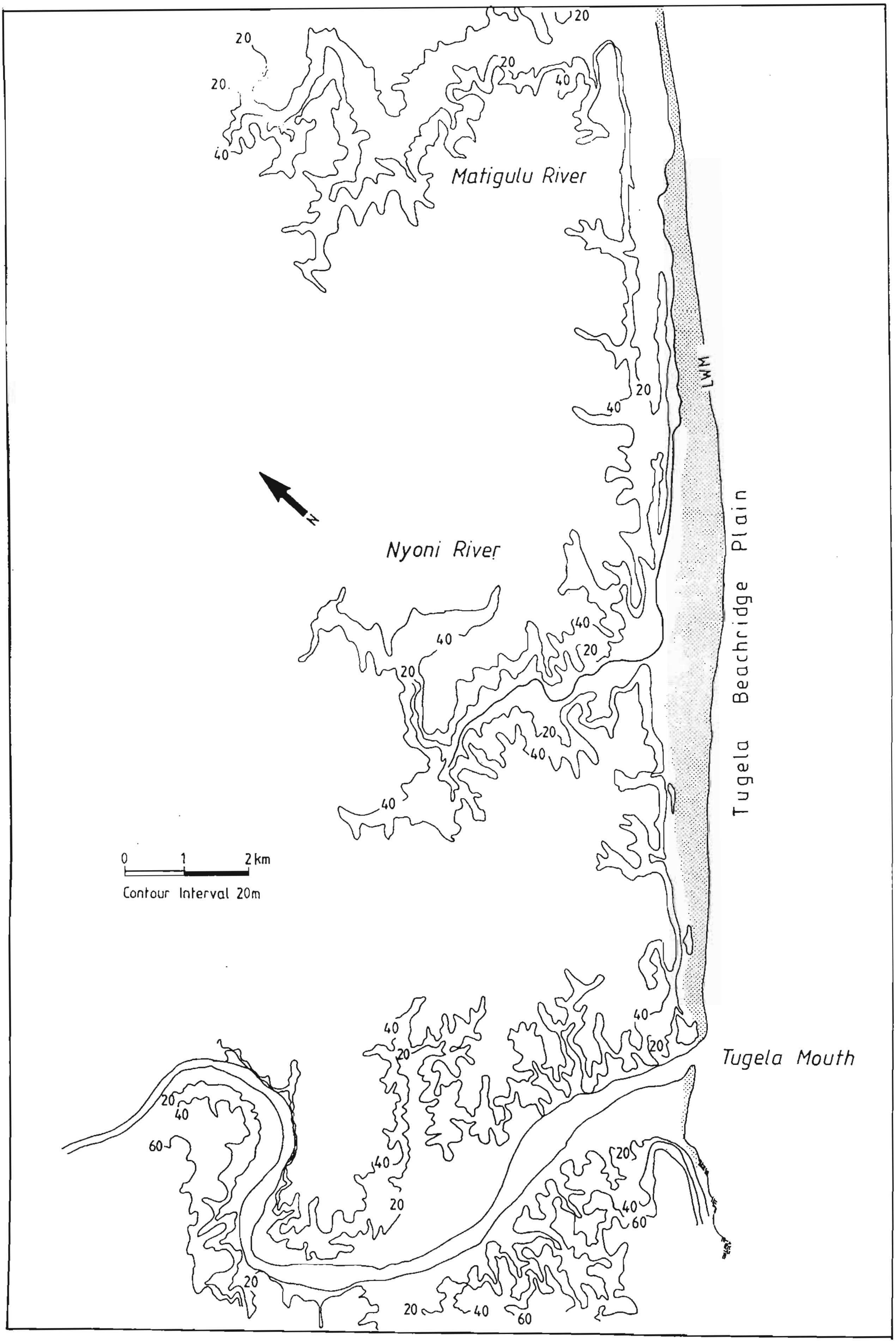


Figure 8.33. The Tugela river-mouth and part of its associated beachridge plain to the north (downdrift) side of the outlet. Note the much reduced scale of this figure in relation to previous figures.

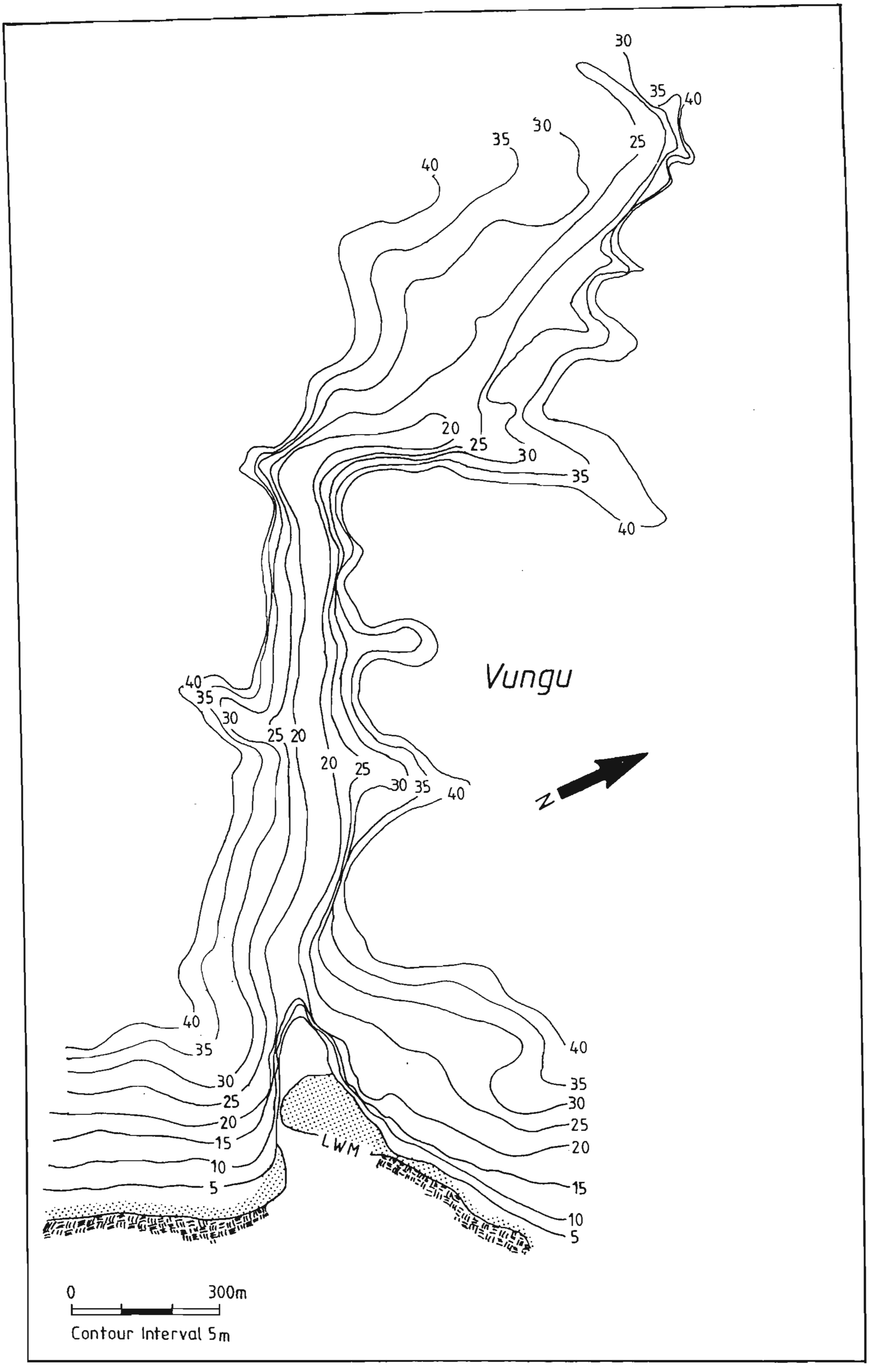


Figure 8.34. The Vungu river-mouth is characterised by a 15 m-high water fall which enters the river-mouth area at the coast. Its unusual characteristics render it an outlier in the classification scheme. The river course is unshaded to avoid obliterating the contours of the waterfall.

pool is covered with organic detritus and anoxia may develop periodically (Begg 1984b). Observations during September 1987, show that the barrier is eroded during severe floods, but it quickly reforms under wave action, isolating the back-barrier area.

8.9.3. Discussion

The results of the classification procedure place river-mouths in groups which coincide largely but not exactly with the basin shape classifications discussed in section 8.7.3. For example, of the Mhlangankulu, Mahlongwana, Mhlungwa, Mtentweni, Kongweni and Mkumbane which were identified as similar small-catchment rivers in terms of basin shape, only the Mkumbane was excluded from the classification (Group 3) produced by the cluster analysis.

Within the identified groups limited morphological variation occurs. In some cases this may be due to differences in the magnitude of some of the controlling factors, for example catchment size. In other cases within-group variation probably results from differences in evolutionary stage. In this respect the above classification based on genetic inputs is invaluable in identifying evolutionary trends. A classification which employed only observed morphology could not achieve this result. This will assist in interpreting future changes in river-mouths correctly, as the likely morphologically mature state can be predicted.

The classification also enables assessment of the impact of human structures or activities on river-mouth morphology and processes, for example in the Lovu and Fafa, and provides a qualitative predictive capability regarding the impact of future developments.

It also highlights the lack of sedimentological information on the largest groups identified. Research up to now has concentrated on the larger-catchment rivers and their river-mouths. As these small river-mouths comprise most of the river-mouth environments and are frequently the sites of development and recreation, assessment of their sedimentological processes is required. The variation in some groups shown above suggest an evolutionary trend which, if identified could assist in the development of environmental management guidelines.

The hypothesis presented can be argued to be generally valid in that the four factors identified can be used to classify river-mouths in the region on the basis of their morphology. The genetic controls identified do appear to be the main influences on river-mouth morphology in Natal but the controls themselves are difficult to define numerically. Sediment input and the morphological response to this was apparently related to the controlling variables. Bedrock of the receiving basin, however, was not the sole control on basin morphology and the role of other variables such as inherited topography, in defining morphology of the receiving basin was highlighted. Minor factors such as topography obscured any clear relationship between basin geology and the shape of the receiving basin thus, while a clear relationship could be demonstrated between floodplain area and catchment size, the shape was due to more complicated combination of factors including topographic variation and lithological changes. The variable was therefore altered to "average floodplain width" which combined the obscuring factors with the bedrock geology and catchment size. The fourth variable, coastal morphology, undoubtedly plays a role in river-mouth morphology but without more information on the relationship between barrier seepage, evaporation, discharge and outlet formation, the range of variables involved in quantifying coastal morphology are too great to carry out at a specific level and had to be reduced to the composite measures of "frequency of outlet occurrence" and "barrier length" which together encompassed the effects of coastal morphology. Further detailed research is required to determine the relationship between discharge, seepage, evaporation and outlet formation in Natal river-mouths.

Assignment of a numerical value to the proposed variables was the main problem encountered and alternative means of measuring the inputs were required. Thus while the classification arrived at does not involve the originally stated genetic variables, it involves others which directly reflect them.

8.10. TERMINOLOGY

8.10.1. Introduction

Given the classification above the range of variation between some groups is greater than between others. This is largely reflected in the nested structure of the dendrogram. To give a separate name to each of the groups would lead to confusion and so a reduced number of terms must be used for particular types of river-mouth, within which morphological variation does occur. The groupings identified distinguish at a high level between those river-mouths with large catchments and those with small. In general terms larger catchments rivers have larger river-mouths to cope with discharge (Reddering 1988a). In the study area, as in southeastern Australia (Roy, 1984), river discharge rather than tidal prism, tends to maintain an outlet. Thus larger rivers have greater and more frequent tidal exchange than smaller ones. Smaller rivers have continuous barriers without outlet to the sea for most of the time. In this respect they warrant distinction from the larger, open, tidally-influenced river-mouths. Within the larger river-mouths there are those which although open to the sea, have little tidal influence.

There are additionally, several unusual outliers which have particular characteristics which prevent similar terminology as the other river-mouths. These were generally identified as outliers on the dendrogram. On this basis it is proposed that the following terminology be applied to combined groups of river-mouths.

8.10.2. Barrier lagoons

This term implies a small-water body, mainly confined to a bedrock valley and isolated from the sea, either permanently or temporarily by a sandy barrier. Such river-mouths are fed by small-catchment rivers and derive salt water mainly by barrier overwash. The river-mouths in groups 1,2,3,4A and 5 can be placed in this category. They do not receive *significant* inputs of freshwater from their small catchments and are essentially tranquil sheltered environments in which barrier overwash of sea water enhances salinity. Some of these lagoons are frequently open to the sea and may exhibit estuarine salinity structure, but as their rivers are so small it is inappropriate to term them estuaries: many so-called lagoons elsewhere in the world have connection with the sea but have insignificant freshwater input. The small river-mouths of Natal match this description.

8.10.3.Delta-top estuaries

This term is suggested for the river-mouths in groups 4B, 6,7 and 8. They are the mouths of large-catchment rivers, which reach the coast through an alluvial floodplain which rests atop a drowned river valley. The bedrock valleys have been infilled mainly with fluvial sediment (Orme, 1974,1975) and the small channels flowing across the delta plains are sufficient to cope with discharge. The channels differ from distributary channels on typical deltas (Coleman & Wright, 1975) only in being few in number, (two at most, even in the widest floodplains), and in recombining behind the barrier before reaching the sea. Distributary channels do not typically recombine and the lateral expanse of deltas which are not confined within a river valley by wave action and steep offshore gradient, generally favour the formation of numerous distributaries (Allen,1965).

The delta-top channels of Natal river-mouths display estuarine circulation when discharge from the large catchments is sufficient to maintain an outlet through the river-mouth barrier. Variation in morphology arises from the nature of the coast (the Mlalazi and Matigulu are located on a prograding coastline) and the size of the catchment (the Mpambanyoni and Tongati have smaller catchments than the other estuaries). Response to changing discharge also varies within these estuaries, according to the degree of channel confinement.

8.10.4.Non-tidal river-mouths

River-mouths in this group generally have wide floodplains which have formed on top of valley fill deposits. Discharge is generally sufficient to maintain an outlet with the sea but tidal influence is minimal or non-existent. This arises from wide floodplains and elongate barriers which together reduce erosive stream power at the coast, through elongating the river channel and promoting seepage through the barrier and evaporation. Reduced stream power causes deposition in the back-barrier delta plain and also limits downcutting at the outlet thus reducing tidal influence. In the Mvoti river-mouth, reduction in stream power is so great that the outlets are only maintained by turbulence across rock outcrops which further limit or totally exclude tidal exchange. River-mouths in this category are the Mzumbe, Mvoti and Lovu (Group 9). The Lovu has been noted to have limited estuarine circulation, and this may be a direct result of human interference. Construction of a railway embankment across the barrier reduced its seepage potential, and reclamation of part of the floodplain as a rubbish dump (Grobbler, 1987) effectively narrowed the channel and limited channel migration or elongation on the floodplain. The nett effect was to concentrate the flow into a single, shorter channel which has the capability to maintain a sufficiently deep outlet and permit limited tidal exchange.

8.10.5. Wave-dominated beachridge delta

The Tugela river-mouth is classified thus because its high fluvial sediment supply, coupled with suitable nearshore topography and hydrodynamic conditions has permitted deposition of a 45 km-long beachridge plain which is in effect its coarse-grained delta. Miall (1979) noted that in areas where powerful longshore currents exist, the area of principal sediment accumulation will be displaced downcurrent from the main distributary mouth. This is the case at the Tugela where linear beachridge sands are deposited parallel to the coastal trend. Fine-grained sediment from the Tugela river is deposited offshore (Goodlad, 1986). Similar separation of the coarse and fine-grained portions of deltas has been noted elsewhere.

The beachridge plain of the Tugela which progrades at rates of up to 5 m per year is a classical wave-dominated delta. It is somewhat similar to the Orange Estuary (van Heerden, 1986) but conditions for coastal sediment accumulation exist at the Tugela mouth, whereas sediment at the Orange River-mouth is dispersed offshore.

Miall's (1979) statement that, "far less information is available for modern wave- and tide-dominated deltas .... and their internal geometry is less well known" is also true of the Tugela delta on which no sedimentological research has been performed.

8.10.6. Drowned river valley estuary / ria

The Mtamvuna river-mouth, which has no floodplain and a deep, bedrock-confined valley, differs from the other river-mouths in the study area in these and other respects. It owes its morphology to a low, mainly muddy sediment supply, and its channel confined nature which limits sediment accumulation. Being confined between bedrock cliffs it cannot be termed a delta top estuary, but is perhaps best termed a drowned river valley estuary. Although the other river-mouths in the study area originated in river valleys, they differ from the Mtamvuna in having attained maturity. It may be argued that the Mtamvuna should rather be classified as a youthful version of the other river-mouths, but because there is little evidence to suggest that any of the others may once have resembled the Mtamvuna, and little hope of the Mtamvuna ever becoming a delta-top estuary under natural conditions, it is here classified separately. If it did infill to flow across a floodplain in the future, its muddy nature would probably render it different to other large-catchment rivers in any case. Its short, valley-confined barrier also render it different to other estuaries in Natal.

8.10.7 Estuarine plunge pool

The Vungu is a unique river-mouth environment in Natal, being situated at the base of a waterfall. Its great depth and limited extent classify it separately. No sedimentological work has been carried out on this river-mouth, which is here defined as an estuarine plunge pool.

8.10.8. Discussion

The three main groups of river-mouths identified may undergo temporal changes in response to variation in discharge and change from one type to another for a period of time. A river-mouth may become a lagoon, if its outlet closes and if, flood-induced scour erodes the barrier and forms an outlet which permits tidal exchange, it may temporarily become a delta-plain estuary, until the flood-breached outlet closes. A delta-plain estuary may temporarily become a lagoon if its outlet closes, excluding tidal exchange, but when it reopens due to increased river flow it reverts to an estuary. It is doubtful if delta-plain estuaries can become river-mouths as suggested by Begg (1984a), unless reduction in discharge becomes a permanent feature. In such cases it is more likely that they would be transformed into lagoons with no outlet, rather than a river-mouth with an elevated outlet. Lagoons can temporarily become river-mouths or delta-plain estuaries when their outlets open and which it becomes, depends on the elevation of the channel base and the effect of any rock outcrops which may elevate the base of the outlet channel and act as a weir.

8.11. DISCUSSION

The four input factors successfully grouped the sixty-five river-mouths into groups with similar morphology and so can be argued to be the controlling variables. The classification also enabled recognition of evolutionary changes in each group of river-mouths and has led to a series of definitions and terminology for Natal river-mouths.

The implications of this classification extend beyond the geological field, because morphology and sedimentary processes impact on other factors. Salinity structure for example will depend on how frequently the mouth is open, itself a function of discharge and barrier porosity, intensity of overwash and degree of mixing within the water column.

The aquatic fauna will be a function of salinity (Whitfield *et al.*, 1981), period of connection with the sea, turbidity (due to catchment geology and flow) (Marais, 1988), substrate (a function of discharge and catchment availability) (Blaber, 1977) and availability of nutrients, controlled to a large extent by cycles of breaching and consequent flushing of nutrients. The degree of mixing and aeration in the river-mouth will depend on floodplain width, channel depth and river-mouth orientation and this impacts on the aquatic fauna. Natural sediment oxygen demand (SOD) may be higher in those rivers which have high organic inputs relative to clastic sedimentation.

Benthic-feeding mullet have been shown to have preferences for particular grainsizes (Blaber, 1977), although the overlap in preferences is very large. Various estuarine fish of Natal exhibit perference for clear or turbid water (Cyrus & Blaber, 1987) and so sediment inputs to a river-mouth may directly influence the aquatic fauna. Benthic organisms also select particular substrates and in Natal the burrowing sandprawn *Callianassa* is replaced in muddy environments by the mudprawn *Upogebia*. The burrowing traces left in the geological record are distinctive (Cooper, 1986a). Forbes (1973) suggested that the absence of *Callianassa* from large Natal river-mouths may be due to instability resulting from floods, and indeed their abundance in more stable, closed river-mouths is noteable.

The flora reflects salinity, discharge, substrate, stability and water level fluctuations. The mangrove *Avicennia*, for example, requires regular tidal fluctuation and cannot withstand inundation of its pneumatophores for extended periods (Berjak *et al.*, 1977) and *Phragmites* reeds cannot grow in salinities exceeding 16‰ (Benfield, 1984). Aquatic macrophytes require stability and particular water salinity and so their distribution is directly controlled by morphology.

It is clear, from the examples cited, that the factors identified are indeed strong controlling factors in estuarine morphological development. The application of a classification scheme involving these factors is important in developing effective environmental management guidelines. It may even be possible to link chemical and biological factors to this classification in order to assess the present state of aquatic habitats in relation to a scientifically determined pristine state and to monitor the impact of human intervention.

If a river-mouth differed from the theoretical morphology predicted from its catchment and basin characteristics, then this would probably reflect human interference. If a river-mouth whose catchment was composed of 100 % granitoid metamorphic lithologies, were found to be particularly turbid, it would probably reflect a direct impact from soil erosion, dumping, or changes in discharge. Gregory & Walling (1973) cite an example where removal of grass during road construction led to increased sediment supply and greater runoff to a small stream. This changed the character of its channel from a straight and meandering one to a braided one.

This chapter has therefore enabled correlation of the genetic controlling factors and resultant river-mouth morphology in Natal. The genetically-based classification reflects the controls on primary river-mouth basin shape and size, coupled with the factors which influence subsequent evolutionary development.

* * *

CHAPTER 9.
SEDIMENTARY MODELS OF NATAL-TYPE RIVER-MOUTHS

9.1. INTRODUCTION

A sedimentary model is a summary of a particular depositional environment which is synthesised from a range of actual examples. Local variability is excluded and only generalities are included from the model. The wider the range of examples, the more comprehensive and refined the model. Sedimentary models of transitional fluvio-marine environments, other than deltas, are still poorly developed (Nichols & Biggs, 1985), largely because examples described in the literature are restricted to a limited number of environmental settings. Few integrated sedimentological studies have been made. The objective in this chapter is to increase the available data base by providing synthesised models for Natal-type river-mouths and suggesting how they relate to other transitional fluvio-marine sedimentary environments. The models presented are based mainly on modern processes but a preliminary assessment of evolutionary trends has been made.

Sedimentary models are used in several applications: for interpretation of ancient sedimentary sequences by analogy with modern environments, particularly in mineral exploration; to enable generalisations regarding sedimentary processes in a particular environment; and as an aid in understanding the role of various components of modern sedimentary systems. Walker (1980) defined a facies model as, "a general summary of a specific sedimentary environment, written in terms that make the summary useable in at least four different ways", subsequently listed as follows:

> "a). it must act as a *norm*, for purposes of comparison;
> b). it must act as a *framework* and guide for future observations;
> c). it must act as a *predictor* in new geological situations;
> d). it must act as a basis for *hydrodynamic interpretation* for the environment or system that it represents."

