I.C. Rust.

Research on Sedimentation in Estuaries

SEDIMENTATION IN THE GAMTOOS ESTUARY

ROSIE REPORT No 7

By: JSV Reddering
K Esterhuysen

Project leader: IC Rust

Department of Geology
University of Port Elizabeth

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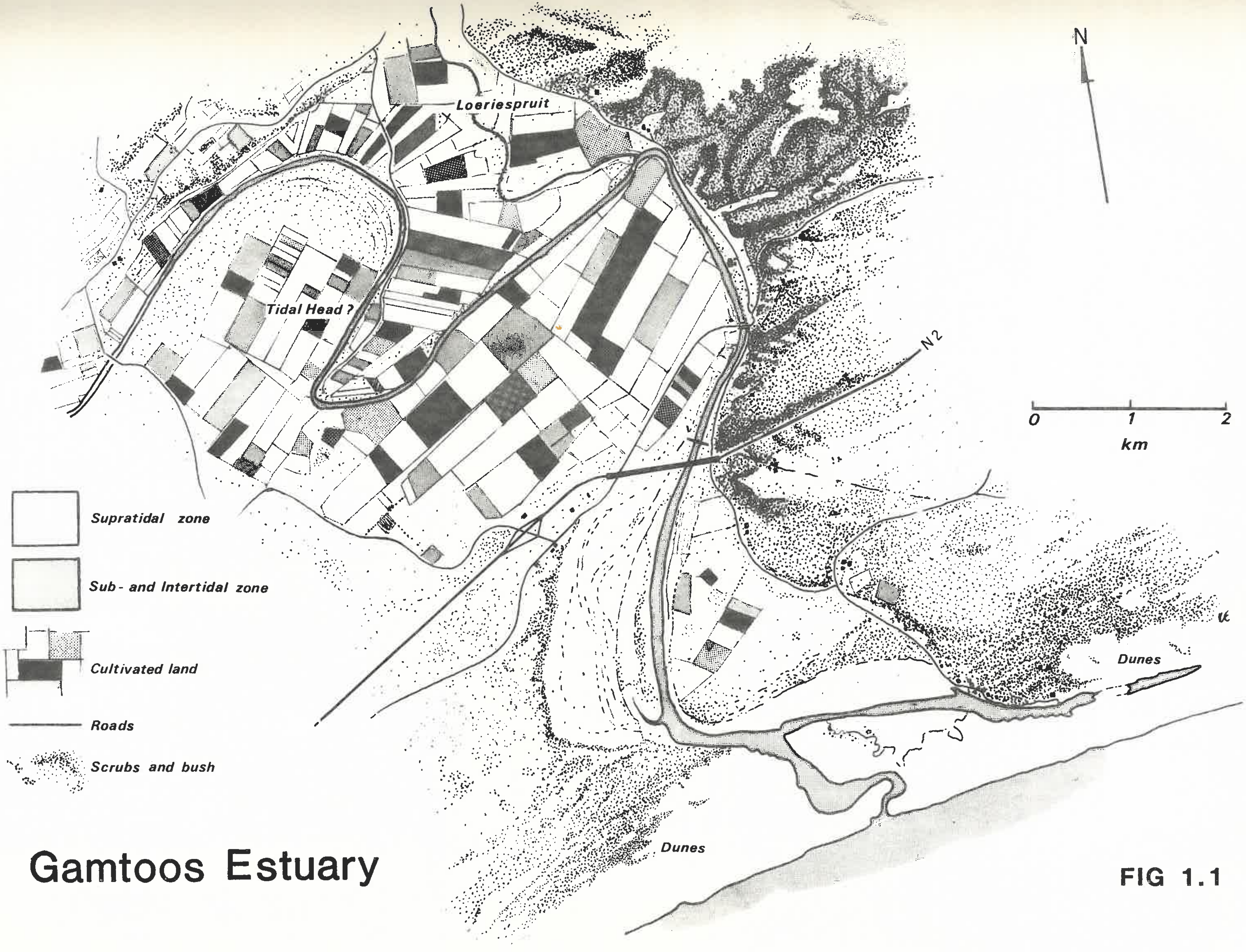
ABSTRACT

Sedimentation in the lower Gamtoos estuary is controlled by interaction of four environmental factors: tidal action, longshore currents, freshwater floods and wind. In contrast to this complicated depositional system the upper estuary is dominated by freshwater floods. The sediment source in the lower estuary is predominantly marine whereas that of the middle and upper estuary is fluvial. Mud found in the estuary is fluvial, and the carbonate component is marine. The marine sediment is generally coarser-grained than the fluvial material.

The Gamtoos inlet migrates eastward under fairweather conditions. This is in the opposite direction to that of the prevailing longshore current. The inlet may be blocked during conditions of heavy swell. During heavy freshwater floods the inlet tends to breach the westernmost part of the barrier.

Environmentally undesirable sedimentation in the estuary does not seem to take place.

Severe freshwater flooding submerges the floodplain of the estuary. During these conditions the inlet channel erodes the shortest route to sea and discharges a large sediment-laden plume into the bay.



Gamtoos Estuary

FIG 1.1

SEDIMENTATION IN THE GAMTOOS ESTUARY

1. INTRODUCTION

The estuary of the Gamtoos River (fig. 1.1), 55 km west of Port Elizabeth on the eastern Cape coast, has a meandering channel deeply eroded into a wide river floodplain. It has a permanent migratory inlet on St Francis Bay (fig. 1.2). This inlet is influenced by wave action, longshore drift, a well developed active coastal dune field and by freshwater floods.

The river has a large catchment area which extends well into the Karoo (fig. 1.2). Various tributaries join upstream of Patensie (fig. 1.3). Below the confluence of the Kouga and Groot Rivers the river is called the Gamtoos River and follows an 80 km long meandering course to the sea.

Agriculture is practised on the floodplain of the middle and upper estuary (fig. 1.1).

Location of Gamtoos River

33° 57' S ; 25° 03' E

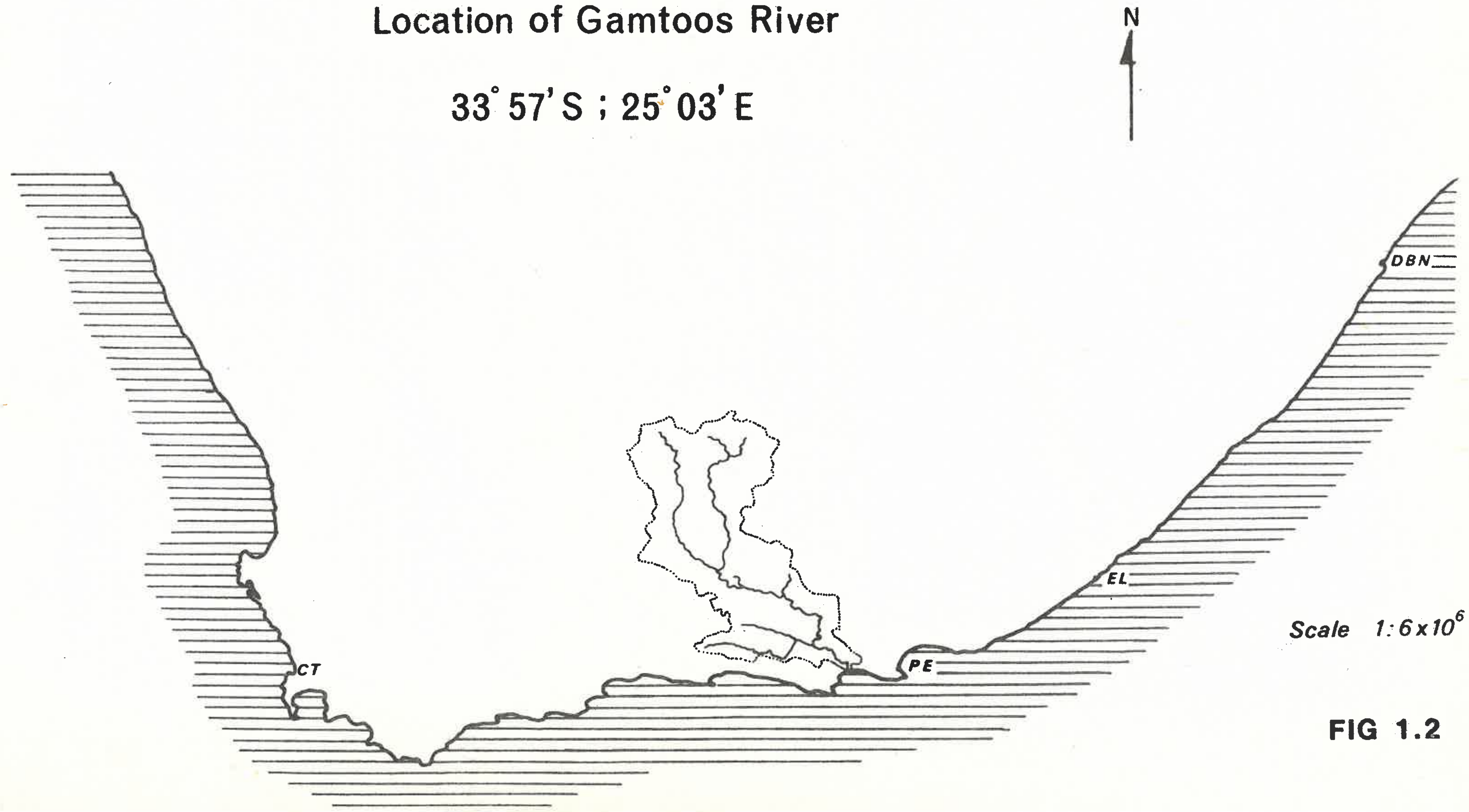
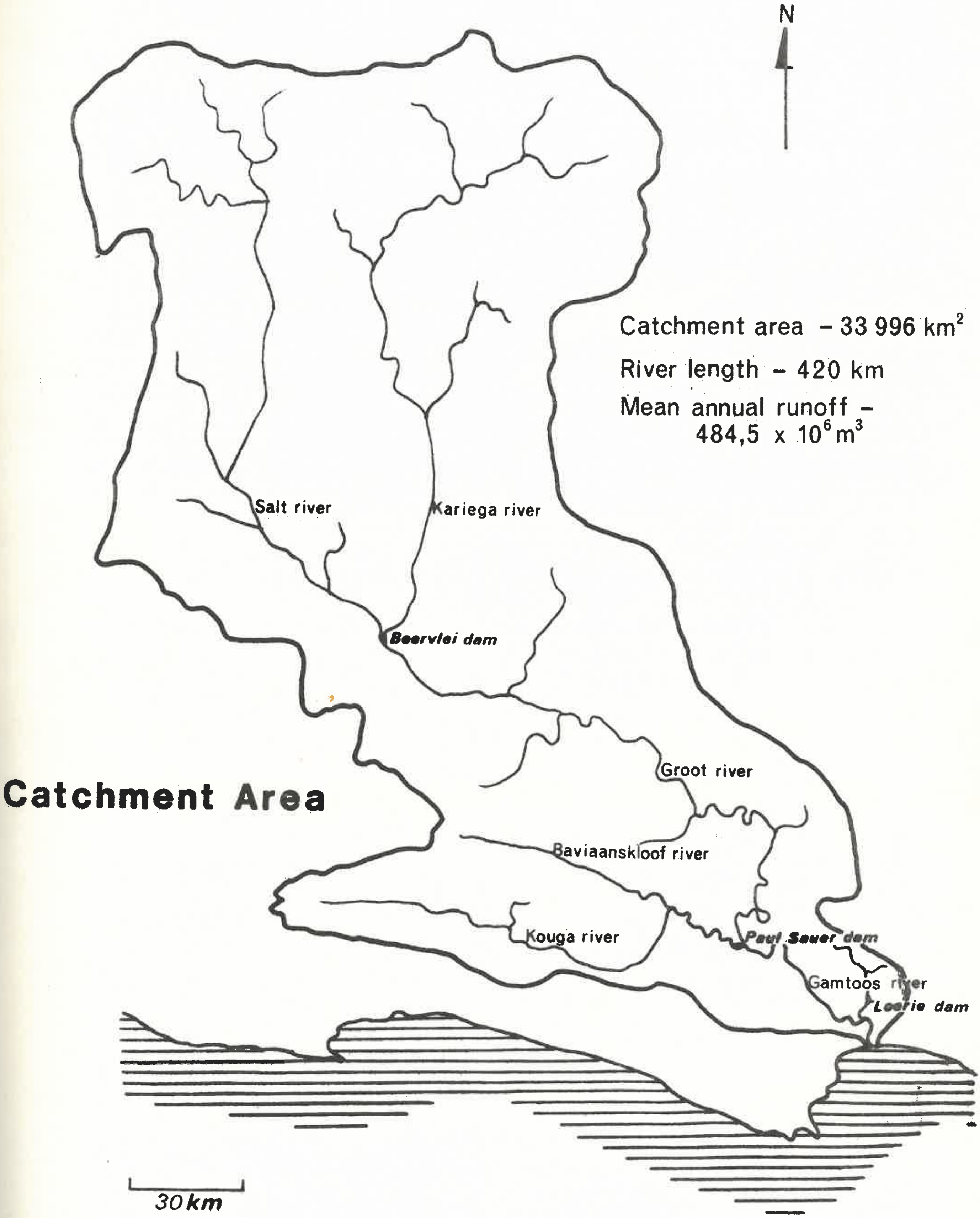