A number of sedimentary models have been established for transitional fluvio-marine environments. Deltas are the best studied, due mainly to their association with petroleum reservoirs. A comprehensive suite of delta models has been presented based on numerous published accounts from a wide variety of environmental settings (Coleman & Wright, 1975; Galloway, 1975; Miall, 1979).

Formulation of sedimentary models for other transitional fluvio-marine environments is less advanced than with deltas. Coastal lagoons, which cover 17% of the worlds coastline (Barnes, 1980) have been the subject of only a limited number of local and regional sedimentological studies (eg. Orme, 1973; Lankford, 1977; Ireland, 1987; Duffy *et al.*, 1989; Pilkey *et al.*, 1989) but sedimentary models are poorly developed. This may be due to their occurrence mainly in less developed countries or sparsely populated areas (Kjerfve, 1986). Recently a number of papers (Kjerfve, 1986; Nichols, 1989; Kjerfve & Magill, 1989) have attempted to assess lagoonal variability and to place them in a conceptual framework. This could ultimately lead to the formulation of general sedimentary models.

Barrier islands and mainland-attached barriers, which can be either be viewed separately or as an integrated component of the lagoon environment, have received more attention than lagoons as a whole (Schwartz, 1973; Leatherman, 1979) and several coastal barrier models have been formulated. These can be basically divided into sand and gravel barriers. Sandy barriers are best studied due to their widespread distribution around the world's coastline (Kraft 1971, 1978; Kraft *et al.*,1973; Kraft & John, 1979; Halsey 1979; Belknap & Kraft, 1981; Thom, 1984a,b; Demarest & Kraft, 1987). Coarse-grained barriers, in comparison, are restricted to high latitudes on paraglacial coasts (Carter *et al.*, 1987; Duffy *et al.*, 1989; Bujalesky, 1990). Evolutionary models for coarse-grained barriers and associated lagoons in temperate latitudes (Carter *et al.*, 1987, 1989) show that they differ from sandy barriers (Carter & Orford, 1984). For example, they are more prone to overstepping due to a slower response time to sea-level change than sand barriers (Forbes *et al.*, 1991).

Synthesis of estuarine sedimentary models is not well advanced, largely as a result of the limited number of descriptions from a restricted number of environmental settings (King, 1980). No comprehensive suite of stratigraphically applicable estuarine facies models yet exists (Frey & Howard, 1986; Zaitlin & Shultz, 1990). Present sedimentary models of estuaries are commonly subdivided on tidal range and are frequently biased toward barrier environments in meso- and microtidal examples (Hayes, 1975, 1979; Boothroyd, 1978; Nichols & Biggs, 1985). Zaitlin & Shultz (1990) recently proposed a division of estuarine sedimentary models based on the relative importance of tides, rivers and waves.

A comprehensive sedimentary model, based on studies in the Bay of Fundy, was proposed by Dalrymple *et al.*, (1990), as a general model for macrotidal estuaries. These generally are funnel-shaped and have high current velocities. Three up-estuary zones exist: elongate tidal sand bars; sand flats with braided channels; and single channel tidal-fluvial transition. Grainsizes decrease headward and maximum energy levels occur in the middle reaches.

Boothroyd (1978) summarised information on mesotidal estuaries (tidal range 2-4 m), suggesting that they are characterised 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 generalised 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.

Sedimentary lithofacies in any estuarine fill depend on short term dynamic processes (waves and tides) and long term dynamic processes (tectonism and sea-level rise) as well as the nature and quantity of available sediment (Nichols & Biggs, 1985, p 165). Roy *et al.*, (1980) and Roy (1984) presented evolutionary models for estuarine embayments in which sedimentation keeps pace with sea-level rise (Fig.9.1). These models predict eventual filling of an estuarine basin and direct injection of fluvial materials into the marine environment.

In an assessment of unsolved questions in estuarine sedimentation, Nichols & Biggs (1985) noted that it is of special interest to compare the end products of *normal* estuarine processes with those of *episodic* processes such as floods or storms to determine what process leaves the greatest impact on the sedimentary record. The humid subtropical climate of the study area with its pronounced episodic and seasonal discharge variability, provides an ideal opportunity to examine this question.

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 delta-plain 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 delta-top estuaries from the wave- and tide-dominated estuarine models of Zaitlin & Shultz (1990).

Preliminary sedimentary models may be presented for Natal-type river-mouths, based on information provided in this thesis and in published articles. The main gaps in knowledge of Natal river-mouths lie in:

a) hydrodynamic studies of sediment transport and bedforms under varying flow conditions;
b) the nature of the valley fills; and
c) barrier stratigraphy.

These aspects require further detailed investigation to refine the models presented below.

In the following section observations to date are used to synthesis sedimentary models for Natal-type river-mouths. In some cases the model is based on several examples, but in others only one example occurs or has been studied. Hence those models are essentially schematic reviews of processes. Refinement of the models will be possible as more information becomes available from future studies.

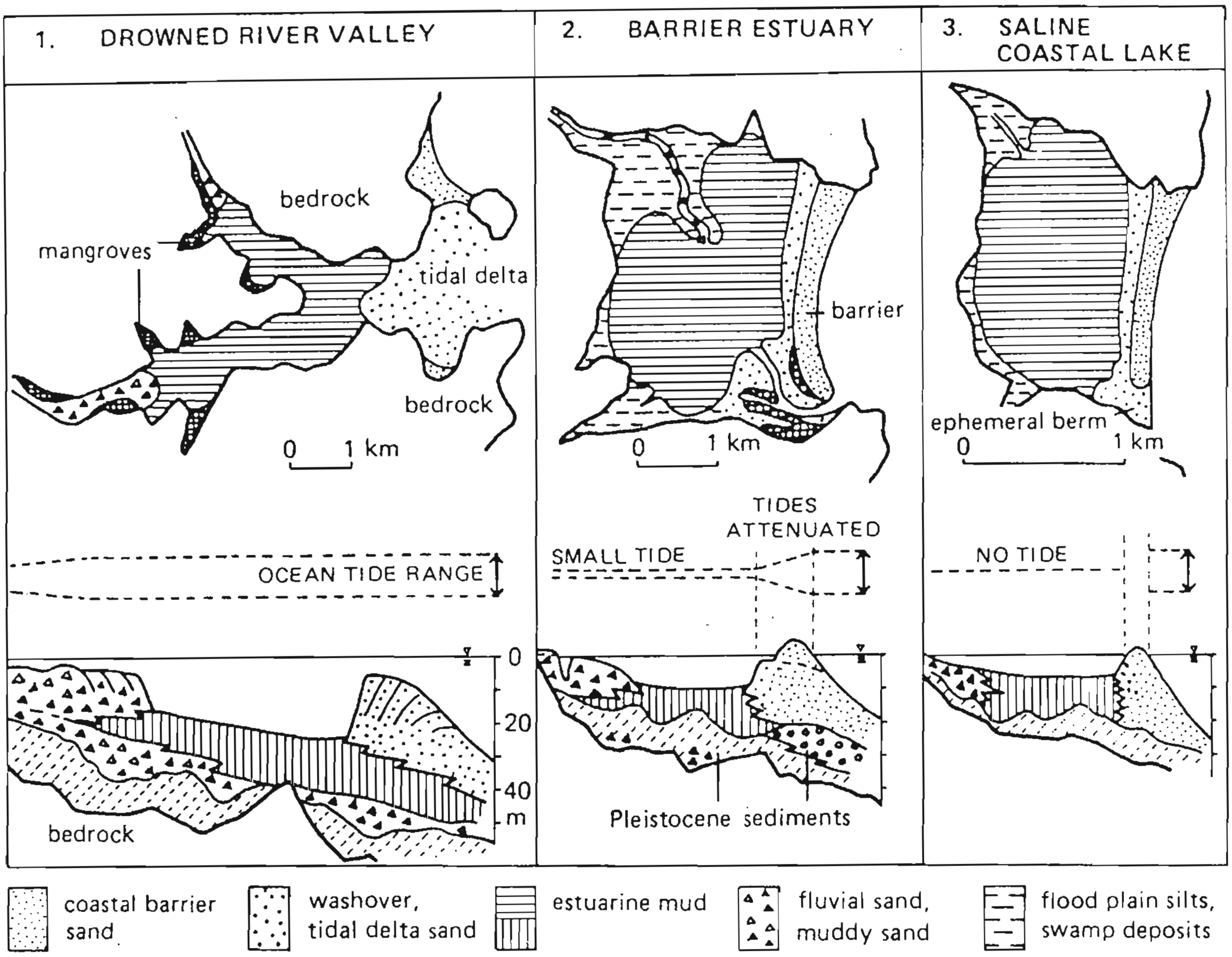


Fig.9.1. Models of wave dominated estuaries in New South Wales, Australia (after Roy 1984). Note the three basic upstream sedimentary units in all three types, from a coastal sandy plug, through a muddy estuarine facies to an upper fluvial zone.

9.2. MODERN SEDIMENTARY PROCESS MODELS

9.2.1. Delta-top estuary

In delta-top estuaries, typified by the Mgeni Estuary, sedimentary processes follow a cyclic path, dominated by flood impacts and long-term, post-flood channel adjustment. A schematic diagram of sedimentary processes is shown in Figure 9.2.

In a mature or stable state (Fig.9.2.A) these estuaries have stable, vegetated or muddy banks with moderately deep (1-3 m) confined channels in which tidal exchange produces semi-diurnal salinity and water level fluctuation. The channel may bifurcate into two distributaries around a central island but these rejoin in the back-barrier area. Tidal currents deposit a small flood-tidal delta at the inlet but ebb-tidal deposition is inhibited by wave action. The seaward barrier face assumes an equilibrium planform and shows little landward migration: washover-deposited sands are reworked by tidal currents. The channels are scoured to an erosion base of rock, compacted mud or gravel. Suspension settling of mud is promoted by flocculation and agglomeration during low flow periods but during moderately increased river flow this is transported seaward in a turbid plume. Supply of sandy sediment to the coast is minimal. Reduction in volume of flood-tidal deltas during moderate floods is followed by subsequent upstream migration. Tidal inlet cross-sections change according to fluvial discharge and wave approach and intensity.

During major floods, (Fig.9.2B) the confined bedrock valleys restrict lateral flow expansion and promote downward erosion and scour. River-mouth barriers are completely eroded. Overbank deposition is limited by relatively narrow floodplains and mud is deposited in sheltered backwaters. Submerged sandy deltas are deposited offshore. Flood channels are deep and filled with fresh water. After floods subside, salinity is re-established and suspension settling of mud begins in the channel. At the same time, the barrier is reformed by emergence and landward translation of the submerged delta through shoreface erosion and overwash in a typical rollover response. Additional sand in the nearshore causes temporary shoreline progradation on the seaward barrier face, but because of high wave energy and steep nearshore slope this is eventually reworked offshore and alongshore to produce a wave-equilibrium planform. Wind dispersal of excess sand may also nourish adjacent precipitation dunes. Major coastal sand supply occurs during floods.

Post-flood bedload transport of fine sand into the estuarine channel from upstream causes shallowing. The uncohesive sandy banks, which are stripped of vegetation during floods, promote braiding (Fig.9.2C). The shallow braided channel reduces the tidal prism and inhibits flood-tidal deposition. Temporary increases in barrier width also reduce stream competence in outlet maintenance and so outlets close periodically.

In the long term, braid bars are stabilised with vegetation (commonly mangroves) which, in turn, promotes intertidal mud deposition. This stabilises the banks and induces downward river scour and formation of deeper channels. Depending on river orientation at the head of the estuary valley, deposition is concentrated either on an interdistributary central island or on the floodplain along one margin of the estuary. In post-flood times, barriers narrow through offshore and alongshore dispersal of flood-deposited

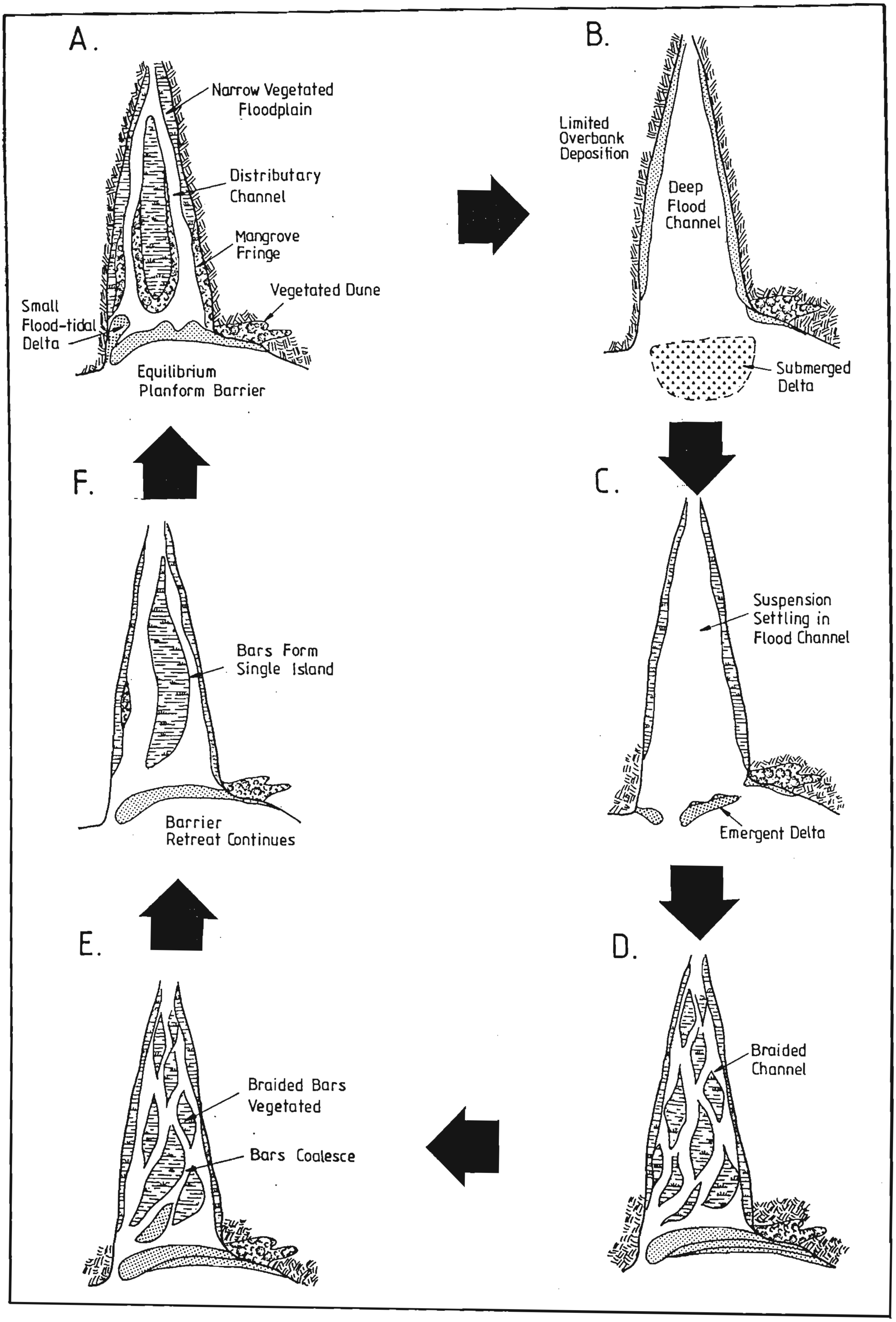


Fig.9.2. Schematic diagram to illustrate cyclic sedimentary processes in delta-top estuaries in the study area.

sediment to regain equilibrium planform morphology. Larger tidal prisms permitted by deeper estuarine channels, maintain barrier outlets and flood-tidal deposition is ultimately renewed as the tidal prism increases.

Facies arrangement (Fig.9.3) in mature delta-top estuaries comprises one or two sand- or gravel-based channels with braid bars or side-attached bars. Facies of the Mgeni Estuary during a mature stage were described by Cooper (1988a). The gravelly channel bases during mature post-flood intervals contain few bedforms or bioturbation and represent an erosion base. Mudball lags, derived from bank erosion may be present. Mud may accumulate in channels temporarily during low flows, only to be 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 of crabs and amphibious fish. The infauna and the mangrove roots produce characteristic bioturbation traces (Cooper, 1986a). Elevated areas behind the mangrove fringe support a salt-marsh 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-scale burrows of sesarmid crabs (Cooper, 1986a).

In the back-barrier area, out of the main channel, muddy lagoonal facies may accumulate, particularly if coastal extension occurs. These deposits are intensely bioturbated by burrowing prawns and may be algae-covered.

Barrier-associated facies include an inlet channel with evidence of reversing tidal currents provided by bedforms, although typically flood- and ebb-tidal currents dominate particular sections of inlet channels (Cooper, 1988a), in a similar fashion to some inlets in the Eastern Cape (Reddering, 1983). Flood-tidal deltas are present in the inlet area of delta plain estuaries and in the Mgeni they extend for 200 m upstream during mature, post-flood periods (Cooper & McMillan, 1987). Ebb-tidal deltas are only developed for short periods of low wave energy, but are small and do not persist.

Intertidal areas are limited in extent and occur on the landward barrier margin and flood-tidal deltas. Structures characteristic of late-stage emergence runoff on intertidal flats are produced on them. Barriers are dominated by overwash lamination and tidal inlets do not migrate. Aeolian deposits may occur north (downwind of the barrier) but are uncommon on the barriers themselves, due to periodic barrier erosion during floods.

Under present conditions flood periods accomplish more sediment erosion and deposition than many months or years of fairweather conditions.

9.2.2. Drowned river valley estuary

The only drowned river-valley type estuary in Natal is the Mtamvuna, although descriptions of estuaries further south in Transkei (Blaber *et al.*, 1974, Dardis & Grindley, 1988; Day, 1981) suggest that this type of estuary is more common there. Sedimentary processes are illustrated schematically in Figure 9.4.

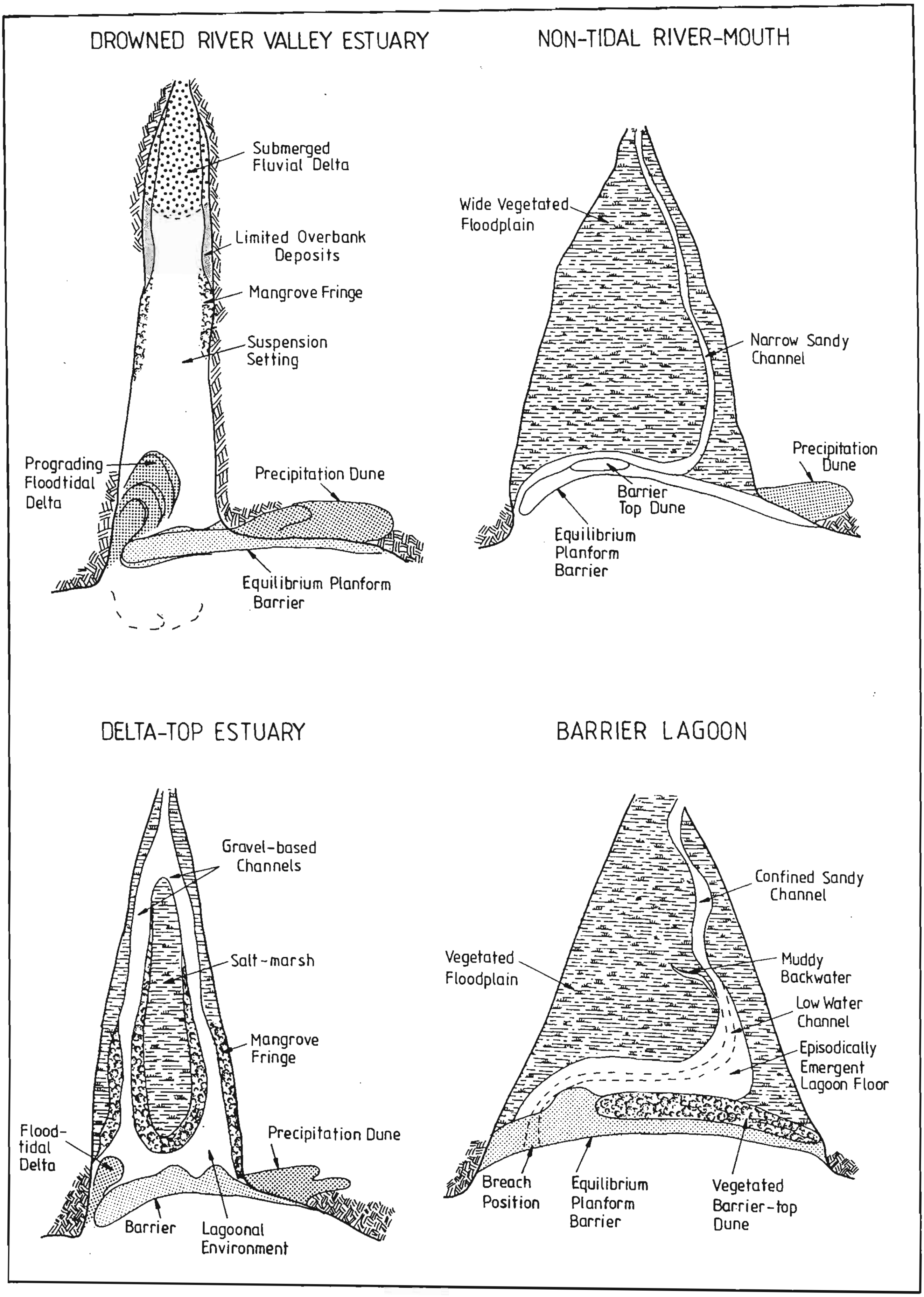


Fig.9.3. Sedimentary facies distribution in the four main river-mouth types in the study area.

Under stable conditions (Fig. 9.4A) the narrow bedrock channel is comparatively deep and overbank deposits poorly developed. A barrier is present across the estuary mouth and a tidal inlet permits regular tidal exchange. A flood-tidal delta is present opposite the inlet. Upstream, the channel deepens and suspension-settling is the dominant sedimentary process. Gravity fall from steep valley sides may also provide a source of sediment. In a small cliff-bound estuary in Wales, King (1980) found that cliff-derived talus accounted for 17% of surficial sediments. In the upper reaches shallow channel areas of sandy sediment represent a fluvial estuary-head delta. This tripartite arrangement of facies is similar to that described from the James River Estuary of Virginia, USA, and proposed as a general sedimentary model for microtidal estuaries by Nichols (1990). It also corresponds closely with the wave-dominated estuary model of Zaitlin & Shultz (1990) derived from descriptions of Roy (1984) and Boyd *et al.* (1987). Under stable conditions, the inlet changes in orientation and size according to the amount of freshwater discharge and nearshore wave conditions.