FIG 1.2



N
Catchment area - 33 996 km²
River length - 420 km
Mean annual runoff - 484,5 x 10⁶ m³
Salt river
Kariega river
Beervlei dam
Groot river
Baviaanskloof river
Kouga river
Paul Sauer dam
Gamtoos river
Loerie dam
Catchment Area
30 km

FIG 1.3

The purpose of this report is to:

1. Describe the sedimentary state of the estuary;

2. Document the migratory behaviour of the inlet;

3. Illustrate aspects of the freshwater flood behaviour of the estuary.

2. BACKGROUND INFORMATION

2.1 Catchment area

In view of the thorough description of this aspect by Heydorn and Grindley (1981) the relevant information is condensed with the addition of some new information:

1. Area:

34 000 km^2 (34 500 km^2; this study)

2. River length:

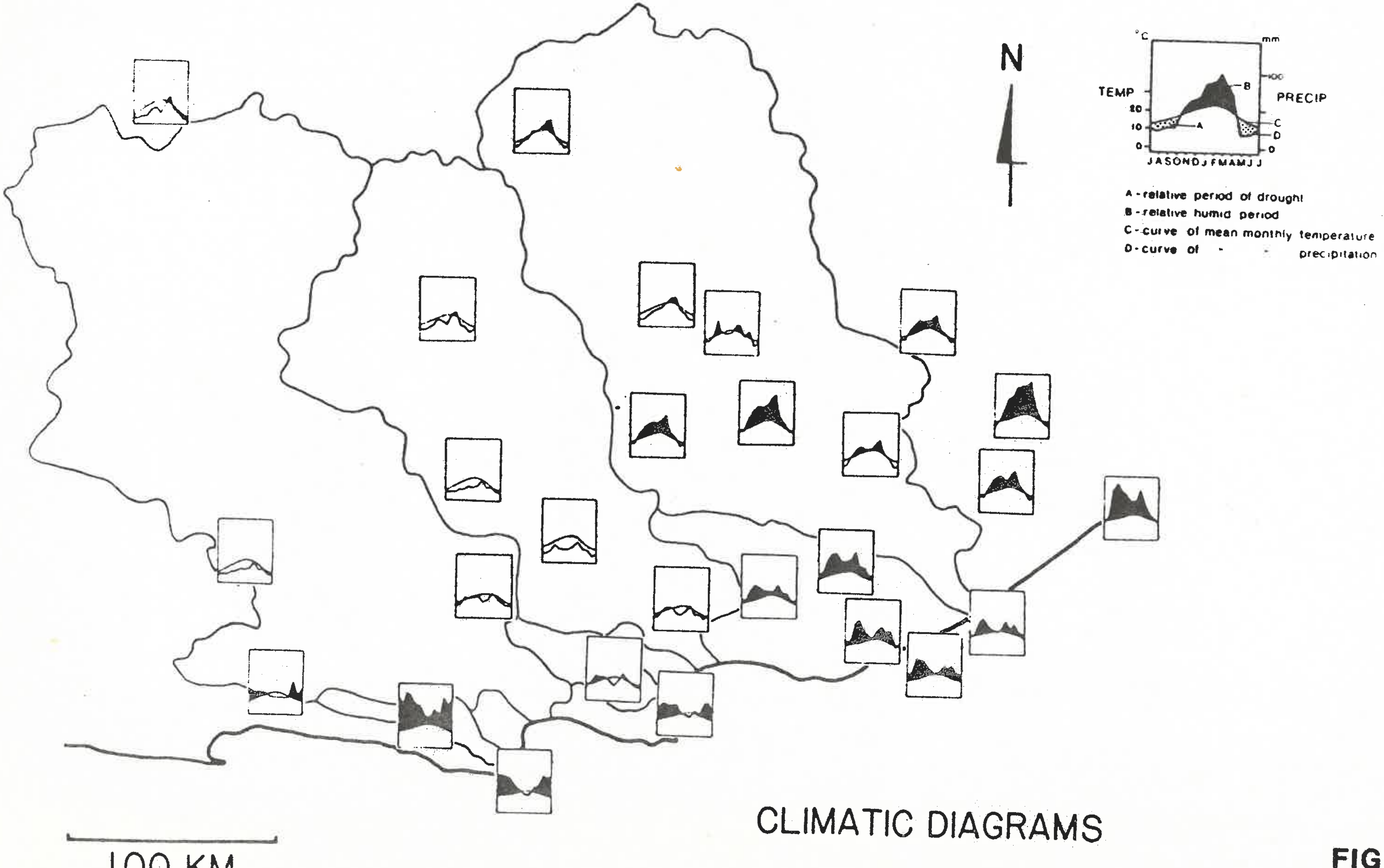
About 400 km

3. Climate (figs. 2.1 and 2.2):

Semi-arid inland, coastal rainfall mainly in spring and autumn. Precipitation is highest in the coastward Kouga Mountain range. Mean annual precipitaion is about 300 mm.

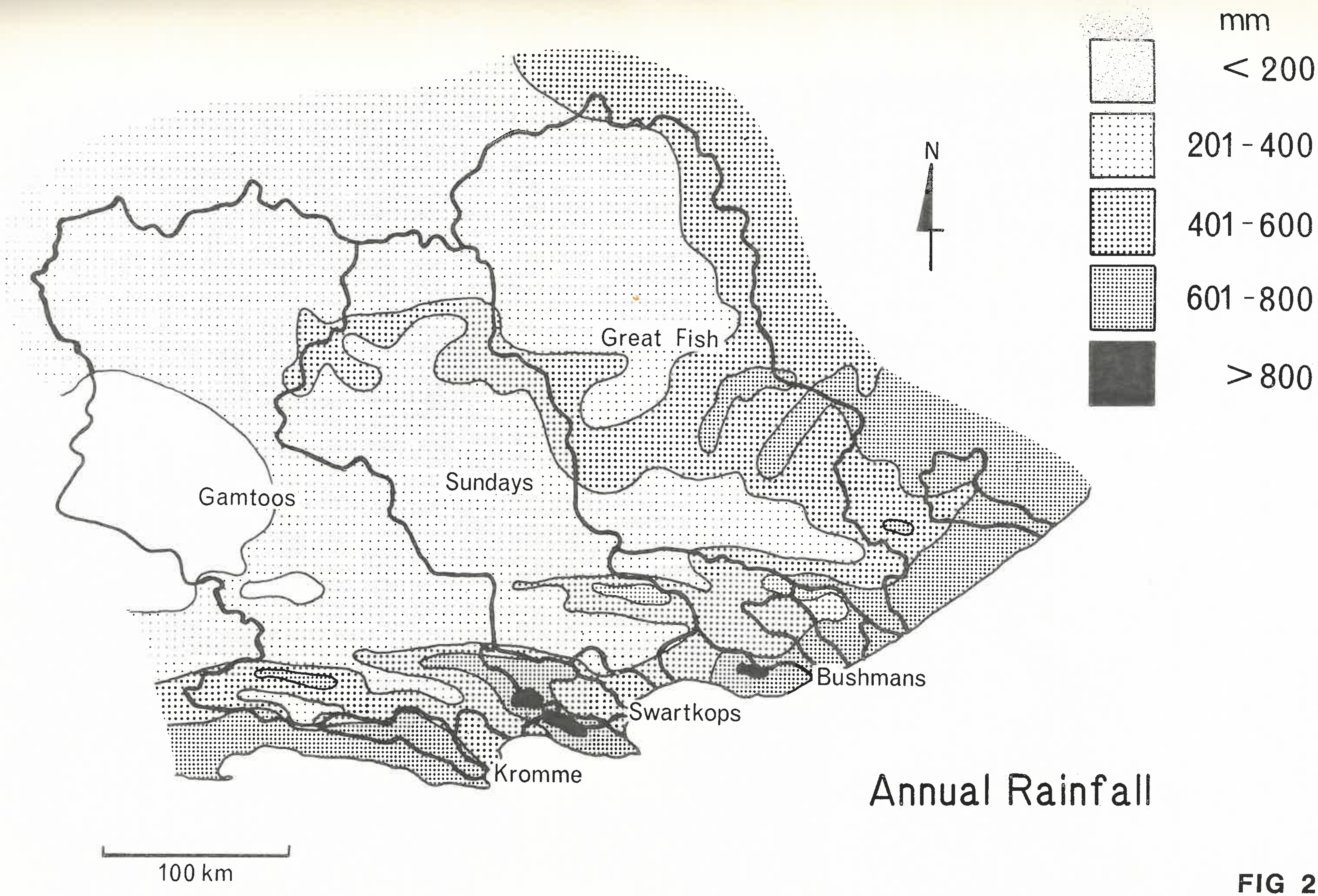
4. Dams (fig. 1.3):

Beervlei Dam on the Groot River tributary; storage capacity - 93,5 X 10^6 m^3; Paul Sauer Dam on the Kouga



CLIMATIC DIAGRAMS

FIG 2.1



Annual Rainfall

FIG 2.2

River tributary; storage capacity - 152 X 10^6 m^3; Loerie Dam on the Loerie River tributary; storage capacity - 3,92 X 10^6 m^3. Water piped to this storage dam from the Kouga Dam is purified for the City of Port Elizabeth.

5. Geology (fig. 2.3):

Mainly shale-rich Karoo Supergroup in the northern part of the catchment basin. Folded rocks of the Cape Supergroup closer to the coast are quartzose. The lower 40 km of the river flows along predominantly sandy and conglomeratic Mesozoic rocks.

6. Soil types (fig. 2.4):

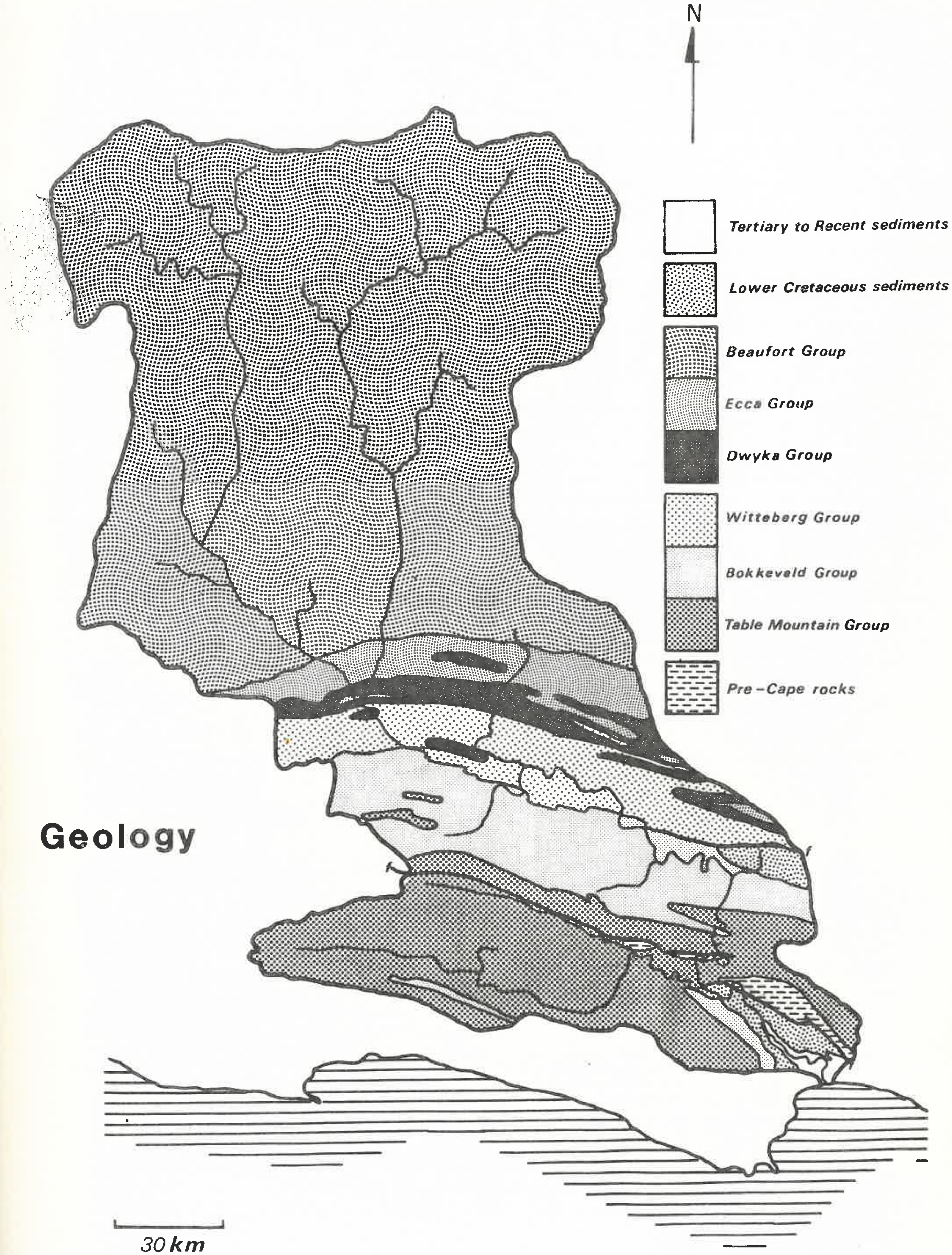
Weakly developed over the largest area. Shallow soil, lithosol and rock outcrops predominate. Lime is present in the Karoo and in the coastal area.