During major floods, the barrier and flood-tidal delta are eroded and a submerged delta is deposited in shallow water seaward of the river valley (Fig.9.4B). Low bedload sediment yield from upstream appears to limit estuary-head delta progradation during floods and relatively deep water in the middle reaches limits downward scour. Overbank deposits are limited in extent in the narrow valley and suspended sediment is carried offshore as a turbid plume. Lack of bedload supply from upstream means that the offshore delta is composed of barrier sands without additional fluvial inputs.

In post-flood periods, submerged delta sands are transported landward. They become emergent through swash action and are gradually reworked under wave action to reform the barrier (Fig.9.4C). In the succeeding weeks or months the reformed barrier retreats into an equilibrium planform by overwash and flood-tidal delta progradation into the estuary channel. Losses of sediment into precipitation dunes (Tinley, 1985) may occur through aeolian reworking, particularly of finer sand grains, but lack of sustained dune growth suggests that this loss is small. It may be limited by lag-armouring of the back-beach through deflation (Cooper & Mason, 1986).

Facies of drowned river valley estuaries, comprise a tripartite arrangement (Fig.9.3). At the upstream limit shallow sandy areas represent a fluvial delta. The internal structure of these deltas in Natal has not been investigated but the delta surface commonly lacks small-scale bedforms, indicating low rates of bedload transport. In the middle reaches suspension-settling of mud occurs in deep water, below the impact of flood scour. In the barrier area, non-cohesive sandy marine deposits predominate and prograde upstream in interflood periods. Mangroves colonise the limited marginal areas and produce distinctive traces in the sediment. They also trap a limited amount of suspended sediment. Upstream *Phragmites* reeds replace mangroves as fringing vegetation.

9.2.3. Non-tidal river-mouth

Sedimentary processes in non-tidal river-mouths are exemplified by the Mvoti (Chapter 6) from which a general sedimentary model can be constructed. The Lovu (Grobbler, 1987) and Mzumbe (NRIO, 1983) which probably displayed such processes in the past, have been altered by embankment construction so

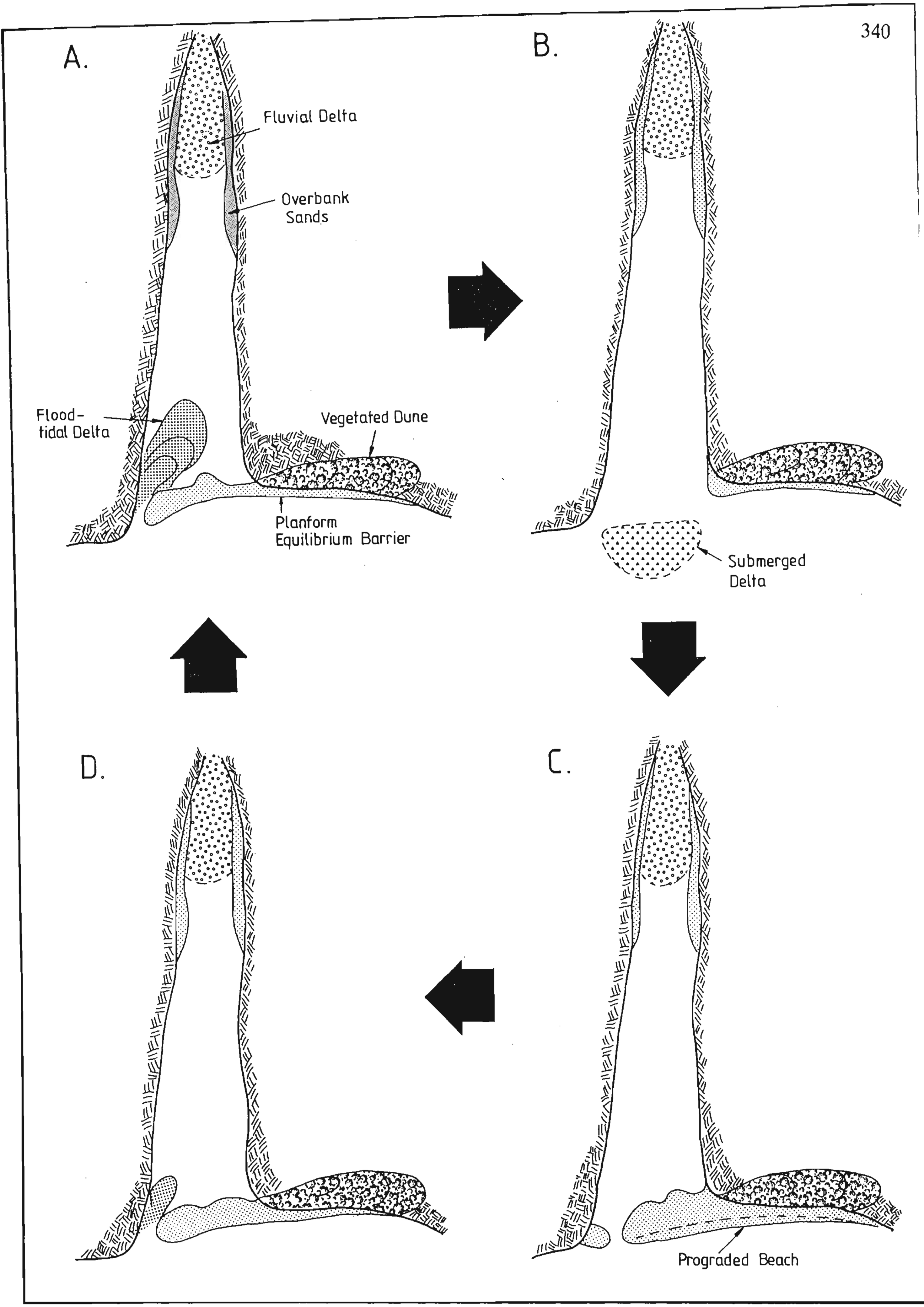


Fig.9.4. Schematic diagram to illustrate cyclic sedimentary processes in drowned river valley estuaries in the study area.

that they no longer conform to this model. Modern sedimentation in such settings comprises river-dominated sedimentation on a back-barrier floodplain in which long-term channel changes tend to produce a narrow channel confined between cohesive muddy or vegetated banks. This process is periodically reset by floods which erode the banks producing a broad, braided channel, after which the process of channel confinement resumes.

Under stable conditions, (Fig.9.5A) these river-mouths comprise a narrow sandy channel whose sinuous course across the floodplain reduces the downstream gradient during low flows. The channel is surrounded by a wide vegetated floodplain and has cohesive muddy and/or vegetated banks. Long coastal barriers assume planform equilibrium with approaching wave fronts and a dune may form in the central part. A precipitation dune is commonly present downwind of the barrier on the mainland.

During extreme floods (Fig 9.5B) floodplains are inundated and broad, shallow flood channels are produced by lateral scour of the floodplain. Remaining floodplain sectors are covered with fine-grained overbank sands which bury existing vegetation. Gully erosion may occur if overbank flow encounters deeper water of former channels. Large parts of the long barriers, opposite main flood channels and overbank flow paths, are eroded but sheltered sections may remain. Submerged deltas are deposited offshore.

In post-flood stages (Fig 9.5C), ephemeral, flood-deposited deltas are reworked landward and become emergent. They are modified by wave refraction patterns and become welded to the barrier remnants. Flood channels narrow through marginal vegetation encroachment and mud deposition on proximal overbank areas. This acts to confine channels and encourages downward scour. Eventually barriers reform and rivers assume pre-flood courses (Fig. 9.5D) as abandoned channel areas become vegetated and shallow. Barriers may prograde temporarily but dispersal of additional sediment results in attainment of equilibrium within a short period. The reformed river channel may migrate across the floodplain in the long term to maximise channel length under low flow conditions.

The floodplains of such river-mouths, although wide, are not sufficiently large to permit channel avulsion as in deltaic floodplains (van Heerden, 1986) but limited crevassing into marginal floodplain areas may occur. Sediment buildup on the floodplain and in the channel is restricted by the equilibrium river profile and excess sediment is transported through the river to the ocean. Bedload movement is erratic and mostly occurs during extreme floods but suspended sediment is transported through the river under lower flow conditions. Long-term preservation of muddy sediments may occur in marginal floodplain environments, particularly those sheltered from flood impacts and the large floodplains offer wide areas for temporary sediment storage.

Periodic erosion by floods limits aeolian dune formation on barriers but precipitation dunes may form downwind of the barrier. Barriers assume planform equilibrium under wave attack and coastal progradation occurs only as a temporary response to floods.

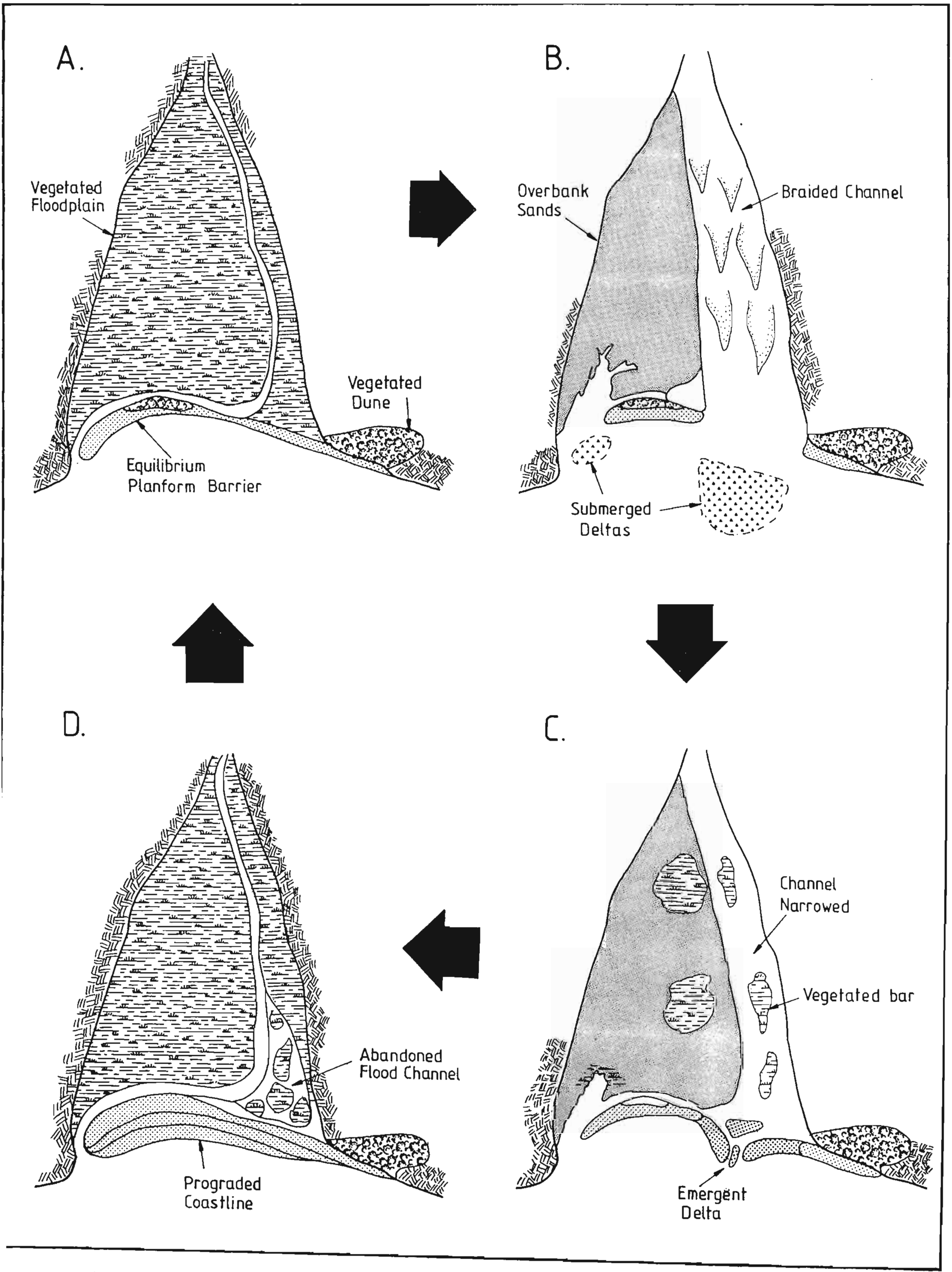


Fig.9.5. Schematic diagram to illustrate cyclic sedimentary processes in non-tidal river mouths in the study area.

Sedimentary facies of non-tidal river mouths (Fig 9.3) comprise barrier and back-barrier units. Barriers are dominated by overwash lamination in common with other barriers in Natal. Inlet migration is limited and inlets tend to be very shallow. Inlet floors are either rocky or sandy, with no evidence of reversing tidal currents. Consequently flood-tidal deltas are absent. Limited-extent ebb-tidal deltas may form temporarily during low wave-energy phases. Overwash-derived marine sediment is concentrated next to the barrier and is reworked by fluvial currents. Limited aeolian dune development may occur on the barrier in sections least frequently breached during floods, but extensive precipitation dunes may be deposited downwind of the barrier, on the adjacent mainland beach.

Back-barrier areas consist of channel and floodplain facies. Distal floodplain sediments comprise only fine sand but in proximal areas these are overlain by vegetated, muddy overbank deposits. Near the river channel crevasse splay deposits may occur. Adjacent to the river channel are lateral migration deposits of mud, which form the cohesive channel banks. Riparian vegetation comprises mainly *Phragmites* and *Scirpus* reeds, in contrast to the mangroves of tidal estuaries.

River channels are sandy with typical braid bar structures. Mud may accumulate in the channels temporarily during low flow periods. Abandoned flood-channels become vegetated when rivers revert to channel-confined flow. Shallow intervening channels rapidly infill with sediment and also become vegetated and incorporated into the floodplain. Lagoon-type back-barrier deposits and backwater deposits are limited because river flow fills the channel. Biogenic traces differ from estuaries because of low salinity conditions and river-mouth sediments are generally poorly bioturbated.

9.2.4. Barrier lagoon

Barrier lagoons represent the most abundant type of river-mouth environment in the study area and the one which shows most morphological variation (Chapter 8.). In spite of the large number of lagoon classes identified in terms of morphology, similar processes operate in all of them, although at different intensities and varying in relative importance. In the barrier lagoons of Natal stable conditions are characterised by high water levels and low energy conditions in which suspension settling dominates sedimentation (Fig. 9.6A). Bioturbation by infaunal molluscs and crustaceans may be locally important in mixing the bottom sediments (Grobbler, 1987; Cooper 1987; Begg, 1984b), particularly in marginal areas. The main sediment sources are the catchment, surrounding vegetation and local bank erosion. Marine sediment input is limited to overwash and deposition is restricted to the immediate barrier area.

The volume of overwash input depends on the length and height of the barrier. In uMgababa Lagoon (Grobbler *et al.*, 1987) marine sediment input through overwash is low due to the short barrier while in Mhlanga Lagoon (Chapter 3) the 900 m-long barrier promotes overwash sedimentation. Lagoon barriers may contain an upper aeolian component, depending on orientation with respect to prevailing winds and frequency and location of breaching. In general those which breach less frequently have better developed barrier dunes. The densely vegetated dune on the barrier of the Ku-Boboyi Lagoon was attributed by Begg (1984b) to prolonged closure. On the barrier of Mhlanga Lagoon, where breaching occurs in one of two positions, aeolian dunes occur in the intervening area. Under all conditions, the seaward faces of

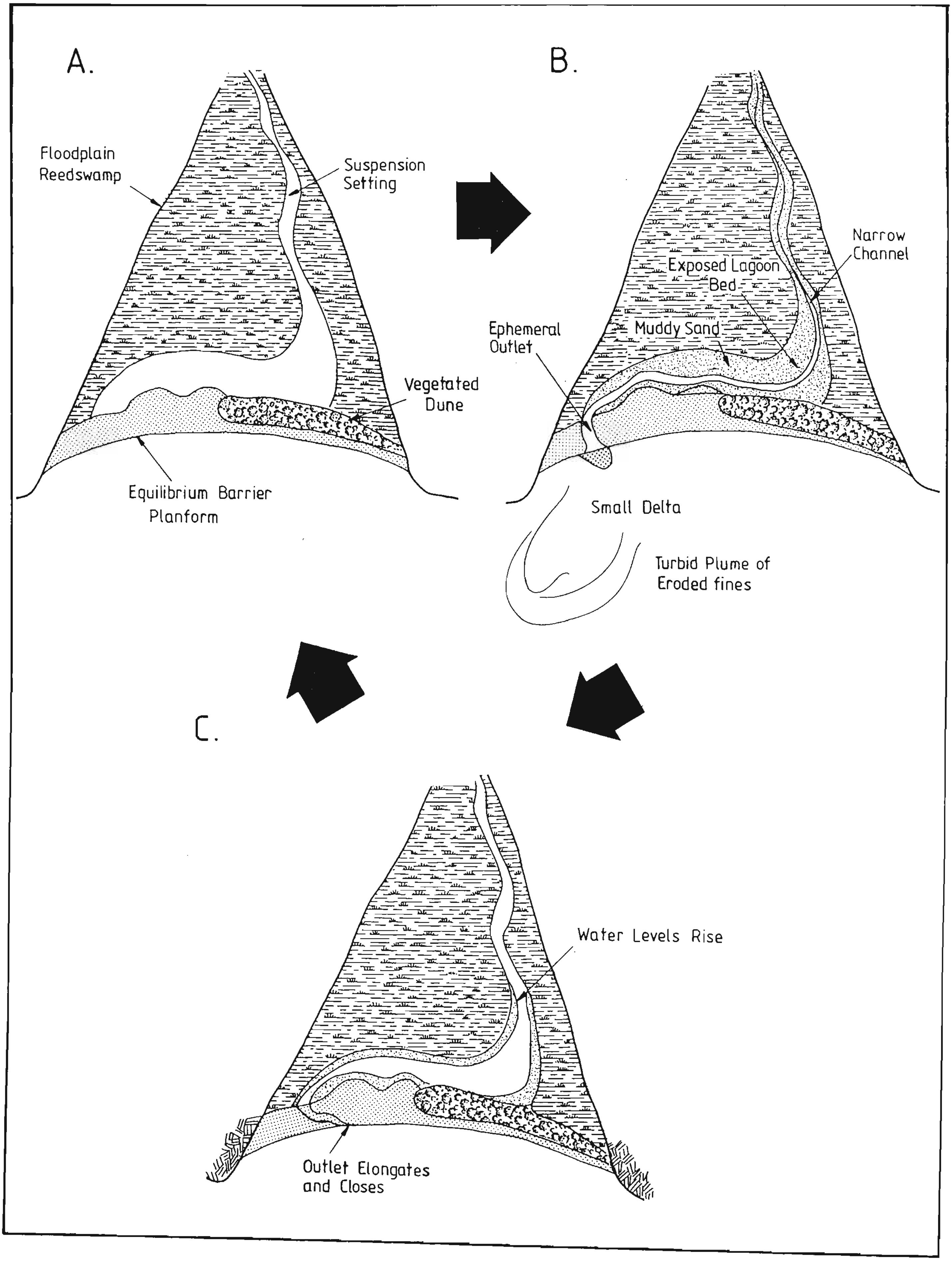


Fig.9.6. Schematic representation of processes in coastal lagoons.

barriers may undergo variation between reflective and dissipative states depending on sea conditions. No long-term accumulative or erosional trends were noted south of the Tugela River (Cooper, 1991b).

Periodic, short-lived, high-energy phases are precipitated by barrier breaching and outlet formation (Fig 9.6B). This appears to be caused mainly by increased fluvial discharge as noted by Carter *et al.*, (1987) in Irish lagoons. In the cell-confined barriers of Natal, where long-term changes are minimal (Cooper, 1991b) alternative processes of breaching such as stretching and separation (Carter, 1982; Carter *et al.*, 1984) have not been documented. Begg (1984b) cites observations of overwash-induced breaching of the Mnamfu over a period of "a few days", through lowering of the barrier to a point where water flowed out (Fig.9.7). Elsewhere, overwash may lower the barrier at a particular position which enables rising water levels to form an outlet there (Begg, 1984b; Cooper, 1987). Rapid outflow of water following breaching causes erosion of accumulated fine sediment from the bed of the lagoon and promotes selective retention of sand (Cooper 1987; Grobbler 1987; Cooper *et al.*, 1988). Characteristic sedimentary structures, similar to those normally associated with late-stage emergence runoff on intertidal flats are generated by outflowing water (Chapter 4; Cooper, 1987; Grobbler, 1987; Grobbler *et al.*, 1987). A small delta, composed of eroded barrier sand, may be deposited at the outlet (Fig.9.6C). This is reworked in the direction of wave approach, elongating the outlet channel across the barrier and ultimately causing it to close. Seaward barrier accretion does not accompany breaching which indicates that bedload sediment supply from the lagoon to the coast is minimal. The sediment storage capacity of a lagoon depends to a large extent on its floodplain width. Wider floodplain lagoons such as uMgababa (Grobbler *et al.*, 1987) accumulate more muddy sediment in backwaters and on the floodplain while breach-induced scour in narrower floodplains such as the Mvutshini (Little Bilanhlolo; Orme, 1974), favours sand retention in the sedimentary record. The size of the catchment determines the height to which flood waters can rise and hence also the potential distribution of overbank deposits.

In the few large-catchment barrier lagoons in the study area, such as the Mdloti, flood impacts are severe and considerable erosion may be effected (Grobbler, 1987), however, under post flood conditions the lagoon reverts to a stable morphology which resembles the Mhlanga and other similar lagoons.

General facies distributions in barrier lagoons (Fig 9.3) comprise a barrier which, because of limited barrier erosion during breaching, typically has a vegetated aeolian dune component. Flood-tidal deltas are absent and ephemeral ebb-tidal deltas form only after floods. Outlet channels are shallow and ephemeral and are rapidly reworked after formation. In this respect they are similar to the outlets described from the Oregon coast (Clifton *et al.*, 1973). Outlets of similar dimension on the California coast (Webb *et al.*, 1989) are more commonly open and permit flood-tidal delta deposition. Antidunes may be produced in outflowing channels (Harrison & Cooper, 1991) but the outlet channels are more frequently shallow and braided on a microscale. Similar structures were described from small stream outlets by Clifton *et al.* (1973) but the preservation potential of such structures in such wave-dominated environments as Oregon or Natal, is extremely low and they are destroyed by swash and overwash (Clifton *et al.*, 1973). Overwash lamination dominates barrier structures.