7. Vegetation (fig. 2.5):

Mostly Karoo and Karoid Bushveld in the more arid areas. False Macchia predominates in the south.

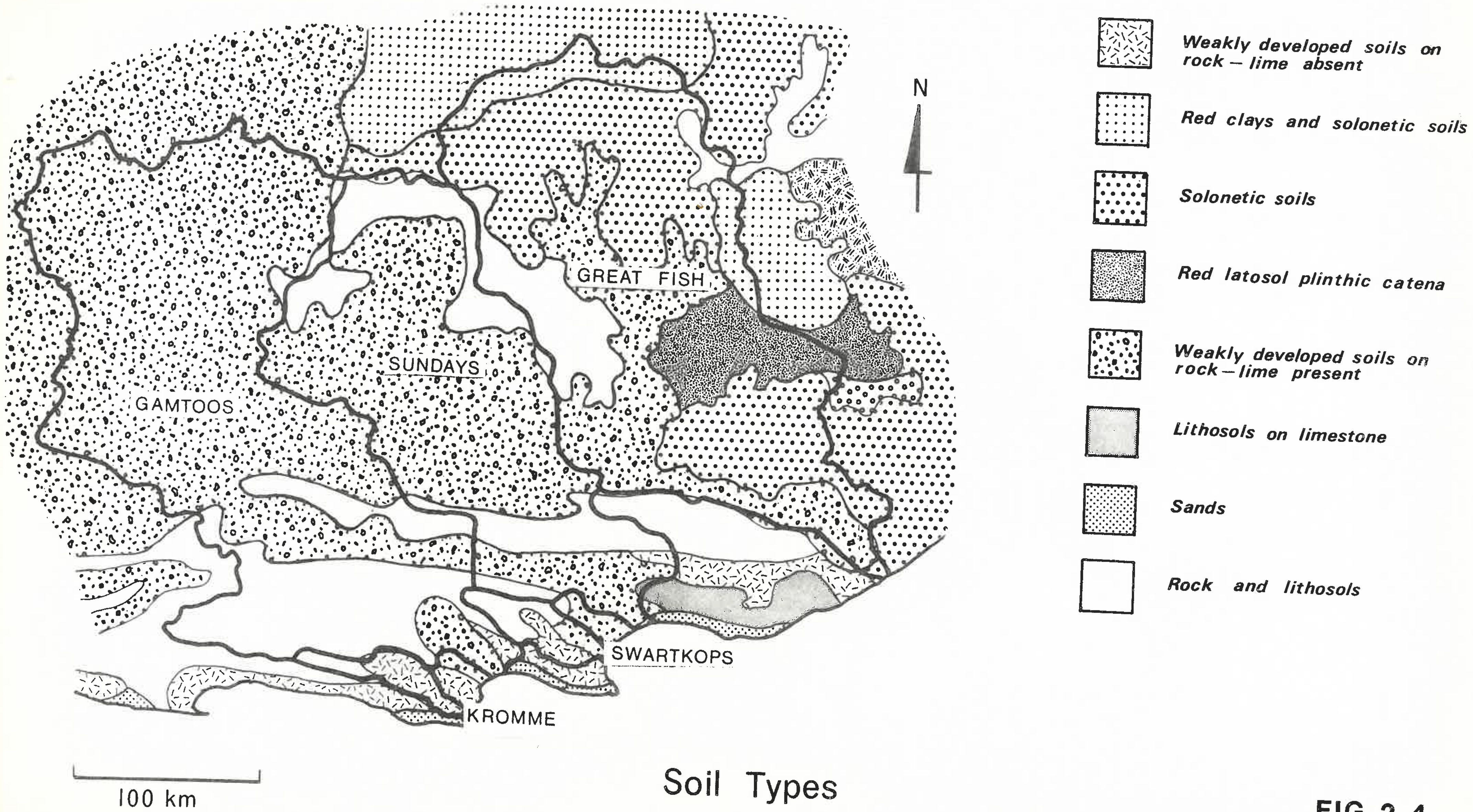
8. Sediment types:

Subequal volumes of mud and fine sand in the river load.