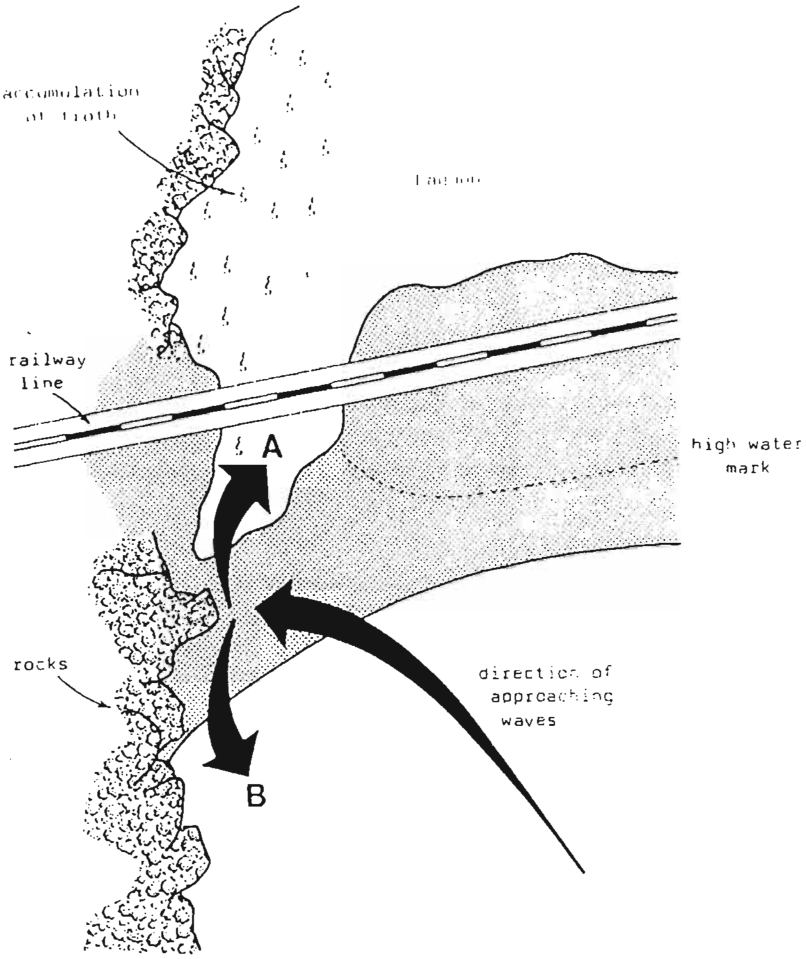


Fig.9.7. Mechanism of breaching by backwash and overwash documented from Mnamfu Lagoon by Begg (1984a). "Two-directional flow of water generated by rocks at the mouth of the Mnamfu lagoon at high tide on 14 September 1982. Flow A served to increase the water level in the lagoon, whilst flow B served to erode a channel towards the sea. Throug h this combination of forces the mouth of the lagoon opened naturally after a succession of high tides a few days later." (Begg 1984a).

Floodplain deposits comprise vegetated wetlands, typically fringed with either *Phragmites* reeds or *Barringtonia*, the "freshwater mangrove". True mangroves are generally absent. Among the lagoons of Natal, variation in the degree of floodplain vegetation, and hence channel constriction, appears to represent an evolutionary trend. Back-barrier channels which are comparatively unconfined are shallow and sandy, while those which are confined are deeper. They are generally sandy, but fine sediment and organic debris may accumulate temporarily during closed phases, only to be removed after breaching. Mud may be preserved in backwaters. Channel structures are similar to intertidal flats, but evidence of eddy currents may be preserved in bedform orientation. The assemblage of biogenic structures, comprising *Tilapia* nests and mullet feeding traces, with localised *Callianassa* burrows, is thought to be diagnostic for this type of environment.

9.2.5. Beachridge plain delta

Despite being the only example of a beachridge plain delta in Natal and one of only two prograding sectors of the South African coast (Tinley, 1985), the Tugela river-mouth has received little concentrated sedimentological or geomorphological study. Consequently, assessment of the sedimentary processes is still at a preliminary stage. Preliminary measurement of morphological changes in the river channel was carried out by CSIR (1990) and several studies have been made of vegetation succession (Weisser, 1979; Weisser *et al.*, 1982; Weisser & Backer, 1983) and regional shoreline changes (Tinley 1985; Cooper, 1991a). CSIR (1983) made an assessment of the likely impact of upstream dam construction on the estuary and adjacent coast in which predicted longshore transport supply of sand and estimated fluvial sand supply were used to predict impacts of reduced sediment supply after dam construction, some 15-20 km upstream of the sea. The calculated annual longshore flux of 1.1 x 10^6 m^3 of sand from areas south of the Tugela mouth reported by CSIR (1983) is problematic because the largely rocky coastline to the south, coupled with the presence of only two major rivers in the 100 km to the south (Mgeni and Mvoti), poses the question of the source of this north-moving sand.

It appears that the longshore transport rate is in fact only a potential one and as noted by May & Tanner (1975), many coastal systems are remarkably inefficient in terms of nett production. Thus the actual supply from areas to the south of the Tugela River mouth is probably very much lower. As Carter (1988, p.207) states " residual drift patterns from refraction data take no account of material factors, so that uncalibrated drift must be described as potential rather than actual". More research is required on the sediment budget of this beachridge-plain delta.

Under non-flood conditions, the Tugela river channel is braided and sandy with little vegetation on the channel bars (Fig 9.8A). Major sediment flux to the sea occurs during floods (Fig. 9.8B) and aerial photographs reproduced in CSIR (1990) show the presence of emergent deltas offshore in periods after floods and significant beachface accretion both north and south of the river mouth. After floods this excess (Fig.9.8D) sediment is eroded northward to augment sedimentation on the beachridge plain and the reformed barrier is worked landward by overwash into the river valley where it is protected from longshore transport and assumes an equilibrium planform. Conditions conducive to delta growth are the large sediment supply, coastal orientation, suitable offshore gradient and northward reduction or reversal in

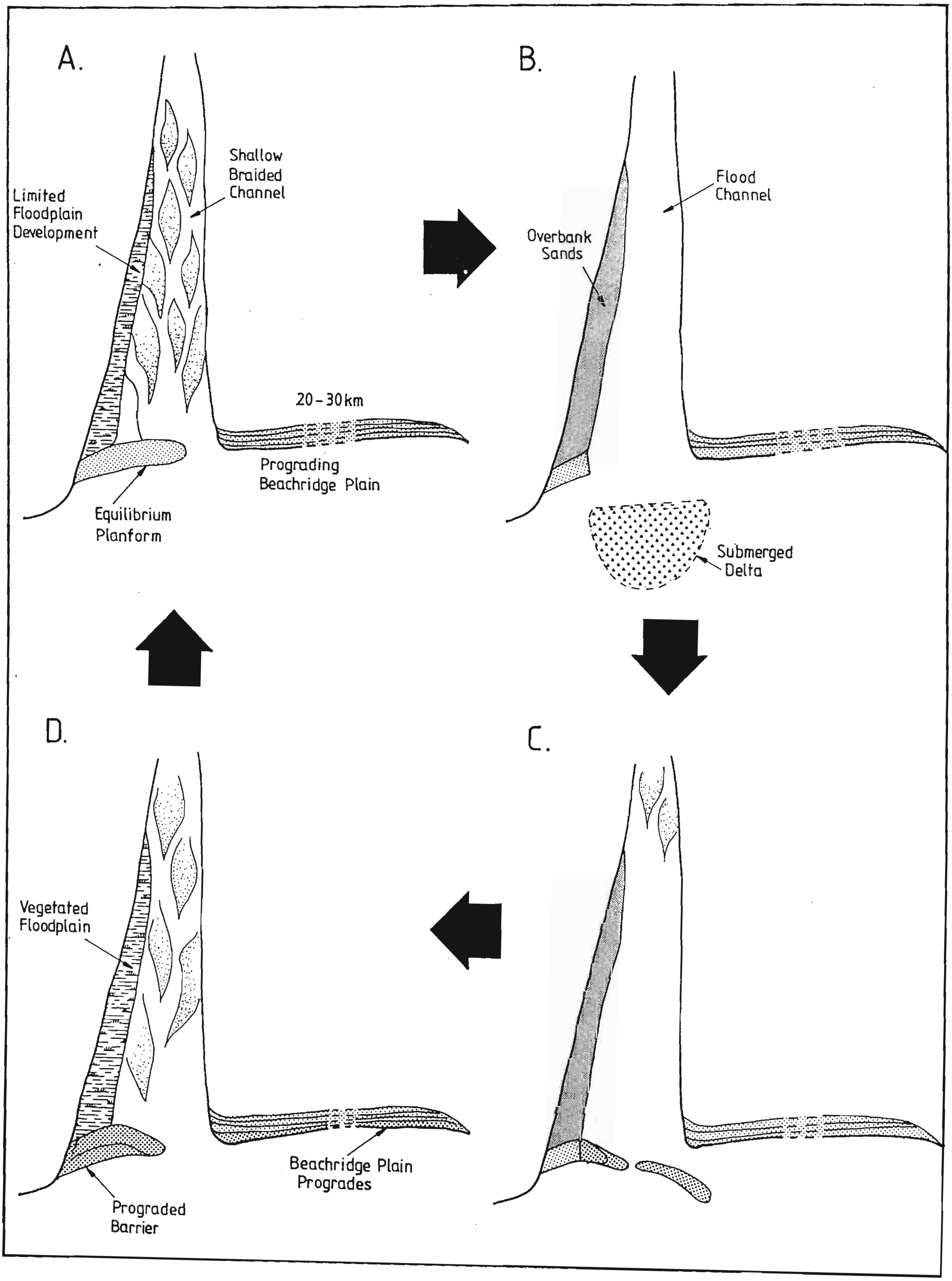


Fig.9.8. Preliminary assessment of processes at a beachridge plain delta.

longshore transport flux (Cooper, 1991). Sandy beachridge plains have been described from various parts of the world (Curray *et al.*, 1969; Dominguez *et al.*, 1987), and their main common characteristic is the formation of extensive shore-parallel sand bodies (Coleman & Wright, 1975).

No facies model can yet be developed for this environment in Natal, but it is likely to combine features of wave-dominated beachridge deltas and facies of braided rivers.

9.2.6. Estuarine plunge pool

Sedimentation in the Vungu river-mouth has not been studied, but observations of the bottom sediment (Airey, personal communication in Begg, 1984b) suggest that the deepest back-barrier section (40 m) is bottomed by organic- rich silt. The sandy barrier maintains an outlet for most of the year (Begg 1984b) but whether or not flood-tidal deposition occurs is not known. The barrier is eroded during major floods, only to assume its original position under wave action during post-flood wave conditions. When the barrier is eroded waves break against the base of the waterfall (personal observation, October 1988).

9.2.7. Prograding coast estuaries

The estuaries of the Matigulu and Mlalazi Rivers represent an unusual group of estuaries, which have been little studied sedimentologically. Although grouped together in terms of their elongate barriers, they exhibit major differences in back-barrier morphology, which make establishment of sedimentological models impossible at this stage. Consequently they, like the Vungu, are excluded from further discussion.

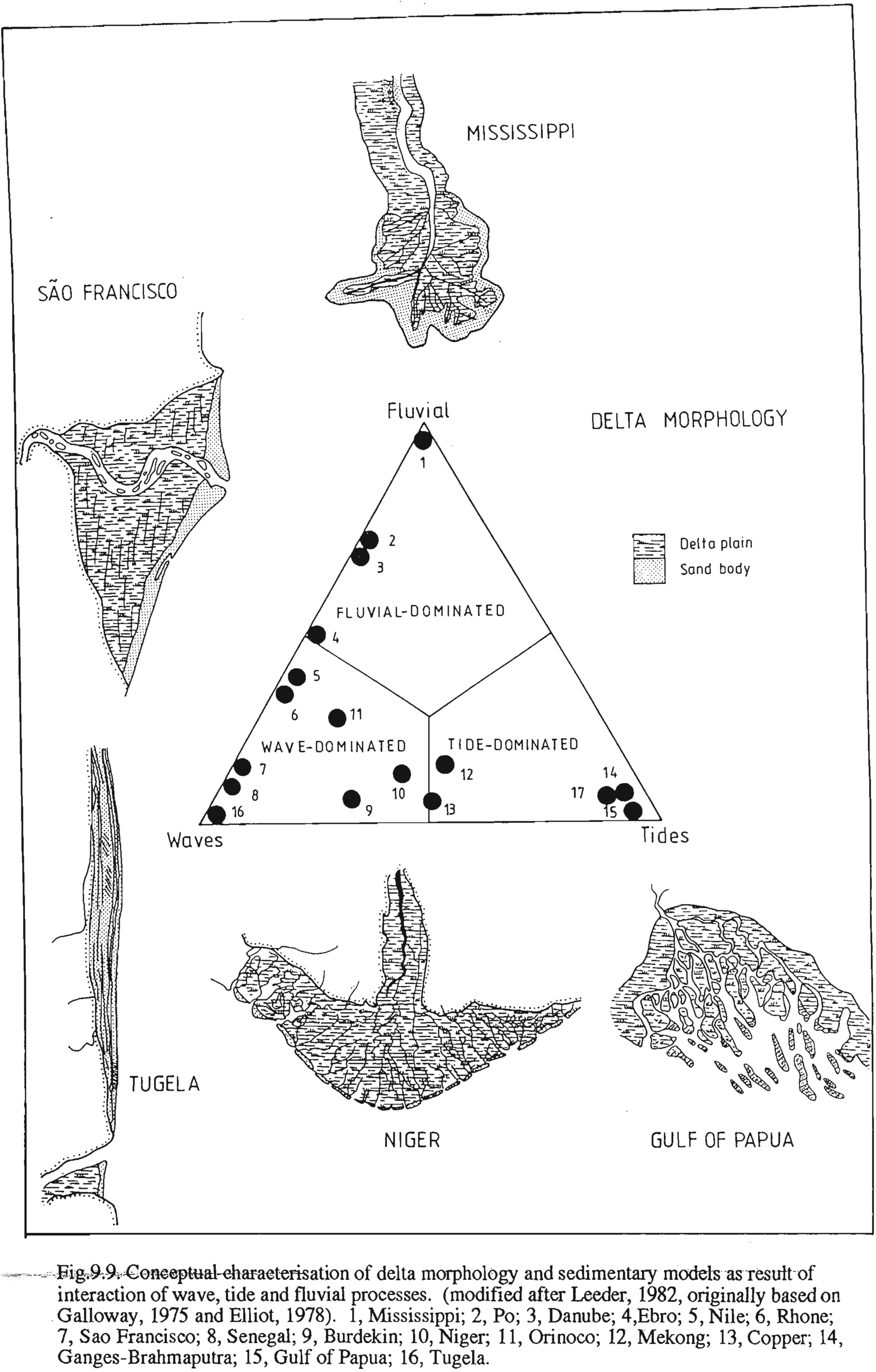
9.3. NATAL RIVER-MOUTHS AND OTHER SEDIMENTARY MODELS

9.3.1. Introduction

In this section the models for Natal river mouths presented above are considered in terms of existing sedimentary models for transitional fluvio-marine environments. Such an approach aids in formulation of a comprehensive suite of transitional fluvio-marine environments. They are discussed below in relation to deltas, estuaries and lagoons.

9.3.2. Deltas

The Tugela beachridge plain is similar to wave-dominated deltas of Galloway's (1975) classification, but is even more wave-dominated as it is driven parallel to the linear Natal shoreline. As such it resembles the Senegal-type delta (Wright & Coleman, 1975). A sedimentary model for such environments described by Wright & Coleman (1975) also includes features, such as shore-parallel sand bodies, common to the Tugela. Consequently the Tugela can be placed at the wave-dominated apex of a ternary diagram of delta sedimentary models (Fig 9.9) as modified by Leeder (1982) . In contrast to van Heerden (1986) who would have classified such systems as the Orange Estuary as a wave-dominated delta, it is argued that the Orange Estuary and other sediment-filled basins which lack coastal progradation should be excluded from delta classification. They are best placed in a scheme for estuaries and other non-progradational valley fills.



~~Fig.9.9. Conceptual characterisation~~ of delta morphology and sedimentary models as result of interaction of wave, tide and fluvial processes. (modified after Leeder, 1982, originally based on Galloway, 1975 and Elliot, 1978). 1, Mississippi; 2, Po; 3, Danube; 4,Ebro; 5, Nile; 6, Rhone; 7, Sao Francisco; 8, Senegal; 9, Burdekin; 10, Niger; 11, Orinoco; 12, Mekong; 13, Copper; 14, Ganges-Brahmaputra; 15, Gulf of Papua; 16, Tugela.

9.3.3. Non-progradational environments

Zaitlin & Shultz (1990) presented a conceptual ternary diagram for estuarine sedimentation, similar to Galloway's (1975) delta triangle. On this they depicted the spatial arrangement of models for wave-dominated and tide-dominated estuaries but deliberately omitted the river-dominated apex. It could be argued that deltas belong there but, if this scheme is limited to non-progradational landforms, channel-confined systems such as the Orange Estuary and many other environments may be accommodated.

Hayes' (1975) mesotidal estuary model, for example, exhibits moderately strong tidal currents in the tidal inlet which promote more extensive tidal delta formation in comparison to wave-dominated (generally microtidal) estuaries (Davis & Hayes, 1984). In the ternary diagram for estuaries (Fig 9.10) it 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 non-tidal river-mouths of Natal, 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 delta-top estuaries of Natal which, although fluvially dominated, experience minor marine inputs through their tidal inlets. The Orange 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 inlet through reversing tidal currents. On the wave-dominated coast of Chile, Araya-Vergara (1985) documented the occurrence of "estuarine deltas" which are sediment filled rias in which coastal progradation is limited by high wave energy. The steep Chilean hinterland rises at 6 to 7° and in the transition between humid and dry temperate climatic zones sediment supply to the coast is high. The similarities to the Natal coastal setting and Natal-type delta-top estuaries are striking. This suggests that Natal's delta-top estuaries 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 suggests that it too can be plotted there as it exhibits the three-zoned divisions recognised 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 inlet. The St Lucia Estuary mouth in Zululand (Wright & Mason, 1990) also plots in this location.

9.3.4. Coastal lagoons

So far as coastal lagoons are concerned, no scheme similar to the above ternary diagrams for deltas or estuaries has yet been formulated. This may be a result of the numerous modes of formation and various environmental settings of lagoons (Lankford, 1977) and the frequent difficulty in distinguishing them from estuaries (Barnes, 1980). In general lagoons experience less river influence than estuaries and tidal currents commonly dominate the flux of water and sediment (Thorbjarnarson *et al.*, 1985).

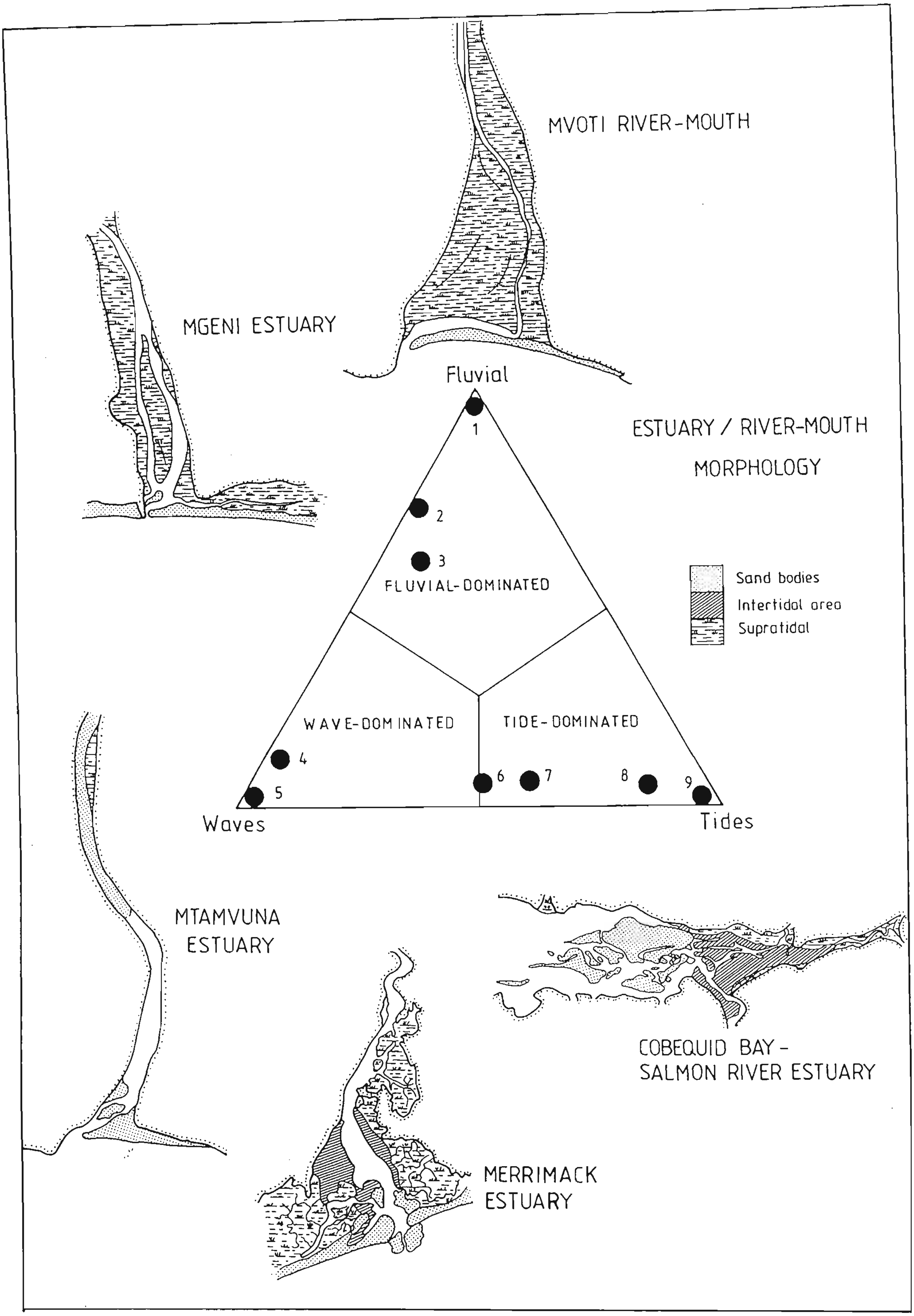


Fig.9.10. Characterisation of estuaries and river mouths (non-progradational features) according to the relative importance of wave, tides and fluvial processes. Note that Natal river-mouths and delta-top estuaries plot at the fluvially dominated end. Marine influence is reduced there or excluded totally. 1, Mvoti river-mouth; 2, Chilean estuarine deltas; 3, Orange Estuary; 4, Mgeni estuary; 5, Mtamvuna estuary; 6, Merrimack estuary; 7, Hayes (1975) mesotidal estuary model; 8, Gironde estuary; 9, Cobequid Bay.

Because of the fine division between estuaries and coastal lagoons noted both in Natal and New South Wales (Roy,1984), it is here considered reasonable to propose such a ternary scheme, at a rudimentary level. Lagoonal morphology is undoubtedly more complicated because of the numerous ways in which lagoons form and so the diagram presented may apply to those lagoons associated with rivers.

On such a ternary coastal lagoon diagram (Fig 9.11), Natal lagoons would plot near the river-dominated end, because of their typical lack of outlets and consequent reduction in tidal influence. Wave action is minimised by the small surface areas and is rarely a major sedimentary process. In keeping with commonly held views, lagoons experience little fluvial influence in relation to estuaries, but in comparison to other *lagoons*, river influences dominate in Natal examples. They are characterised by sand and muddy sand deposits behind a barrier of clean marine sand. Limited overwash introduces marine sand to the back-barrier. Those which contain fresh water plot right at the apex (Fig 9.11), as would the freshwater coastal ponds of New South Wales (Roy, 1984). Lagoons which are brackish through increased overwash or ephemeral inlets plot below this on the river-wave continuum.

Wave-dominated lagoons can be viewed as those with minor fluvial discharge and limited tidal influence. In these lagoons, deep areas below wave-base are sites of slow accumulation through suspension-settling of fines. Organic material may contribute significantly to deposits below wave base. Shallow marginal areas are dominated by wave action and wave-formed oscillation ripples dominate sedimentary structures. Lake Sibaya and the upper reaches of the Kosi Bay system (Orme, 1973; Cooper *et al.*, 1989) in Zululand would plot in this location. They receive little fluvial input from small streams and are separated from tidal influences. However, their large surface areas permit formation of wind-formed waves which produce water currents and short-period surface waves.

In this conceptual scheme, tide-dominated lagoons would include the large lagoons of the eastern seaboard of the U.S.A. such as Great Sound in New Jersey (Thorbjarnarson *et al.*, 1985) which receives fine-grained sediment influx from the ocean and within which wave action is limited by a short fetch. Sedimentary facies are dominated by bioturbated mud and silt. The Wadenzee Lagoons of western mainland Europe which have similarly bioturbated facies (Reineck & Singh, 1973) also fall in this category. Although the tidal forces in such lagoons do not compare with those in tide-dominated estuaries, they are large in terms of lagoon hydrodynamics and also in relation to the other sedimentary processes operative.

The variations in relative importance of these three sediment transporting mechanisms have been linked to facies development in other publications, although not in a formal scheme. For example, Thorbjarnarson *et al.* (1985) noted that sedimentary characteristics of specific lagoons are controlled by "local factors such as tides, rivers and waves". They noted that while the subtidal regions of most lagoons are bioturbated and muddy (Shepard & Moore, 1955), those with a strong fluvial influence (Howard & Frey, 1973) may be coarser-grained with muddy sand. They also pointed to the association of sandy facies with tidal currents (tide-dominated areas) and washover (wave-dominated areas). Oertel *et al.*, (1989) also referred to particular Virginia coastal lagoons as wave-dominated (Black Bay) and tide-dominated (Metokim Bay).

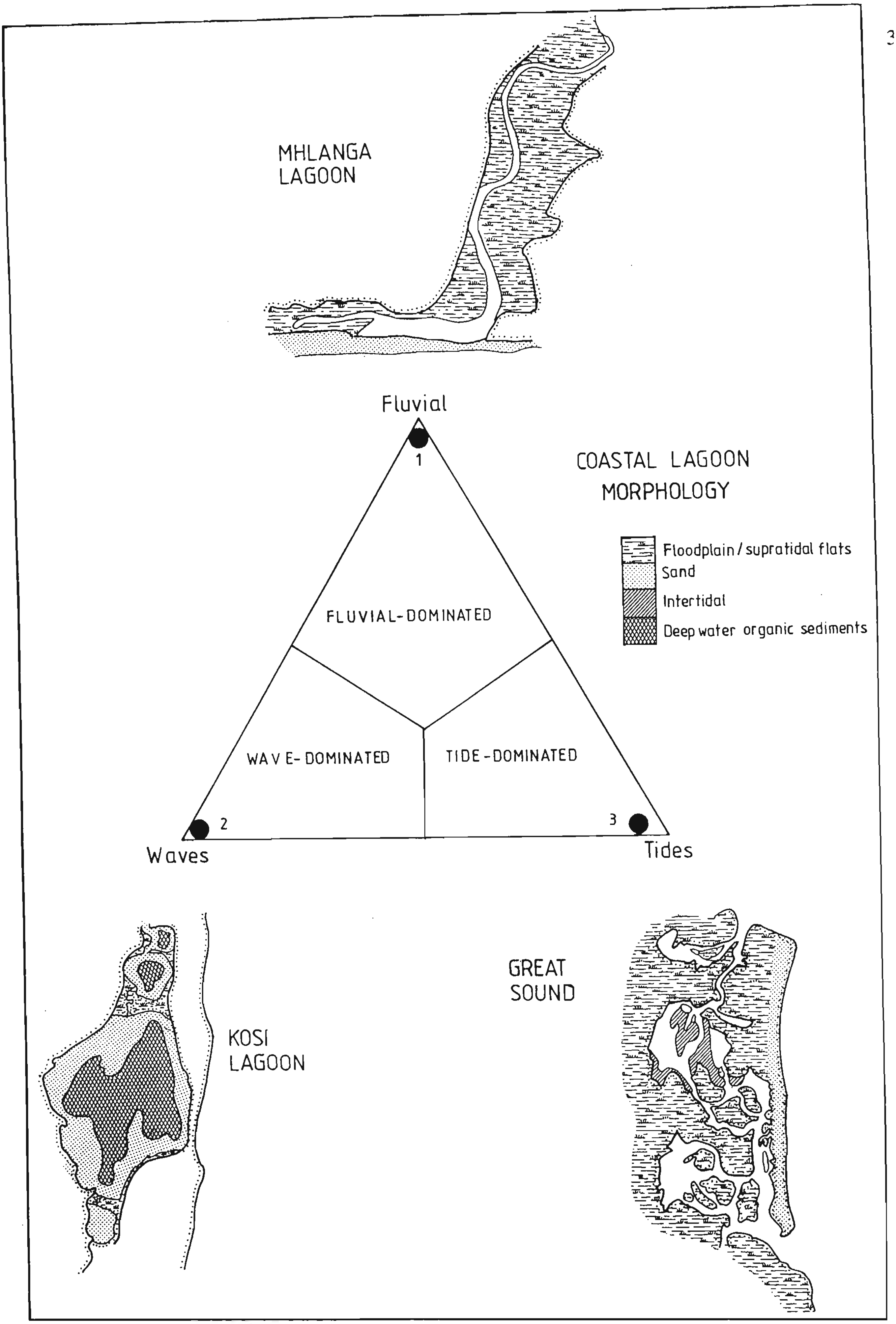


Fig.9.11. Coastal lagoons viewed as a result of the interaction of tides, waves and fluvial influences. Overall the influence of fluvial processes is reduced in relation to estuaries and river-mouths. 1- Natal-type lagoons, are fluvially dominated and contain a distinctive facies architecture. Periodic breaching reduces infaunal habitation. 2- wave dominated lagoons eg Kosi Lagoon have sandy margins dominated by wave-formed structures. Deep sections may be sites of organic accumulation. 3- tide-dominated lagoons eg Great Sound, experience regular tidal rise and fall.

The ternary diagram scheme proposed for lagoonal sedimentary models does appear to be broadly applicable at this stage, but further scrutiny and more rigourous testing may require future modification.

Duffy *et al.* (1989) described small barrier-lagoons from Maine, which although not sited in incised drowned river valleys, were similar in morphology to those of Natal. Most Maine lagoons (111 examples) are confined behind a transgressive pocket barrier. Sedimentary processes are dominated by wave action and organic deposition, which may necessitate the addition of an organic axis in the lagoon diagram or formation of a different class of organic lagoons. It may be feasible to create a further triangle in which fluvial influence is non-existent and is replaced by an organic-dominated apex.

9.3.5. Discussion

In the above schemes it has been possible to view each of three problematic transitional fluvio-marine environments in a similar way, by comparing the relative importance of three sediment transporting processes which produce distinctive sedimentary models. When sufficient case studies have been documented this may enable collation of a comprehensive suite of sedimentary models for all transitional fluvio-marine environments. Having assigned each river-mouth type to a position in one of three ternary diagrams it is desirable to determine the relationship of each ternary diagram to each other in terms of a linking axis. This would enable the initial assignment of a particular environment to one of the three diagrams, after which its precise location could be assessed.

In differentiating deltas, estuaries and coastal lagoons geomorphologically, the single most important factor is the relative importance of fluvial processes. While fluvial processes have already been addressed in all three schemes relative to wave and tidal energy, the relative importance of fluvial inputs also appears to differentiate the three transitional types. Deltas are, by their very nature, fluvial landforms modified by marine processes and so have the greatest fluvial influence. Estuarine sedimentation is mediated by mixing of marine and fluvial processes to varying degrees. In all estuaries fluvial inputs are inherent in the definition but these are reduced in importance relative to deltas. In lagoons fluvial inputs are much reduced and are not necessarily even a component of lagoonal sedimentation, although most lagoons receive even minor streams. They may be replaced by diffuse runoff and groundwater flux as in the small Laguna Joyuda of Puerto Rico (Kjerfve, 1986).

Consequently, in this conceptual scheme of transitional fluvio-marine environments a host of sedimentary models can potentially exist (Fig 9.12). Clearly there are large gaps in current knowledge stemming from inadequate site descriptions and sedimentary investigations but by establishing a suite of preliminary models and linking them in this type of scheme, a framework for further investigation is provided. It highlights gaps in knowledge and helps place existing accounts in perspective. Even if it requires significant subsequent modification, at least the basis has been laid for an all-embracing suite of sedimentary models for transitional fluvio-marine environments. A similar approach to transitional coastal landforms was proposed in personal discussions by Brian Zaitlin (oral communication, July 1990) and the above classification, although developed independently, may well have been influenced subconsciously by

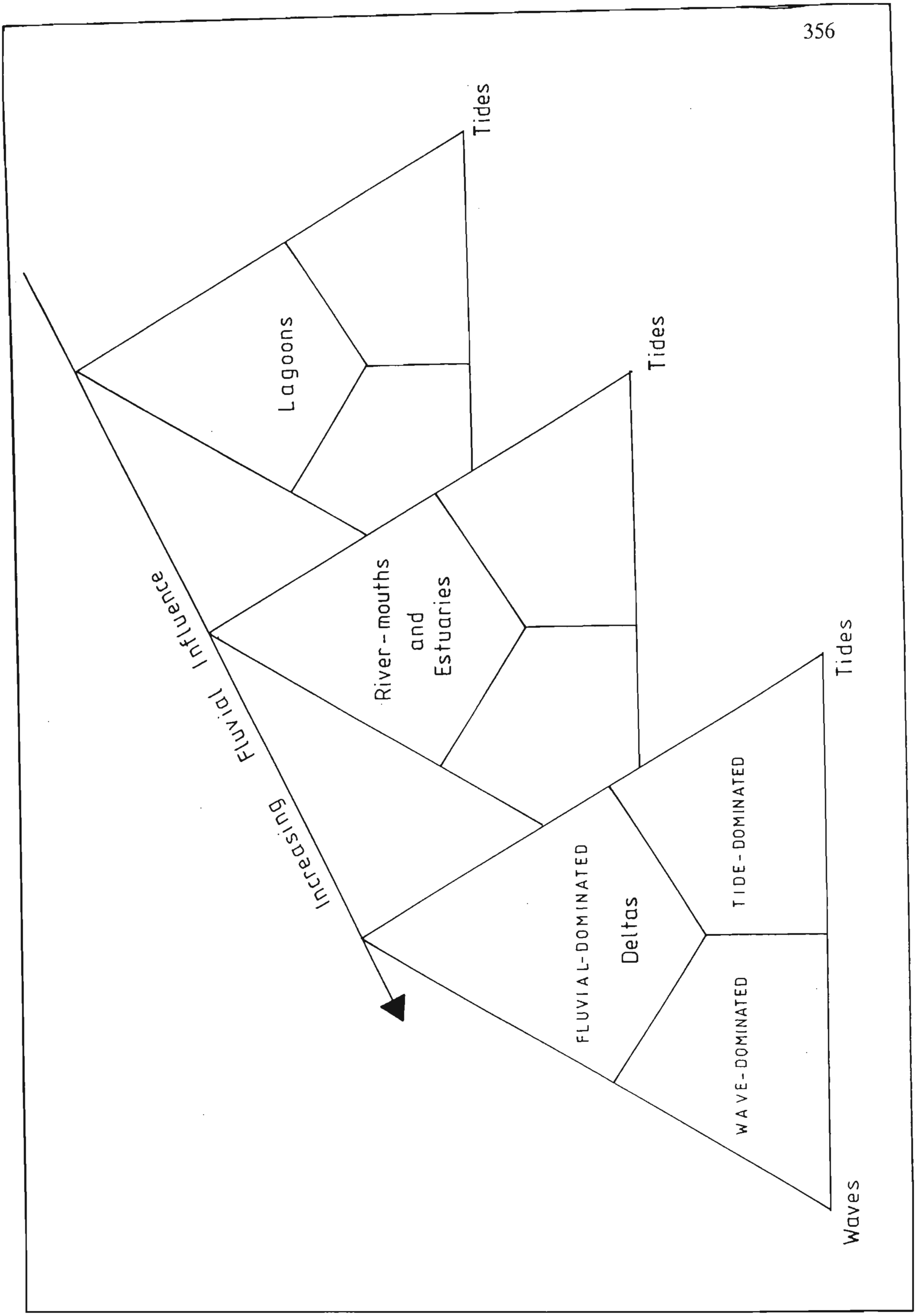


Fig.9.12. Conceptual diagram linking deltas, estuaries and lagoons into a common scheme for transitional coastal fluvio-marine landforms. The linking axis is fluvial influence which decreases from deltas through estuaries to coastal lagoons. Extension of the axis to zero fluvial influence and its replacement with organic influence could potentially incorporate more coastal environments. Such a scheme serves to illustrate the range of sedimentary models required for a comprehensive suite of stratigraphically applicable models. It serves to highlight gaps in knowledge and casts light on the relative importance of traditionally enigmatic coastal environments such as non-tidal river mouths.

those discussions. However, the model envisaged by Zaitlin and co-workers was subsequently presented by Boyd *et al.*, (1990) who proposed time or transgression/regression as the fourth axis linking all environments. In the classification proposed above it is fluvial sediment supply which dominates. This type of classification which may imply an evolutionary change from one triangle to another, does not necessarily do so because other variables such as relative sea-level rise compared to rate of sediment supply also play a role. An estuary need not necessarily become a delta with time, nor are deltas necessarily transformed to estuaries during transgression as the classification of Boyd *et al.* (1990) implies. Sediment supply and palaeotopography were, however, recognised by Boyd *et al.* (1990) as locally important variables which needed to be incorporated into an all-inclusive model of coastal variability.

9.4. RIVER-MOUTH EVOLUTION

9.4.1. Introduction

The evolution of river-mouth environments may be divided into two inter-related parts, valley fill and barrier. Although they are interlinked and affect each other, they are subject to different combinations of processes during their evolution and are commonly treated separately. While it was not a major aspect of this research, each aspect is discussed below in relation to Natal river-mouths.

9.4.2.Valley-fill stratigraphic sequences

The maximum depth of a bedrock valley at the present coast, in relation to Holocene sea-level rise, determines the length of time during which present river-mouths have existed and have been infilling. Clearly those with shallower bedrock valleys (generally the smaller catchment rivers) have existed for shorter periods than the deep-valleys of the large-catchment rivers. Subsequent variation in the nature and rate of sediment supply in relation to sea-level, controls the nature of the valley fill.

Stratigraphy of estuarine valley fills has not been investigated systematically in Natal and data of variable (generally poor) quality are available for only a limited number of river-mouths. Core logs from foundation investigations are generally poor for environmental interpretation, but using such information, coupled with a personal examination of a set of cores from the Mgeni Estuary, Orme (1974; 1975) constructed cross-sections of several Natal estuary fills. In this section some of the more complete of these cross-sections, combined with additional data, are used to illustrate variation in the nature of valley fill stratigraphic sequences. Although the data base is limited, some interesting patterns emerge whose significance is discussed subsequently.

9.4.3. Mdloti lagoon

A comprehensive cross-section of the Mdloti bedrock valley fill 1200 m from the coast (Fig 9.13A) was presented by Grobbler (1987). This reveals a 40 m-deep bedrock valley whose cross-sectional area expands rapidly above a rock terrace in the mid-valley. The stratigraphic sequence passes upwards from a 1-2 m thick conglomeratic channel base into 20 m of sandy sediment. This is overlain by up to 15 m of muds and is capped with 5 m of fluvial sands flanked by muddy floodplain sands. A section 1000 m from the coast (Orme 1974) reveals the same general sequence. Here, 9 m of fine sands are overlain by a

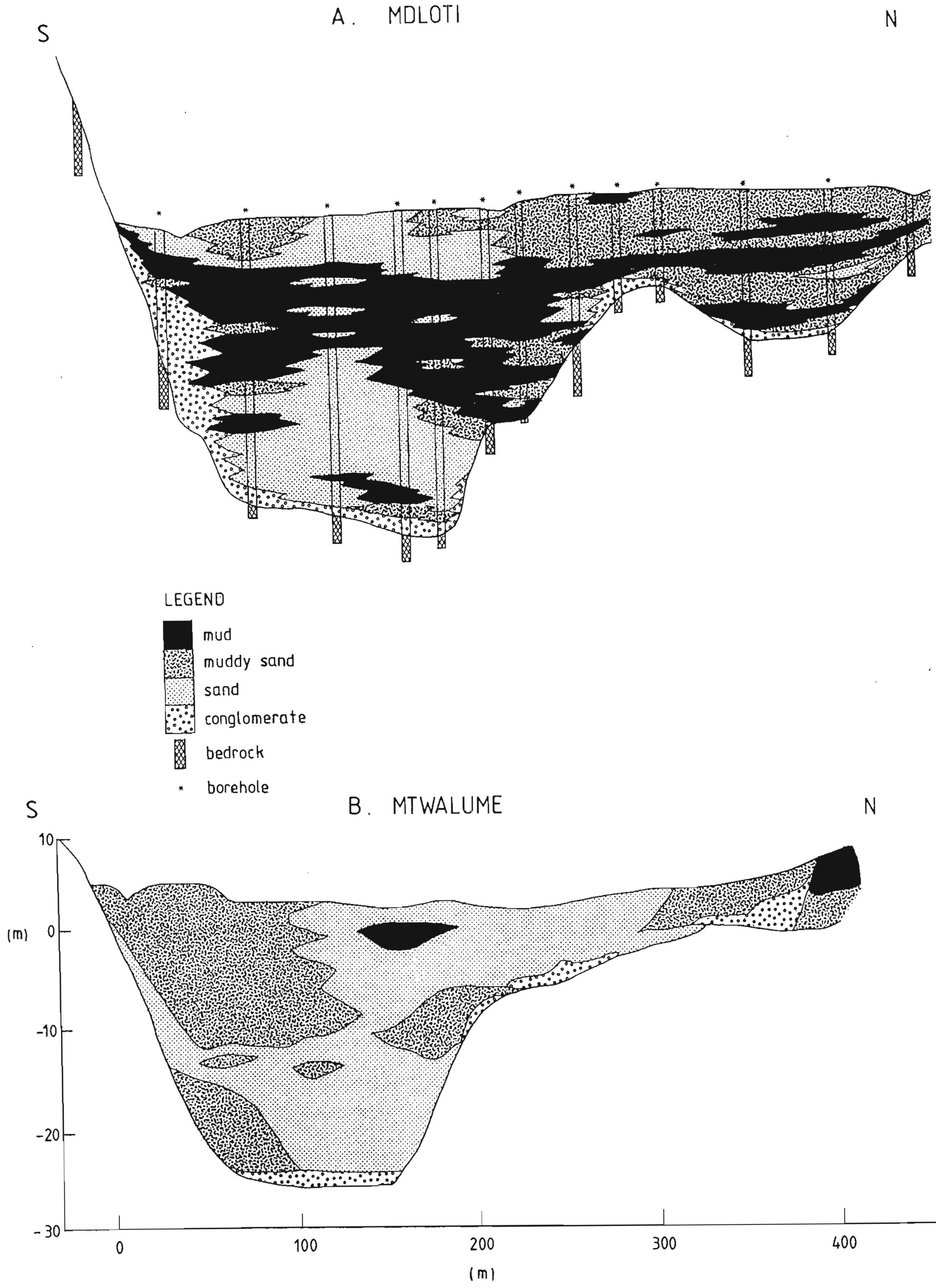


Fig.9.13. Cross-sectional diagram of the valley fill of A.Mdloti Lagoon (after Grobbler, 1987) and B. Mtwalume Lagoon (redrawn after Orme 1974). Both drawn to same scale.

widespread 2 m-thick muddy horizon. This is followed by up to 18 m of very fine sand with mud lenses, interpreted as lagoonal deposits, which are capped with a 4 m thick layer of coarse-grained fluvial sand.

Both cross-sections suggest that a period existed in the Mdloti when increase in basin volume exceeded fluvial sediment supply and so the water deepened, promoting suspension settling in quiet lagoonal conditions. The rapid increase in volumetric increase probably coincided with or slightly post-dated the period when sea-level rose above the level of the pronounced terrace in the bedrock channel at -20 m and persisted up to about present sea-level. Reference to the Holocene sea-level curves presented in Chapter 1 shows sea-level reached -20 m between 7500 and 8000 BP and its present level about 5700 BP. The intervening period (approximately 2000 years) probably represents the timespan of lagoonal conditions in the Mdloti. The presence of fine-grained lagoonal sediment indicates that wave action was attenuated and that a barrier was present across the mouth of the Mdloti when sea-level was at -20 m.

The sandy sediments in the lower section of the valley fill suggest excess sediment supply and with consequently shallow water. Under such conditions muddy sediments would only reside temporarily in the channel before being flushed during increased river flows. In the upper part of the sequence, which formed during the past 5700 years sea-level fluctuated a little about its present level and sedimentation from the catchment was able to fill the vacant volume of the basin by estuary head delta progradation. Since then periodic floods have removed fine-grained sediment from the channels and have only enabled its storage on the distal parts of the floodplain. Sediment accumulates only temporarily in interflood periods and the river-mouth is subject to cyclic changes in morphology, regulated by floods.

9.4.4. Mtwalume lagoon

The valley fill of the Mtwalume (Fig 9.13B, redrawn after Orme, 1974) shows a different sequence to the Mdloti. The bedrock valley extends to 27 m below sea level and contains a terrace flanking the main bedrock channel. It is similar to that of the Mdloti both in size and shape. The valley fill, 1000 m from the ocean, comprises a basal lag conglomerate overlain by a sequence of fluvial sands and silty sands with little evidence of quiet lagoonal conditions (Orme, 1974). A single muddy lens in the sequence probably represents a backwater of localised scour depression. Floodplain deposits of silty sand are widespread in the upper parts of the valley fill.

In comparison to the Mdloti, the Mtwalume did not pass through a quiet lagoonal phase. This implies that the rate of sediment supply was always adequate to keep pace with the rate of volumetric valley increase in relation to the depth of scour of floods. Under these conditions fine-grained sediments did not accumulate and so the fill is predominantly sandy. The catchment area of the Mtwalume is 553 km^2, compared to the 474 km^2 catchment of the Mdloti. Sediment supply from the slightly larger catchment must have been adequate to maintain equilibrium throughout the Holocene.