Geology

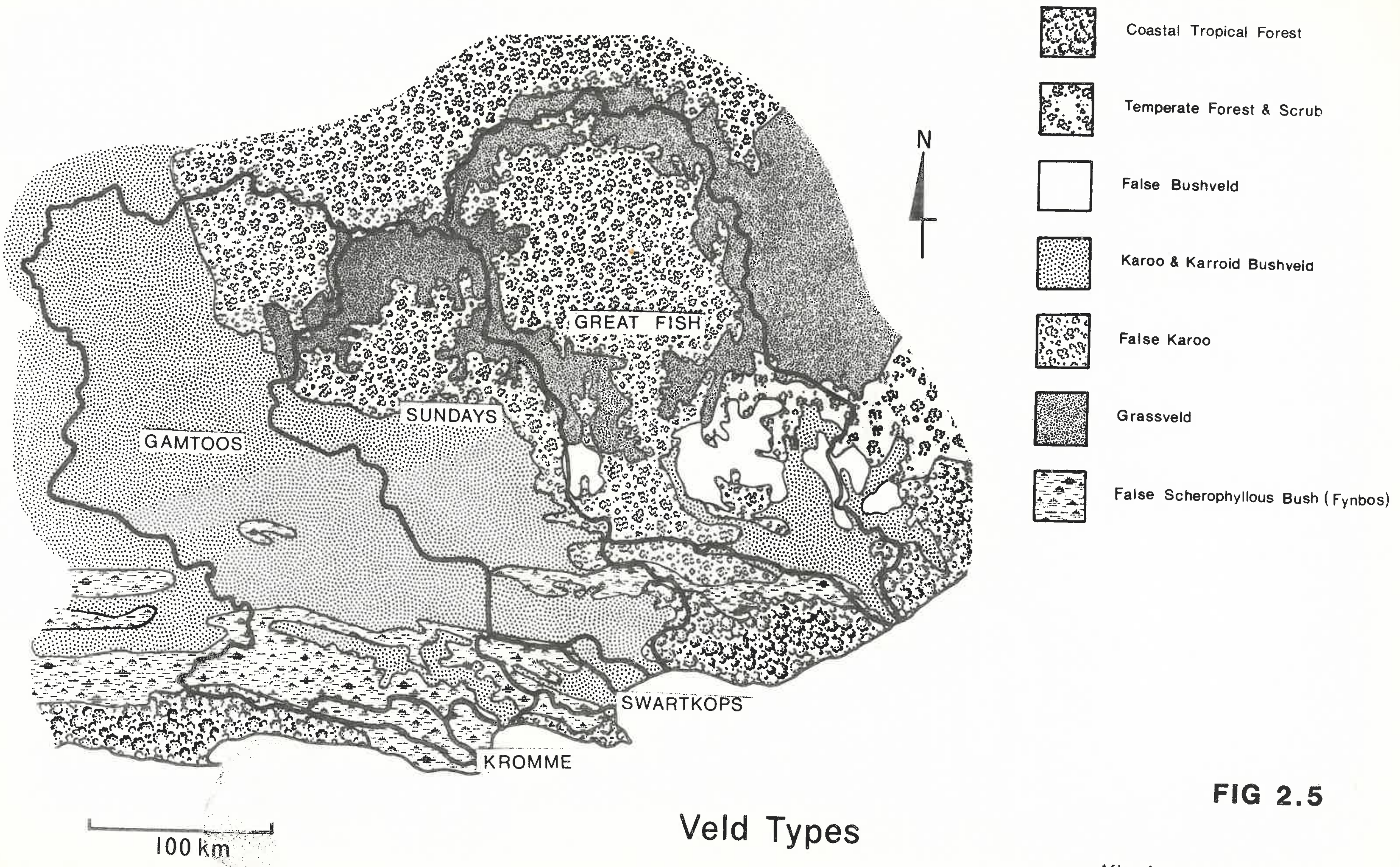
FIG 2.3



Soil Types

After Macvicar et al

FIG 2.4



Veld Types

FIG 2.5

After Acocks

2.2 Estuary

2.2.1 Physical characteristics

The channel of the estuary is incised into the river floodplain and has narrow intertidal areas. The 3 m high, consolidated silty sand banks in the middle and upper estuary are mostly vertical. The inlet area is a complex system of active and abandoned channels. These channels form by interaction between the adjacent coastal dune field to the south-west, longshore currents and freshwater floods. The inlet migrates under the influence of these conditions (chapter 5).

Eastward migration of the inlet and wave action cause a barrier to be deposited parallel to the wave fronts. This barrier separates the landward inlet approach channel from the sea. High discharge river floodwater tends to erode a channel through the westward end of the barrier. When the barrier is breached the eastern section of the inlet approach channel behind the barrier is abandoned (section 5.3). This abandoned channel can be seen on the more recent aerial photographs (section 4.2).

Heydorn and Grindley (1981) indicated that the tidal head reaches the confluence with Loeriespruit (fig. 1.1) but tidal effects are actually evident for a considerable distance farther upstream. It is not possible to pinpoint the exact position of the tidal head because there is no sharply defined obstruction in the channel. The channel section about 6 km upstream from the confluence with Loeriespruit is shallow as a result of many sand bars. It is probable that the tidal effect of the system is negligible in that part of the channel. The tidal head of the system can for practical purposes be taken to lie there among the sand shoals (fig. 1.1). Salt water extends upstream from Loeriespruit but is unlikely to each as far as the tidal head.

The deposits of the estuary and the river floodplain overlie the Mesozoic sandstone that also outcrops as high hills in the surrounding country side. This sandstone occurs at a depth of 47 m below river level (Davies, 1972). Beach rock with pebble layers and well developed cross-bedding, outcrops on the western bank of the channel near the inlet and is overlain by part of the coastal dune field.

2.2.2 Human influences

The recreational possibilities of the estuary close to the Port Elizabeth metropolitan area attract many over weekends and holidays. Two caravan parks are developed on the banks of the estuary. One park lies on the abandoned inlet section and the other just to the south of the national road bridge about 3,5 km from the inlet. Other amenities include holiday shacks, day tripper facilities and slipways. A hotel, situated about 6 km up-estuary from the inlet, also caters for the tourist trade.

Crop farming is practised on the floodplain of the estuary and livestock farming is carried out on a limited scale on the banks near the inlet.