9.4.5. Mvutshini and Mhlangeni lagoons

In smaller-catchment lagoons only a few stratigraphic cross-sections are available and in many cases these are restricted to only a small part of the floodplain. Orme (1974), however, illustrated complete cross-sections, spanning the full bedrock valley, from both the Mvutshini (Little Bilanhlolo in Orme, 1974), and Mhlangeni Lagoons (Fig 9.14 A, B, C). These rivers have catchments of 7 and 38 km^2 and bedrock valleys which attain maximum depths of -12 and -19 m, respectively. By reference to sea-level curves in Chapter 1, the Holocene sea reached the Mvutshini about 7100 BP and the Mhlangeni about 7800 BP. In both instances the valley fills are dominated by sand and silty sand with occasional lenses of pebbles and boulders of surrounding country rock (Orme, 1974). The silty sand may be a result of bioturbation, causing the downward mixing of muddy sediments deposited on the lagoon floor during low flows or closed barrier phases. A thin clay layer at the base of the Mhlangeni channel is probably weathered bedrock. The two Mvutshini cross-sections were located on the rear of the barrier and about 50 m upstream and show the thinning of the barrier sand into the lagoon. They also depict its transgressive nature over the silty sands of the lagoon.

The sandy nature of both these valley fills indicates that sediment supply matched the increase in basin volume, removing fine-grained sediment during floods or periodic barrier breaching. Neither lagoon experienced a period when deep water conditions prevailed.

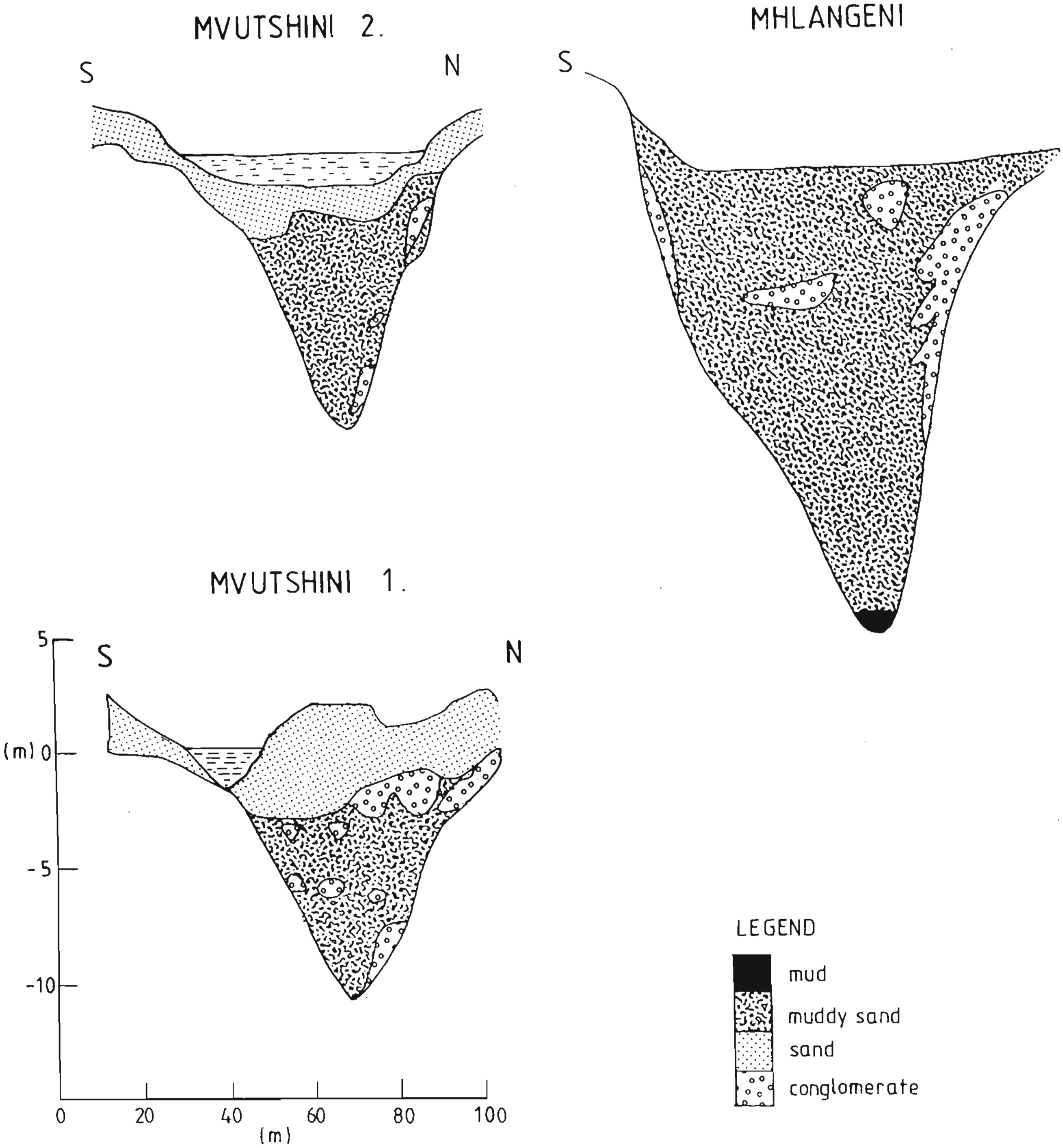
9.4.6. uMgababa and Msimbazi lagoons

Partial cross-sections and isolated borehole cores exist for two wide-valley lagoons, the uMgababa (Orme, 1974; Grobbler *et al.*, 1987) and Msimbazi (Orme, 1974). In both cases the incomplete cross-sections across the bedrock valleys urge caution in precise interpretation. The Msimbazi section covers only 90 m of the 450 m-wide floodplain and the uMgababa only 90 out of 400 m. Consequently they give only a limited impression of the nature of the valley fill. Both valleys are incised to between 12 and 20 m below sea-level and the cross-sectional diagrams indicate they are filled with a mixture of silty sands, fine- to medium-grained sands, silt and mud (Orme, 1974). Recent additional borehole data (Grobbler *et al.*, 1987) shows the uMgababa valley fill to comprise mainly silt and mud with thin (2-3 m) sand lenses. The silts and muds were interpreted as shallow lagoonal and floodplain deposits. The generally finer-grained deposits in these lagoons, is a reflection of their large volume compared to small catchment areas (37 and 35 km^2).

Holocene rise in sea-level caused the drowning of progressively larger volume of the bedrock valley. Sediment yield from the small, mud-dominated catchments was insufficient to fill the increasing valley volume and consequently deep water lagoonal conditions developed, in which suspension settling dominated sedimentation. Late Holocene relative fall in sea-level caused incision of these deposits from which brackish-water lagoonal mollusc shells have been recovered (Grobbler *et al.*, 1987).

9.4.7. Mgeni estuary

The Mgeni Estuary, which has a bedrock channel at least 55 m below sea-level (Maud, 1968), began to be infilled approximately 10 000 years BP by comparison with Holocene sea-level curves. Despite the construction of several bridges across the Mgeni and widespread human development around it, the nature of the valley fill has not been investigated as a whole. Francis (1983) studied the geotechnical properties of the valley fill in the Springfield Flats area, upstream of the present estuary. Kantey & Templar (1964)



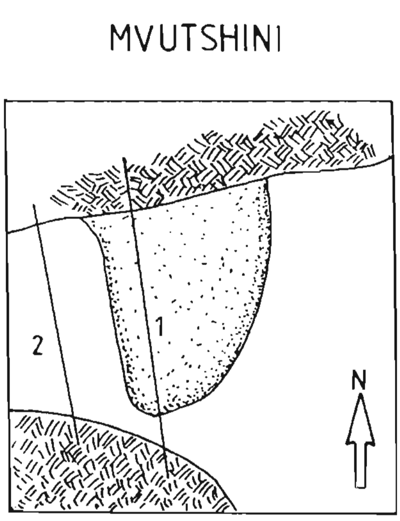


Fig.9.14. Cross-sections of Mvutshini (A, B) and Mhlangeni (C) Lagoons. Note the dominance of muddy sands in the sedimentary fill with isolated lenses of gravel and boulders. No trace of deep water lagoonal environment is preserved, which suggests that in both lagoons sedimentation matched increase in basin volume during transgression. Periodic breaching removes accumulated muddy sediment from the back-barrier. The Mvutshini cross-sections depict the clean sands of the transgressive barrier overlying muddy sands of the back-barrier. The barrier sands thin landward from section 1 to 2.

and Orme (1974) presented cross-sectional interpretations of the valley fill at the Athlone Bridge. Additional borehole data from the coast-parallel Mgeni alluvial plain has been produced from foundation investigations for buildings in Durban (King, 1962; King & Maud, 1964).

In the lower Mgeni valley, Francis (1983, p 19) noted the presence of lenses of dark grey to black silty clay in estuarine fill. In foundation investigations between the Umhlangane confluence and the Connaught Bridge upstream of the modern estuary, an extensive black silty clay occurs between -25 and +1 m MSL. This overlies medium and coarse sand between -25 and -37 m which in turn overlie a basal layer of up to 7 m of cobbles and boulders.

At the Springfield Services Bridge (Fig 9.15A), the stratigraphy comprises a lower cobble and boulder layer, overlain by 4 m of sands which is succeeded by a laterally continuous clay averaging 15 m thick. This is succeeded by mainly sands with a prominent clay lens up to 7 m thick and 300 m wide near the top of the succession.

At Connaught Bridge (Fig 9.15B) the stratigraphic sequence comprises, from the base upward, a 2-3 m basal conglomerate, 20 m of fluvial sands, a distinctive clay layer 12 m thick between -4 and -22 m MSL, and 9 m of fluvial sands. Krige (1932) noted that twenty species of marine bivalves and gastropods were retrieved from boreholes in the Mgeni from between 30 and 60 ft (10 to 20 m) below sea-level, which corresponds with this clay layer. Although he did not list them in his paper, Krige (1932) observed that all were extant species.

The downstream thickening and increase in depth to the base of the clay indicates it was deposited during a rapid increase in valley volume during which sediment supply from the catchment could not keep pace. The fact that the muddy clay exceeds sea-level in places suggests that lagoonal conditions may have persisted beyond 5700 years when sea-level reached its present level. Only during the Late Holocene has incision and continuing fluvial sediment supply enabled the infilling of the valley. Despite the fact that the Mgeni has a large catchment and correspondingly large sediment yield, its large bedrock valley, particularly in the Springfield Flats basin (Fig 9.16), offered a large sediment storage capacity during the Holocene. The bedrock valley volume was reduced at the valley constriction upstream of Connaught Bridge (Fig 9.16). When sea-level rose and began to expand into the valley the rapid increase in basin volume resulted in deep water lagoonal conditions, even within the constricted Mgeni valley. The presence of unidentified shells within the clays between 16 and 20 m depth (Francis, 1983) lend weight to a lagoonal rather than floodplain interpretation of the depositional environment. The fact that lagoonal muds are preserved at depths of 9 m at Connaught Bridge sets a maximum limit for historical flood scour.

King (1962) examined several boreholes in alluvium from the Durban area as did King & Maud (1964). A widespread clay termed the "Black Mud Stratum" (King & Maud, 1964) is present beneath the alluvial plain, overlying Cretaceous bedrock (Maud, 1978) but does not extend to the modern Mgeni Estuary (Fig.9.16). It varies in thickness from 5 to 30 feet (1.5 to 9 m) and is persistently encountered between 80 and 110 feet (26 to 36 m) below sea-level. Radiocarbon dating of peat samples from this horizon of 24

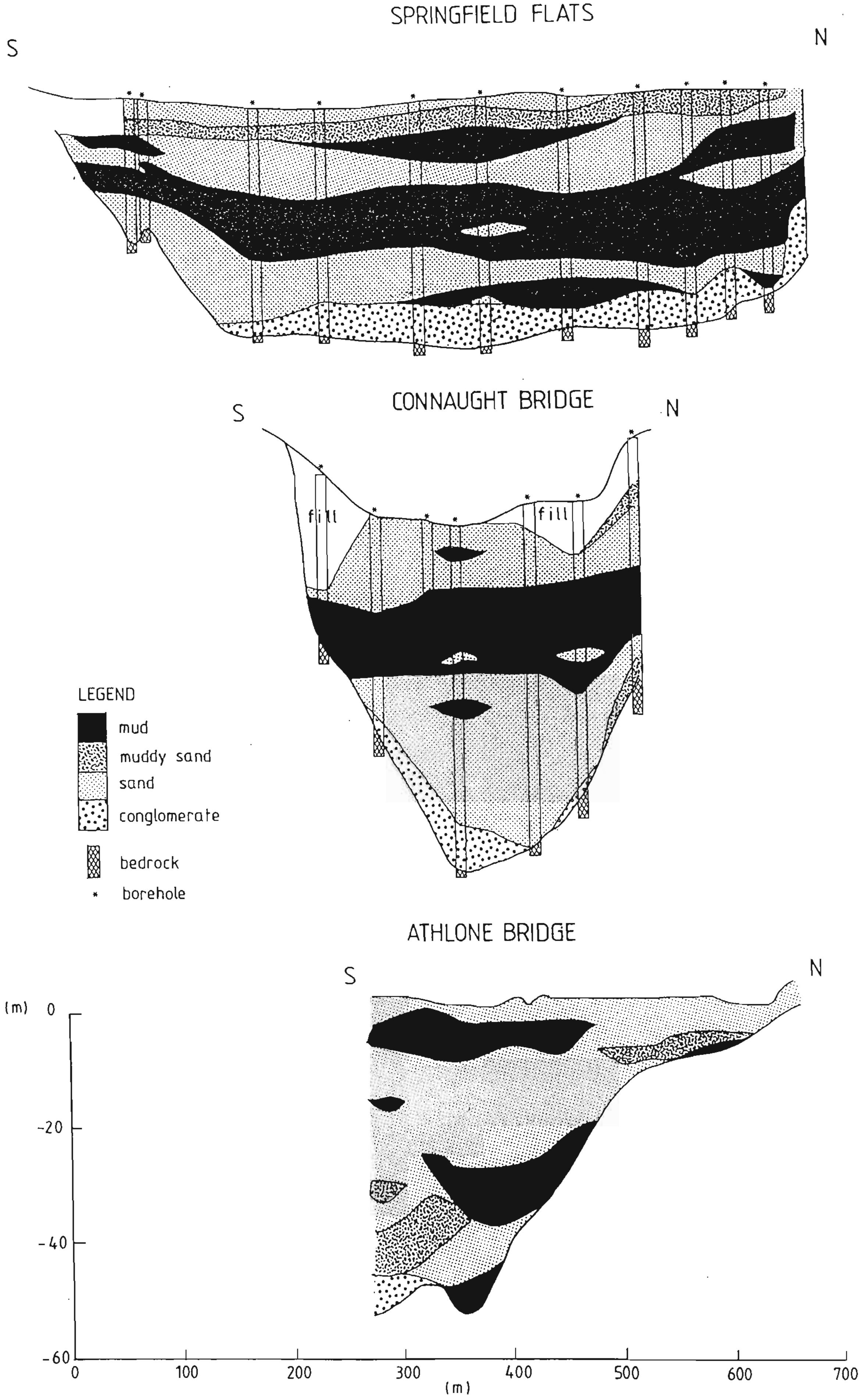


Fig.9.15. Cross-sections of the Mgeni channel at A. Springfield Flats (after Francis, 1984) B. Connaught Bridge (after Francis, 1984) and C. Athlone Bridge (After Kantey & Templar, 1964 and Orme 1974). For locations see Figure 9.16. All three sections depict a lower sandy section, a pronounced muddy horizon and an upper sandy layer. The muddy lagoonal horizon is least preserved at the lowermost section at Athlone Bridge.

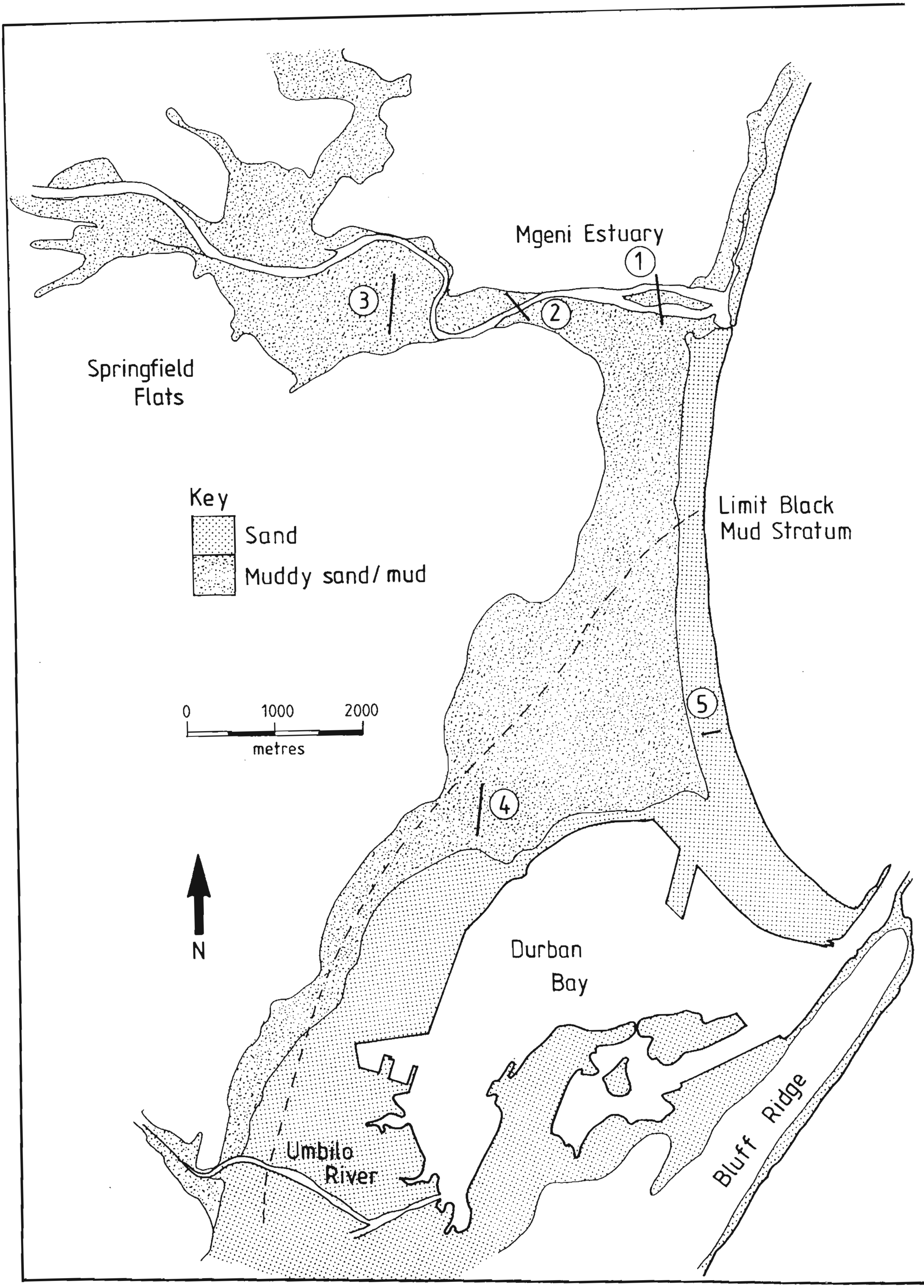


Fig.9.16. Map of the Durban area, showing locations of sections in Figure 9.15 and 9.17. in relation to Mgeni River. The area under Durban represents the former alluvial plain of the Mgeni, from which it was isolated probably during the Late Holocene incision. Periodic floods in the last century flowed across the alluvial plain before the estuary mouth was stabilised in its present position.

950 +/- 950 years (sample GaK 1390; Maud, 1968) and 48 000 BP (no sample number; Maud, personal communication, 1989) suggest that it is of late Pleistocene Age. It may be a correlative of the Port Durnford Formation of Zululand (Hobday & Orme, 1974).

Over much of the the alluvial plain the Black Mud Stratum is overlain by fluvial sands, some of which are coarse-grained and similar to modern feldspathic Mgeni river gravels (King, 1962). A pronounced black clay layer containing lagoonal molluscs is present between 35 and 45 feet (10 to 13 m; King & Maud, 1964). A series of boreholes in the Botha Gardens area (Francis, personal communication, 1989) shows the Black Mud Stratum overlain by fine unfossiliferous sand with lenses of gravel (Fig 9.17A). These are Holocene fluvial sands derived from the Mgeni and deposited in a back-barrier environment. Borehole logs reveal the local presence of abundant shells in sandy clay lenses which further suggest a back-barrier depositional environment. The sequence is capped by a peaty clay, probably representing a swamp environment atop an alluvial plain.

At the modern coast the Black Mud Stratum is overlain by marine sands containing shell fragments of probable beach and dune origin (King & Maud 1964. Francis (personal communication, 1988) provided an engineers cross-section of the area under Marine Parade (Coconut Grove) 200 m from the present coast (Fig 9.17B) which offers a limited view of the coast-normal estuary fill. In it the Pleistocene Black Mud Stratum overlies Cretaceous bedrock at -31 m MSL. An erosion surface (probably marine) is cut across the Black Mud Stratum at about -16 m MSL and is overlain by 15 m of fine to medium-grained sands of probable marine origin (Francis, personal communication, 1988). The sequence is capped with fine-grained aeolian dune sand between present sea-level and + 9 m MSL.

The valley fill of the Mgeni therefore points to at least one major lagoonal phase in the mid-Holocene in both the main channel and in the coast-parallel area. During this time comparatively deep water prevailed, beyond the scouring effect of contemporary floods. This has been infilled during the Late Holocene by fluvially-derived sands, probably moving downstream as a delta, infilling having been accelerated by Late Holocene incision This was succeeded by peats and clays of a swampy deltaic plain in the coast-parallel section of the former basin, now under the City of Durban. Historical records (Goetzsche, 1966) indicate that at the time of European colonisation in the 1850s, the area which Durban now occupies was a low-lying swamp which was occasionally flooded by the Mgeni. It has since been reclaimed and filled.

It is interesting to note the presence of a pre-Holocene lagoonal deposit at the base of the coast-parallel Holocene fill. This is absent from the main river valley where incision during the last glacial maximum eroded all accumulated Pleistocene sediments. This appears to be the case in most valley fills.

9.4.8. Discussion

The examples of valley fills discussed above reveal a range of stratigraphies which do not appear to vary systematically in relation to the river-mouth classification presented in the previous chapter or sedimentary models presented in this one. By comparing the above fills it is clear that either muddy or sandy sediments

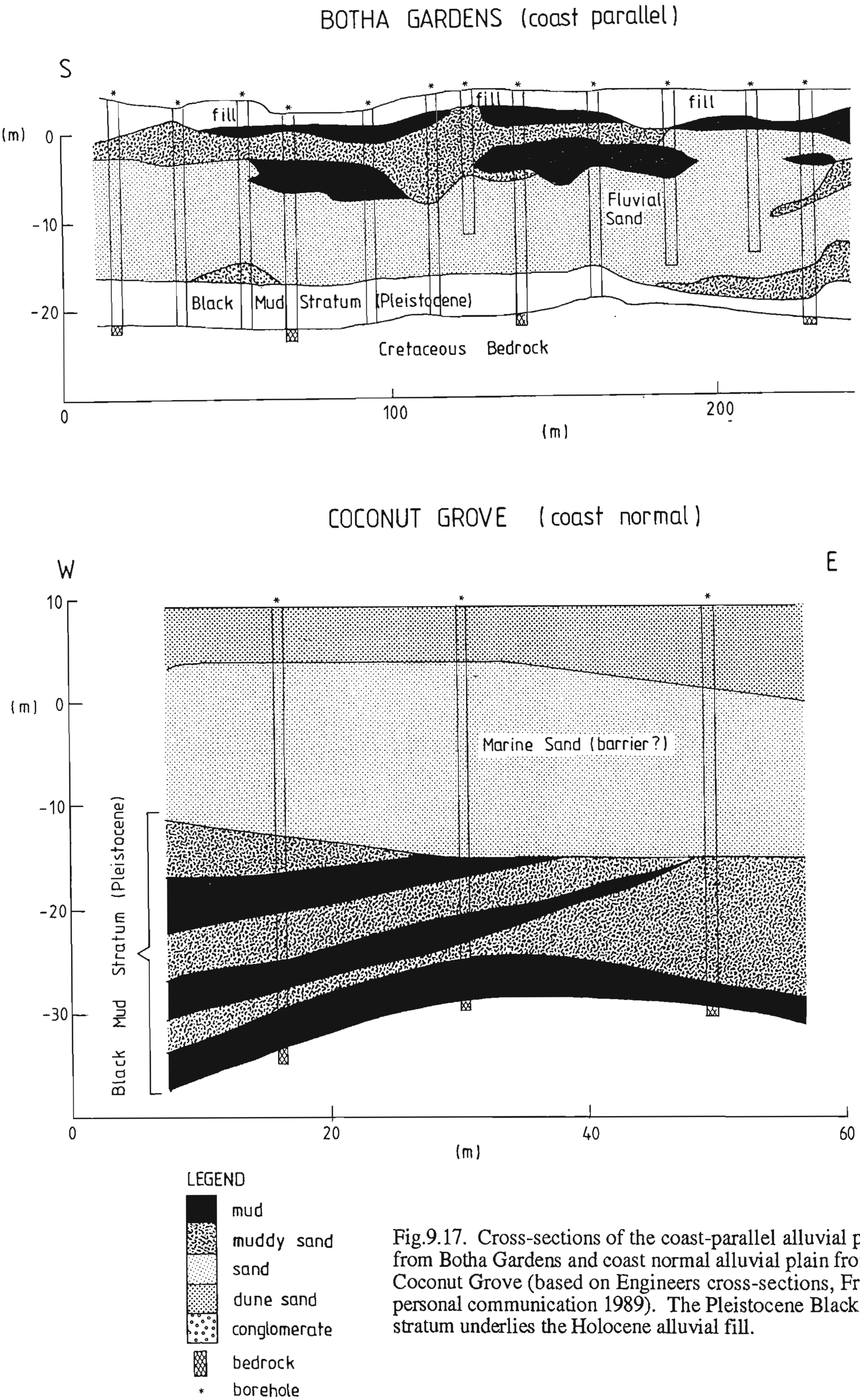


Fig.9.17. Cross-sections of the coast-parallel alluvial plain from Botha Gardens and coast normal alluvial plain from Coconut Grove (based on Engineers cross-sections, Francis, personal communication 1989). The Pleistocene Black Mud stratum underlies the Holocene alluvial fill.

dominate at any particular time. The deposition of muddy sediment requires quiet water conditions and protection from erosion during floods. Such conditions only exist in backwaters and deep water areas below flood level. Sandy sediments are indicative of current action and, as evidenced from modern river-mouths, they are retained preferentially at the expense of mud which accumulates periodically but is removed during increased flow.

Of the modern river-mouths in the study area only the Mtamvuna has widespread muddy bottom sediments which persist after floods. In other rivermouths mud is restricted to backwater and floodplain deposits, none of which are markedly rich in body fossils (mollusc or foraminiferal remains) at present. Clearly therefore, conditions in some rivermouths were different to present and enabled the formation of relatively deep, quiet lagoonal conditions. Under which circumstances this can occur is of importance both in understanding valley fills and Holocene development and in placing the modern river-mouth environments in context.

The preservation of pre-Holocene rivermouth valley fills in Natal only appears to occur in the coast-parallel sections which were not incised during the Last Glacial Maximum. In the study area, pre-Holocene sediments have only been identified below sea-level in the Durban Harbour beds. Northward, pre-Holocene lagoonal sediments are preserved at depth in the extensive lagoon of the Mhlatuze River (Richards Bay; Maud, personal communication, 1989) where incision did not extend across the previously accumulated deposits. Undated deposits from Kosi Bay, known from unpublished seismic profiles and vibracores, are probably also of pre-Holocene age. Above sea-level, pre-Holocene lagoonal deposits are known from the Port Durnford Formation (Hobday & Orme, 1974; Hobday & Jackson, 1979).

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, 1987). Extending this concept to Natal river-mouths, sedimentation and basin shape must strive for equilibrium by attaining a balance with fluvial discharge. Clearly, major flood events exceed equilibrium 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 as external factors come into play, such as vegetation encroachment and bank stabilistation.

In one concept estuaries are ephemeral features which fill and become non-tidal river-mouths, deltas or swamps (Friedman & Sanders, 1978; Schubel & Hirschberg, 1978; 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 equilibrium with sedimentation and sea-level changes and so retain its estuarine characteristics indefinitely. The stratigraphic sequences through some river valley fills suggest this may have been the case in several Natal estuaries. Thus it is wrong to assume that all estuaries are simply ephemeral features, although they may change from what King (1980) succinctly distinguished as, "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 water body at the top of the sequence.

Nichols (1989) presented the view that a large increase in sediment supply can cause an increase in the accumulation surface in lagoons such as those in Zululand (Orme, 1973), and establish a new equilibrium at the fluvial base level. Under such circumstances, the ability of a lagoon to accumulate and store sediments depends on the level of flood scour (Orme, 1974). In terms of Natal river-mouths, 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).

Given the restricted size of Natal river-mouths and the naturally high rates of sediment supply, this situation is unlikely, and the maintenance of 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. This situation is presently restricted, in the study area, to the Mtamvuna Estuary and, elsewhere on the eastern seaboard of south Africa, to a few large lagoons in Zululand. Consequently, measured changes in bed level in recent times in Natal river-mouths must be viewed as morphological responses to short- or medium-term discharge variation. As 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.

A conceptual view of long-term processes in the four main types of river-mouths is depicted in Figure 9.18. This illustrates that in delta-top estuaries and non-tidal river-mouths, equilibrium has been achieved and variation in sediment volume fluctuates with fine-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. A similar situation prevails in barrier lagoons where the impact of floods or breaching is less marked and the volume of scour is reduced, simply eroding accumulated fines. In river-valley estuaries, there is a slow sediment accumulation because of the low sediment input. Instantaneous increases are envisaged to occur after landslides and minor removal of accumulated fines occurs during floods.

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 two end members : a "surplus" lagoon in which accretion exceeds relative sea-level rise and a "deficit" lagoon in which

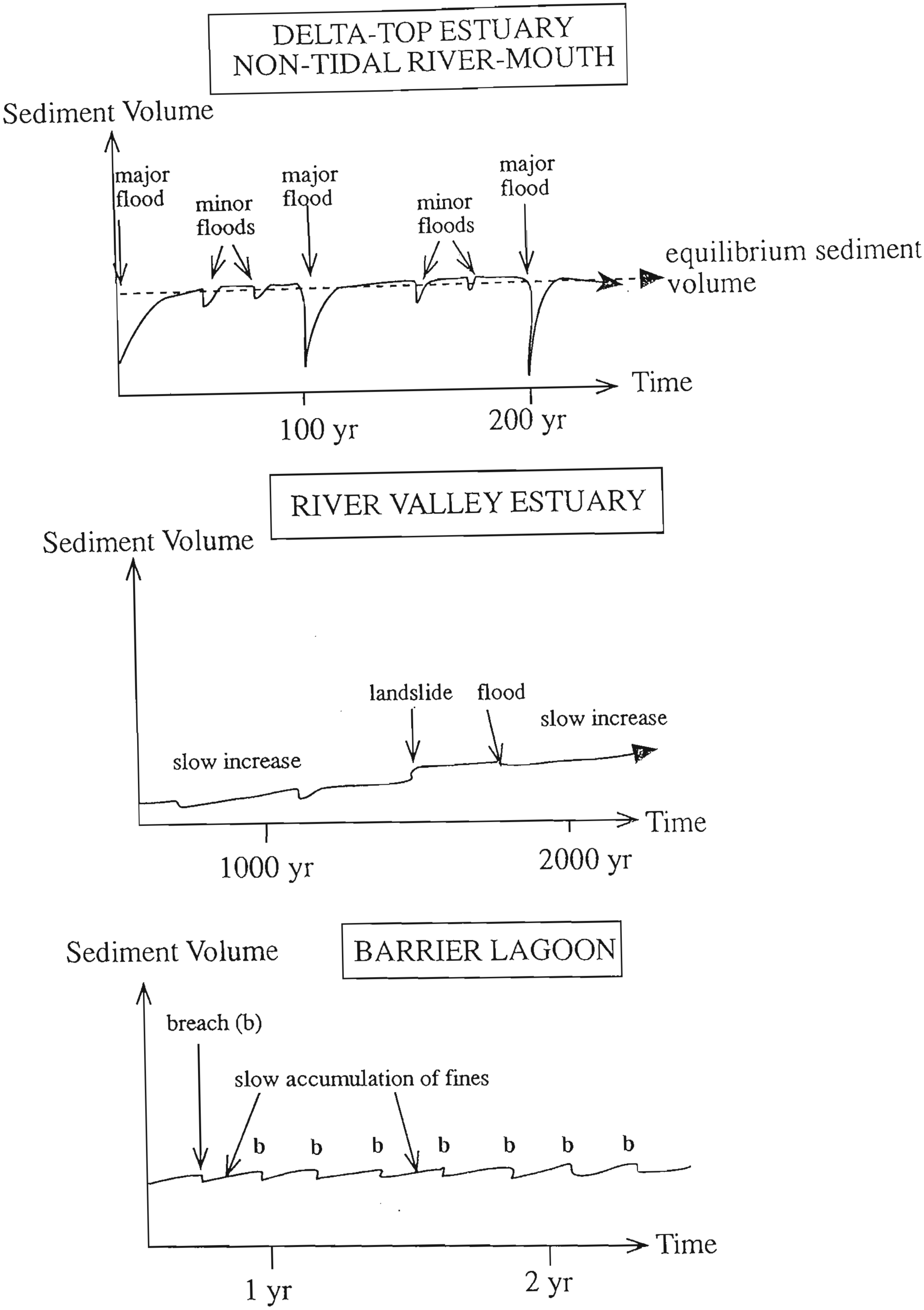


Fig. 9.18. Schematic representation of cyclic sedimentation processes in A. non-tidal river-mouths and delta-top estuaries; B. drowned river-valley estuaries and C. coastal lagoons. Note the variation in time scales depicted. Only the drowned river valley estuary type shows progressive infilling, albeit at low rates.

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 river-mouths of Natal and elsewhere, in an evolutionary context. In Natal there is no evidence of differential rates of Holocene sea-level rise (Chapter 1) and so sediment supply might seem to be the only variable. However, as sea-level rises and drowns a bedrock valley, the rate of increase in bedrock valley volume changes in response to its cross-section (Fig 9.19). Cross-sectional areas of valleys increase upward from their narrow bases, either gradually or suddenly at rates dependant on the surrounding topography. At the same time sediment is being supplied from the catchment at a rate which, averaged over the timespan of most lagoons, can be assumed to be more-or-less constant.

If the rate of increase of basin volume exceeds the cumulative sediment supply rate then a basin will deepen. Otherwise it remains stable and passes excess sediment to the coast. Coastal sediment excess to barrier equilibrium requirements is dispersed and fine-grained (muddy) sediments accumulate offshore (Goodlad, 1986). When sea-level reached its present level about 7000 years BP, the rate of volume increase stopped and sedimentation infilled existing basin volumes and transferred excess sediment to the coast. This concept is illustrated diagramatically in Figure 9.19.

In this conceptual model, cumulative fluvial sediment supply is shown as a dotted line. It has been assumed in the case illustrated that sedimentation rates have not varied over the Hololcene. The total volume of the bedrock valley during the Holocene transgression is plotted as a solid line. Times t_0, t_1 and t_2 correspond to times on the lower diagram. The lower diagram represents a cross-section of a drowned river valley and sea-levels at various times are illustrated as dotted lines. From the time at which the rising sea-level reaches the lowest level in the bedrock valley (t_0) to time t_1 the rate of increase in the basin volume is slow as the apex of the valley is narrow. Sedimentation rates exceed the rate of volume increase and so the valley remains shallow through filling the basin. The seiment will tend to be sandy as under shallow conditions in narrow Natal river-mouths, fine-grained sediment is flushed from the river-mouth during episodic floods or barrier breaching. Excess sediment passess directly into the sea. At sea level SL1, at time t_1, a bench in the bedrock valley is reached and the width of the valley cross-section increases. This causes a marked increase in the rate of volume increase in the valley (a similar effect would be caused by an increase in the rate of sea-level rise) which is reflected in an increase in gradient in the basin volume curve in the upper diagram. At some stage the rate of volume increase exceeds the cumulative sediment supply and deep water conditions develop in the lower reaches of the river valley. Under such conditions, suspension settling dominates sedimentation and flood impacts are minimised in the deeper water, as in the modern Mtamvuna river-mouth. The river-mouth becomes a low energy muddy environment in which infaunal habitation may occur. This situation persists until the total basin volume is again exceeded by the cumulative sediment supply. In Figure 9.19 this situation occurs shortly after sea-level stabilises at time t_2, preventing further increase in basin volume. At this stage sedimentation catches up with basin volume and fills it, passing excess sediment to the sea and preferentially preserving sandy sediment in the sedimentary record. At time t_3, sea level drops by a few metres from a Holocene highstand, effectively reducing the

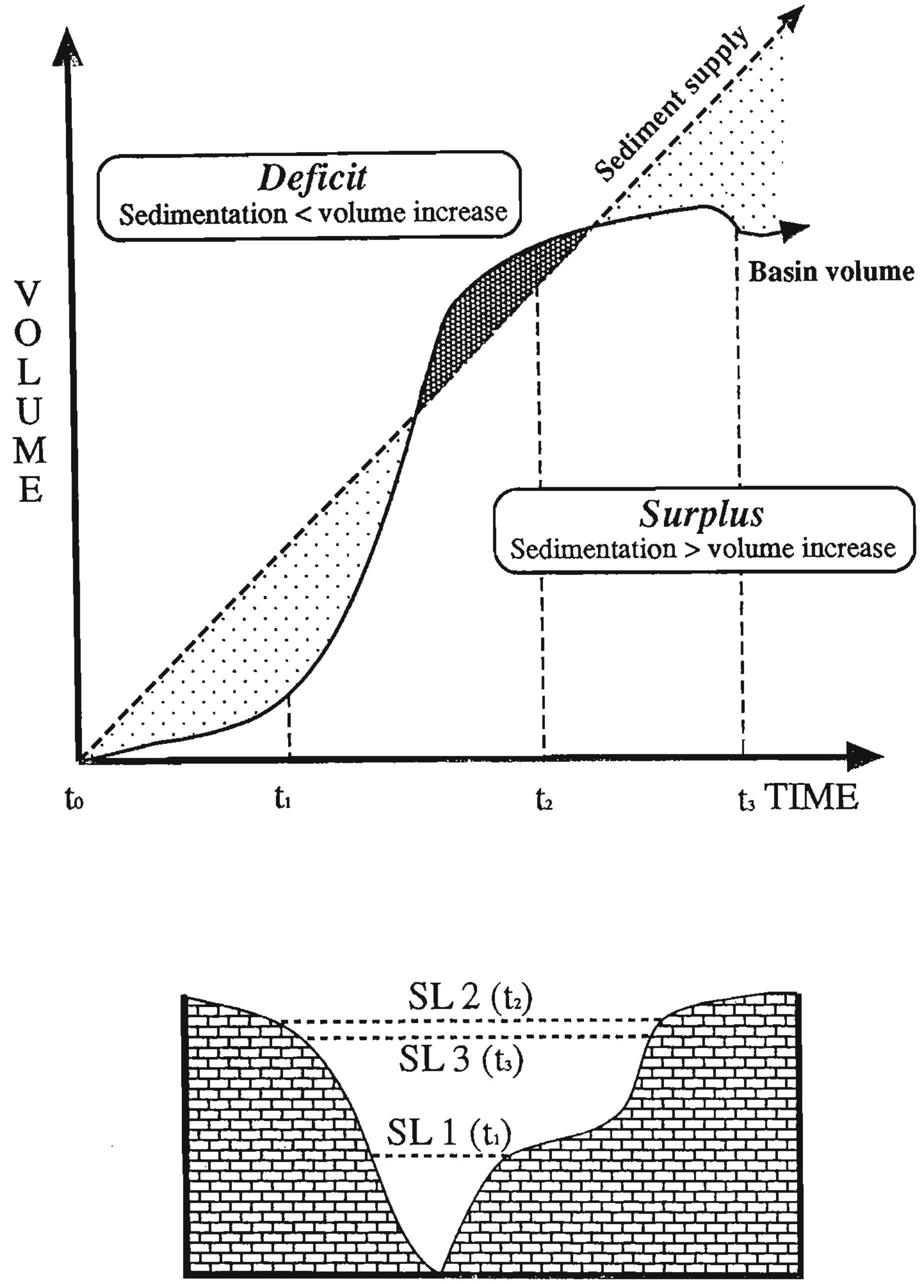


Fig 9.19. Diagram to illustrate the relative importance of sediment supply and basin volume during transgression. If sediment supply is regarded as constant then the cumulative sediment supply plots as a straight line. Bedrock basin volume (including portions which are already infilled) increases according to the rate of sea-level rise and the cross-sectional area of the valley. A marked increase in sea-level rise or in the valley width, causes a dramatic increase in rate of volume change. This leads to a deficit situation in which deep water lagoonal facies could accumulate. Subsequently basin volume decreases and ultimately reduces as sea-level first stabilises and then drops to its present level. With the exception of the Mtamvuna, all Natal river-mouths are in the upper stage in which cumulative sedimentation exceeds basin volume. Some like the Mdloti and Mgeni passed through a lagoonal phase in their evolution while others such as Mtwalume and Mhlangeni did not.

total basin volume and under these conditions the channel is incised into older accumulated sediments and excess sediment is passed directly into the sea, after only a temporary residence period.

Nicholls & Biggs (1985) noted that estuaries on the US southeast coast, which have high sediment supply, were filled to capacity as fast as the advancing sea-level rise drowned their valleys. Thus in Natal, the Mtamvuna cannot be accepted simply as a less-well developed variant of the delta plain estuaries. Firstly, the Mtamvuna may never reach this stage, and secondly some delta plain estuaries may never have undergone a period when sea-level rise outstripped sedimentation to form a deep estuary dominated by suspension settling.

In contrast to elsewhere where preserved estuary sequences rarely result from a single fill event (Clifton, 1982, 1983; Demarest *et al.*, 1981; Nicholls & Biggs, 1985), the confined channels of Natal rivers, coupled with steep river gradients, have resulted in the complete erosion of pre-existing facies from earlier fill cycles, except in the extensive coastal plain areas of Durban Bay and Zululand lagoons, where only a part of the valley was incised.

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 stratigraphic interpretation. The implication, which remains to be rigourously tested by drilling, is that 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.

An additional implication for environmental management is that, with the exception of the Mtamvuna, other river-mouths in the study area have progressed to the latest evolutionary stage illustrated in Figure 9.19. Some did so by delta progradation into a comparatively deep lagoon, while others maintained equilibrium throughout the Holocene. In most cases sea-level stabilisation since about 5700 BP enabled the complete infilling of residual basin volume. The Late Holocene fall in sea-level which caused minor incision of river courses has reduced the effective basin volumes and has had the same effect as an additional 1.5. m of vertical sedimentation (Reddering, 1987).

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 the river-mouths studied, but in the deep offshore areas where mud presently accumulates, seaward of the current-swept continental shelf. Martin (1987) has indeed demonstrated a marked increase in sedimentation rates there, which he attributed to human influences in the hinterland.

Under present conditions, changes in channel and floodplain morphology arise through discharge changes which range in scale from seasonal, to decade-long cycles of drought and non-drought, to daily and fortnightly tidal discharge variation in the larger estuaries. 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.

9.5. BARRIER EVOLUTION

9.5.1. Introduction

Barrier formation was the subject of a prolonged debate in coastal sedimentology (see for example volumes edited by Schwartz, 1973 and Leatherman, 1979). It is now generally accepted that several modes of origin exist (Leatherman, 1979). The mode of barrier formation in Natal appears to have been through landward translation across the shelf during the Holocene Transgression. The mode of translation has not been elucidated but the dominance of rollover over erosional processes (Carter, 1988) in post-flood responses at the mouths of large modern Natal rivers (Cooper, 1991d), coupled with evidence of similar processes in Pleistocene barrier sequences in Zululand (Hobday & Orme 1974; Hobday & Jackson, 1979), suggests that the processes of barrier translation through shoreface erosion and overwash, (Swift, 1975; Hoyt, 1967) may have been dominant. This process would leave little trace of a transgressive barrier on the shelf which through its current-swept nature would destroy any trace of transgressive barrier deposits, unless lithified early as beachrock or aeolianite (Cooper, 1991c).

9.5.2. Transgressive barriers

During the Holocene Transgression large quantities of sediment would have been available on the shelf, because the low gradient on the outer shelf (Fig 9.20A) would have promoted the deposition of fluvial sediment there during lowered sea-level, rather than its direct injection into deeper water. Felhaber (1984) described a mud depocentre off the Tugela River which he related to lagoonal deposition during a Pleistocene lowstand. During transgression, landward reworking of sandy sediments by wave action is seen as the source of barrier sands. These would not have been augmented significantly by fluvial sediment supply because much of the fluvial sediment was being deposited in estuaries during the transgression. Thus the probability of barrier overstepping was decreased.

According to Carter (1988) during barrier translation by the rollover mode, the rate of migration ($\partial R_1/\partial t$) is related to the rate of sea-level ($\partial s'/\partial t$) rise via the basement slope (β).

$$\partial R_1/\partial t = (\partial s'/\partial t) / \tan \beta$$

According to this calculation, using the distance to the -130 m contour for various coastal areas, the rates of barrier translation averaged over the Holocene are shown in Table 9.1.

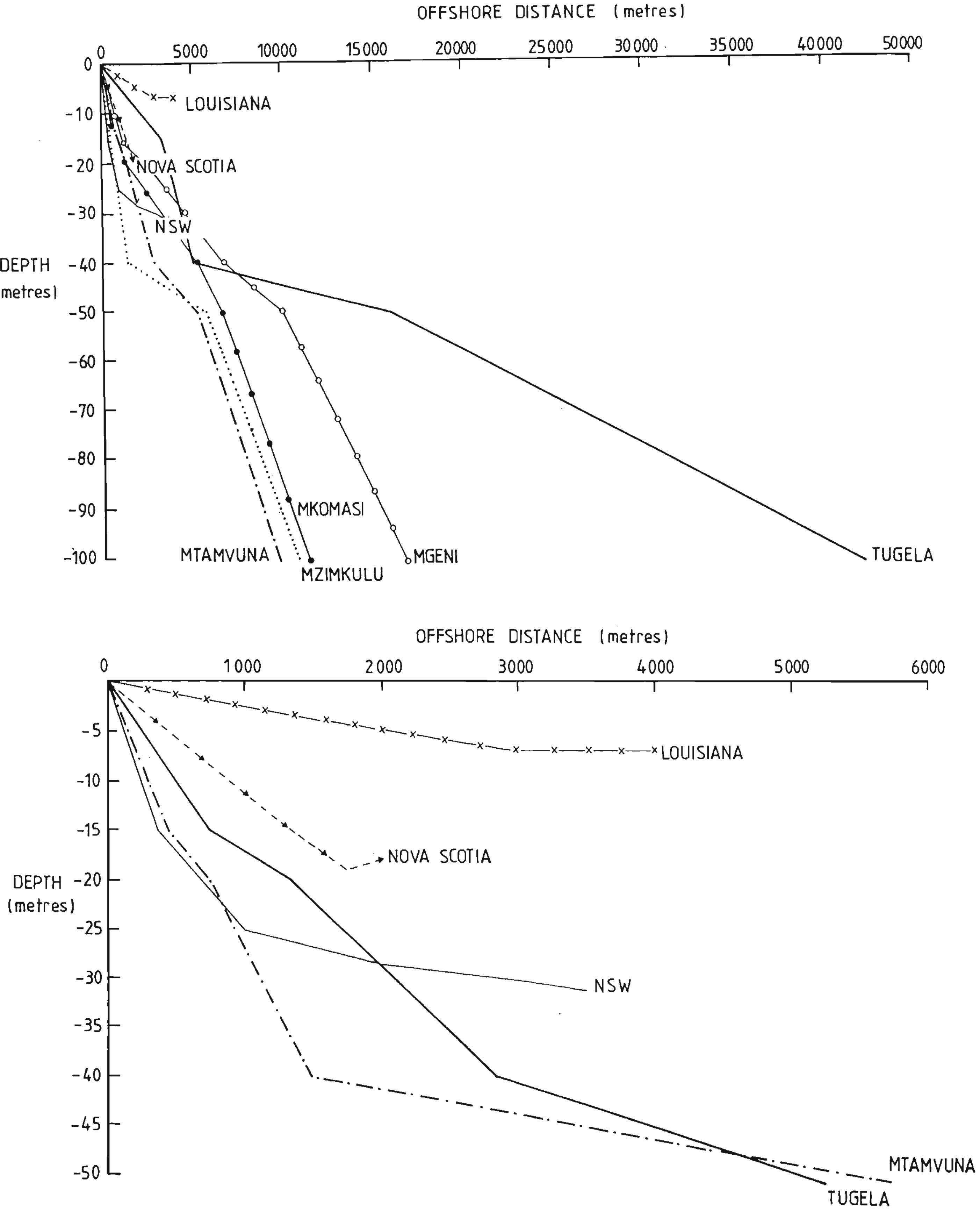


Fig.9.20. A. shelf gradients opposite rivers on the Natal coast. B. Natal shelf gradients compared to New South Wales, Nova Scotia and Mississippi Delta (after Boyd *et al.*, 1984).

Area	Distance to -130 m (m)	Average migration rate (m/100 yr)
Mtamvuna	9975	58.6
Mzimkulu	10935	64.3
Mkomazi	12255	72.1
Mgeni	14850	87.3
Tugela	42390	249.3

Table 9.1 Barrier migration rates under rollover response.

Boyd & Penland (1984) described the conservation of sediment during landward translation of barriers in Nova Scotia during Holocene sea-level rise, by transport through tidal inlets into flood-tidal deltas, accompanied by barrier overwash and aeolian transport. They found that barriers stabilised when a set of headland anchor points were encountered. Their seismic evidence for a thin veneer of transgressive sand on the inner shelf is unlikely to be reproducible in Natal due to the current-swept shelf, but as noted previously, the Natal shelf has a particularly thin Holocene sediment veneer along the south coast, offshore from the Mtamvuna and other rivers with low sediment supply (Flemming & Hay, 1988). It thus appears likely that sediment was retained during transgression in Natal and that the transgression is probably represented on the shelf by a ravinement surface (Swift, 1968).

In New South Wales, an area comparable to Natal in terms of wave energy and nearshore slope (Fig 9.20B), Boyd & Penland (1984) implied from published work that landward rates of shoreline translation exceeded the capabilities of landward sediment transfer in the period from 9000 to 6000 BP and barrier sediments consequently remained submerged during this period. This was the essence of Roy's (1984) model of river-valley estuary barriers where modern barrier formation resulted from emergence of flood-tidal deltas when the shoreline stabilised after 6000 BP. Barriers subsequently prograded to establish equilibrium about 3000 BP. During rapid sea-level rise, sediment is retained on the inner shelf following the model of Belknap & Kraft (1981) but during stillstands, wave energy transports inner shelf sediment landward to form coastal and river-mouth barriers.

In the absence of drill cores from modern barriers it cannot yet be firmly established whether modern barriers arose from emergence of flood-tidal deltas. However, since the nearshore slope (Fig 9.20B) and wave energy of the Natal coast are similar to New South Wales, it is not impossible that some Natal river mouths experienced a non-barred phase in their evolution during the Holocene. The absence of marine sediment far upstream coupled with the presence of lagoonal facies in some valley fills, however, argues against this.

Based on the sea-level curve for the South African coast presented in Chapter 1, sea-level rose from -130 m at 17 000 BP to 0 m at about 7000 BP at an averaged rate of 0.013 cm/year. Based on the horizontal distance between the 130m contour and the coast off the Mtamvuna river-mouth (approximately 10 km) this is associated with a net landward shoreline translation rate of 1 m/year.

Carter (1988) cites five instances during which barrier overstepping may occur:

a) increase in rate of sea-level rise in slow response barriers;
b) sediment influx retards barrier migration;
c) interplay of seaward and landward transport mechanisms;
d) stranding against inherited topography; and
e) held between two equal wave climates.

Available data on South African Holocene sea-levels does not indicate any change in rates of sea-level rise between 17000 and 7000 BP. Such a situation is unlikely to have promoted barrier overstepping on the Natal shelf during the mid-Holocene, as documented from New South Wales (Roy 1984; Boyd & Penland, 1984).

The presence of discrete submerged Pleistocene aeolianite and beachrock ridges on the Natal shelf (Martin & Flemming, 1986; Ramsay, 1990) as opposed to a continuous thin sand veneer indicates the ability of wave action to form emergent barriers during lowered sea-level stillstands. These cemented shoreline deposits caused a marked reduction in volume of unconsolidated Pleistocene sediment on the shelf and probably reduced the volume of sediment available for landward translation during the Holocene Transgression (Cooper, 1991c).

Given that Natal barriers respond rapidly to sea-level rise, there was no increased sediment influx, no apparent interplay of landward and seaward processes, and no holding between opposing wave climates, stranding against aeolianite ridges is the only way in which overstepping could occur. Martin & Flemming (1986) observed that these submerged aeolianites "dam" Holocene sediment behind them. This dammed sediment on the inner shelf would have reduced the potential for barrier stranding by providing sufficient sediment for renewed barrier formation behind the aeolianite ridges.

Relative sea level has fluctuated within 3 m of the present level since about 7000 BP (Chapter 1) and during this period river-mouth barrier formation could indeed have been precipitated from submerged nearshore sand as in New South Wales. There is evidence north of the Mgeni Estuary for a narrow progradational beachridge plain (Chapter 3) which may have formed during this period in common with the New South Wales estuarine barriers (Roy, 1984) and the beachridge plain north of the Tugela could also have been initiated then.

Markedly wetter conditions between 16000 and 10000 years BP (Deacon & Lancaster, 1987) suggest that sediment supply may have been increased during that period. Conditions became drier between 10 000 and 7500 BP which could have reduced the rate of sediment supply at the time when sea-level rise and shoreline migration comparatively slow. Between 7000 and 4000 BP conditions again became wetter and warmer, just at the time of high sea-level rise. This would therefore probably have been a period of high sediment supply and could possibly have caused overstepping but barriers were close to the present coast by that stage and the possibility is therefore reduced.

9.5.3. Modern barrier development

In the late Holocene, since sea-level stabilised, various barrier morphologies have developed according to several factors. In the study area 3 types are distinguished on planform shape: headland-bay barrier; large-scale coastal planform; and prograding barrier. All three barrier types are dominated by overwash lamination with an upper aeolian component: tidal inlet sequences are reworked by wave action and are not preserved. The major controls on barrier morphology appear to be antecedent topography and sediment supply (Oertel, 1979).

Thom, (1984b) described four basic sandy barrier morphotypes from NSW: prograded; stationary; receded and episodic transgressive. Duffy *et al.*, (1989) distinguished five types of gravel barrier in Maine based simply on plan form: barrier spit; looped barrier; cuspate barrier; double tombolo and pocket barrier.

When pre-Holocene slopes are steep no opportunity exists for barrier stabilisation seaward of the mainland and hence transgressive littoral sediment is driven landward to stabilise against headlands (Carter *et al.*, 1984; Boyd *et al.*, 1987) to form mainland-attached beaches and headland-bay barriers. Back-barrier areas in such instances are limited in extent and confined mainly to the lower reaches of river valleys. When underlying slope of the pre-Holocene surface is gentle, barriers may form in a seaward position and enclose extensive back-barrier lagoons. Stabilisation may be enhanced by a break in slope (Evans *et al.*, 1985) or "groundings" on antecedent topographic highs (Shepard & Moore, 1955; Halsey 1979).

The barrier types of the study area are discussed briefly below.

A. Headland-bay barrier. Headland bay barriers are joined to the mainland and assume a planform equilibrium with approaching waves by pivoting about these points as in coarse-grained barriers (Carter *et al.*, 1984; Boyd *et al.*, 1987). They are similar to the pocket barriers of Duffy *et al.* (1989). As the barriers assume a planform equilibrium with approaching wave fronts and show no discernible historical regressive or transgressive trends, they may be regarded as similar to the stationary barrier of Thom, 1984b). The Natal coast is not deeply embayed and barriers commonly span only a single river-mouth (Fig. 9.21). Occasionally a river-mouth forms only part of the planform (Fig 9.21) which extends to the adjacent mainland shore. In this type of environment, depending on the coastal bedrock slope and wave refraction patterns, coastwise extension of the lagoon may occur (Fig 9.21).

Aeolian dunes may form on top of these barriers, particularly at the mouths of smaller rivers where periodic flood erosion is minimised. In large-catchment rivers frequent flooding inhibits aeolian dune formation and the aeolian component accumulates on the adjacent mainland shore. In some cases the barrier dunes are thickly vegetated, suggesting stabilisation during the Late Holocene.

B. Large-scale coastal planform. The only large scale coastal planform barrier spans the area between the Durban Harbour entrance and Umhlanga Rocks (Fig 9.21). It spans the Mgeni river-mouth and has

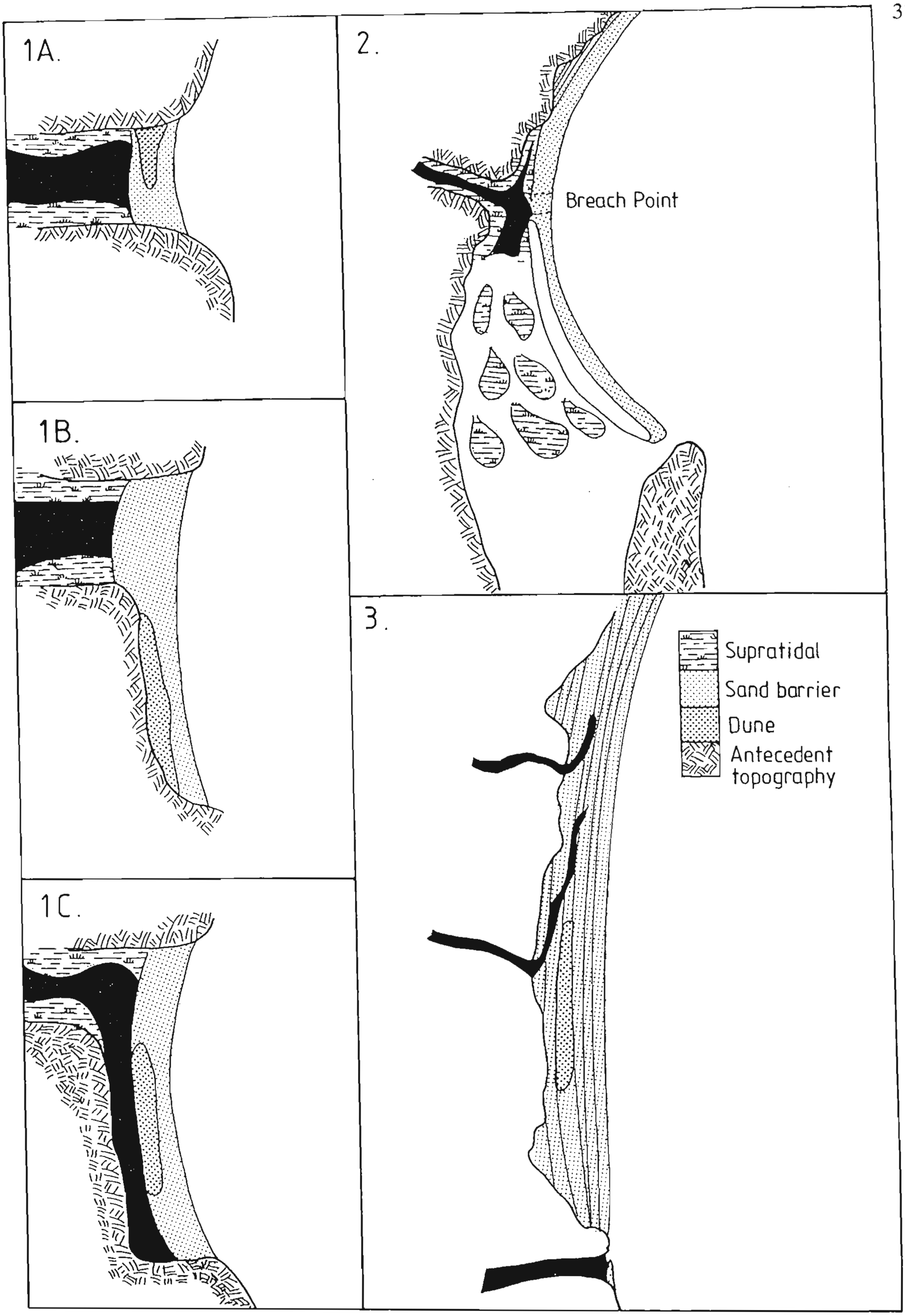


Fig. 9.21. Barrier types on the Natal coast. 1A-1C. Headland-bay barriers, which are typically located in shallowly indented embayments on the near-linear Natal coast. Three types are identified: 1A. valley-confined barriers; 1B. valley forms only part of embayment planform; and C. Coastal lagoon extension is permitted by gentle bedrock slope and wave refraction patterns in embayment.
2. Large-scale coastal planform produced where bedrock gradients are reduced on Cretaceous and Pleistocene remnants.
3. Prograding coastal barriers intercept terrestrial drainage channels, causing them to move underground, elongate in a coast-parallel direction, or be captured by larger rivers.

enabled coastal extension of the river course during its evolution. It is probable that the preservation of Cretaceous lithologies and the Black Mud Stratum under Durban by Tertiary cover reduced the slope of the pre-Holocene surface, and enabled the transgressive barrier to stabilise in a location seaward of the mainland shore, where it adjusted to wave action by assuming an equilibrium planform during the Late Holocene. The planform shape appears to be controlled by refraction of long-period, southeasterly waves around the end of the Bluff. A similar situation appears to exist at the Bay of Maputo in Moçambique.

C. Prograding beachridge plain. Progradation is presently occurring north of the Tugela River at rates up to 5 m per year (Cooper 1991a), in the form of accretionary sandy beachridges (Fig 9.21). The scale of progradation is such that the mainland coast is located some distance landward of the present sandy coastline and several large and small-catchment rivers are located behind it. This linear sandy coastline is the largest single expanse of shoreline in the study area in which littoral drift operates. The impact of progradation has been to divert river courses northward in the direction of longshore drift. In some cases this has resulted in river capture (Begg, 1978) and channel elongation (Cooper 1991a). The prograding barrier vegetation shows a distinctive succession from older to younger ridges (Weisser & Backer 1983). The sedimentary structure of these barriers has not been studied but it is likely that aeolian cross-bedding predominates in the upper parts.

9.6. DISCUSSION AND CONCLUSIONS

In the study area, river-mouth environments span classifications of deltas, estuaries, river-mouths and coastal lagoons. The main differences result from the amount of fluvial discharge. Sedimentary models for each type of environment have been synthesised and compared to existing models for other types of transitional fluvio-marine environments. The four main river-mouth types in Natal are river-dominated coastal lagoons, fluvially-dominated delta-top estuaries; wave-dominated estuaries; and non-tidal river mouths. A single wave-dominated delta is present.

Although river-dominated lagoons were subdivided into several morphological groups in the previous chapter, they all experience similar sedimentary processes but within moderately differing frameworks. The facies arrangements in these environments are distinctive from wave- and tide-dominated environments described from other areas. Organic sedimentation is temporary, and fine-grained sediment is eroded from Natal lagoons during periodic breaching so that sand and muddy sand dominate the sedimentary record. The narrow valleys restrict wave action and formation of broad marginal areas as in wave-dominated lagoons. Irregular breaching cycles as opposed to regular tidal oscillation, limits infaunal habitation and bioturbation in comparison to tide-dominated lagoons.

In estuaries the lack of progradation is due to the wave-dominated coastline and thus they do not qualify as deltas. Being dominated by fluvial sediment and discharge, they are similar to river-mouths in other high sediment load and high wave-energy areas. In contrast to wave-dominated estuaries, upstream facies variation is poorly developed and the preferential retention of coarser grainsizes reflects the impact of periodic floods. Marine influence is limited to non-existent, and the association of essentially fluvial deposits directly adjacent to a coastal barrier is a distinctive feature of this type of environment.

In drowned river-valley estuaries the effects of reduced sediment supply may be seen. There is an upstream facies variation into the three zones identified from wave-dominated estuaries of New South Wales, which are less fluvially-influenced than the other estuaries of Natal. The similarity of the Mtamvuna to the New South Wales examples (Roy, 1984) supports the recognition of this type of environment as a general sedimentary model for wave-dominated estuaries (Zaitlin & Shultz, 1990; Nichols, 1990).

Where sediment supply is particularly high and an adjacent area is aligned suitably with respect to approaching wave fronts, progradation occurs in the form of beachridges which, in their shore parallel orientation, are similar to wave-dominated deltas from elsewhere in the world.

An attempt has been made to link these environments using the amount of fluvial discharge as the main source of variation between the three ternary diagrams presented. Deltas are differentiated as a separate group which display coastal progradation. Estuaries and river mouths exhibit no progradation on their own accord, although they may occur on prograding coasts. In lagoons river influences are minimised in relation to estuaries and deltas. In all three groups systematic variation occurs based on the relative importance of waves, tides and river discharge. In this way fluvio-marine environments may be viewed conceptually

Sedimentary environments observed in Natal and the sedimentary models proposed extend the known range of depositional environments in the fluvio-marine transition zone and may be representative of general classes of landform in similar environmental settings. This will enhance future efforts to develop generalised sedimentary models.

Sedimentary processes in modern Natal river-mouths are dominated by floods and a cyclic pattern of scour followed by equilibrium adjustment is followed. In drowned river valley estuaries, flood impacts are restricted mainly to the barrier.

Evolutionary development of all types of river-mouth in the study area is controlled by the relative importance of sediment supply to the rate of increase of the basin volume. The latter is controlled by sea-level rise and bedrock valley cross-section. Subsidence is relatively unimportant due to the mainly sandy valley fills. In any type of river-mouth the potential exists for deep water facies or prolonged equilibrium during sea-level change, thus no generalised model of development can be applied to all environments. All Natal river-mouths have been accelerated in their development by a Late Holocene fall in relative sea-level, which has resulted in incision of river channels into older alluvium or subaqueous deposits.

Barriers are important in the evolution of estuaries and lagoons in eliminating the effects of wave action and in their effect of restricting tidal influx. They also act as modifiers to the sedimentary sequence preserved in the sedimentary record. The nature of Natal river-mouth barriers reflect nearshore slope and antecedent topography, and their development during transgression is yet to be elucidated. Preliminary observations suggest that they rolled over during sea-level rise.

The sedimentary facies deposited in certain Natal river-mouth environments could act as petroleum reservoirs because of their predominantly sandy fills and the capping of each sequence with a muddy floodplain deposit bounded by bedrock outcrops, although, as pointed out by Zaitlin & Shultz (1990) from ancient estuarine facies, the yield may be higher from more porous barrier-associated sand bodies than from the back-barrier poorly sorted fluvial sands. The muddy sands in many estuary fills would limit porosity and petroleum storage capacity. Only those with high organic inputs and suitably deep water for retention of organic sediment, could form petroleum source rocks.

In terms of the sequence stratigraphical principles in use in the petroleum industry, the sedimentary fills of laterally confined river-mouths can generally be regarded as a single sequence comprising a transgressive systems tract marked by infilling of fluvial channels and floodplain aggradation. The impact of fluctuations in mid to late Holocene sea-level on the highstand systems tract requires further detailed investigation.

Clearly the results presented in this thesis are based on a limited number of case studies and field observations. There remain several aspects of Natal river-mouths which require further investigation. The hydrodynamic impacts of breaching, systematic investigation of valley fills and investigation of barrier evolution are but a few of the more important aspects. Improvement of the Holocene sea-level curve by more radiocarbon dates from appropriate samples is a prerequisite for all aspects of coastal geomorphology in Natal.

* * *

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