Three man-made structures cross the estuary. These include the single-carriage, steel girder bridge (completed in 1895), the national road (N2) bridge (1974), and a raised water supply pipeline. Both road bridges have bridge supports in the present estuarine channel but the pipeline is suspended between the opposite banks. The national road bridge has a 1,5 km long raised embankment across the floodplain. This embankment was ill-conceived as it only has two gaps where water could pass: one at the main river channel and the other at where the old N2 road passes underneath. In the event of a freshwater flood the embankment lies in the way of flood water flowing across the floodplain. It is likely to dam up water on the upstream floodplain during floods which would aggravate the associated damage to property.

3. SEDIMENT DISTRIBUTION

3.1 Introduction

The Gamtoos estuary is dominated by freshwater floods and consequently obtains the major component of its sediment budget from the catchment area. Sediment consists largely of fine-grained sand and mud. Near the inlet, wind blown sand from the adjacent aeolian dune field to the west enters the lower estuary. Sediment also enters through the inlet from the sea. Storm washover across the barrier, which separates the sea from the abandoned inlet channel (fig. 1.1), introduces marine sediment into that part of the estuary. These varied sediment types contribute toward the overall distribution of sediment in the estuary.

Sediment samples were collected on a pre-determined grid in the estuary (fig. 3.1). The samples were analysed in the laboratory for grain size statistics, carbonate content and for organic content. Selected samples were microscopically examined to determine the source dispersal of sediment in the estuary. The samples were collected at the bed surface and at a depth of 50 cm below the sediment surface. Results are given in APPENDIX I.

Sediment Sample Sites

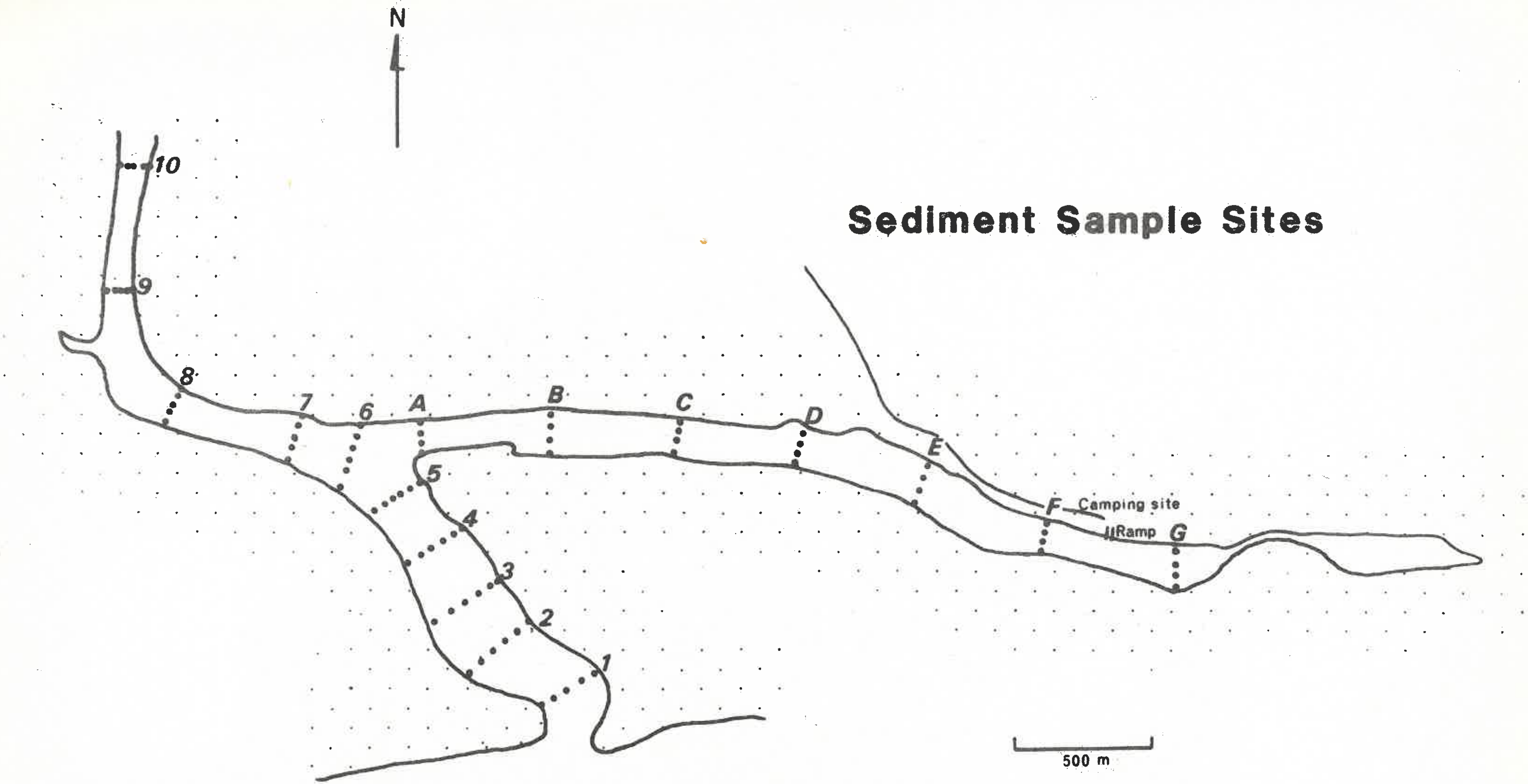


FIG 3.1

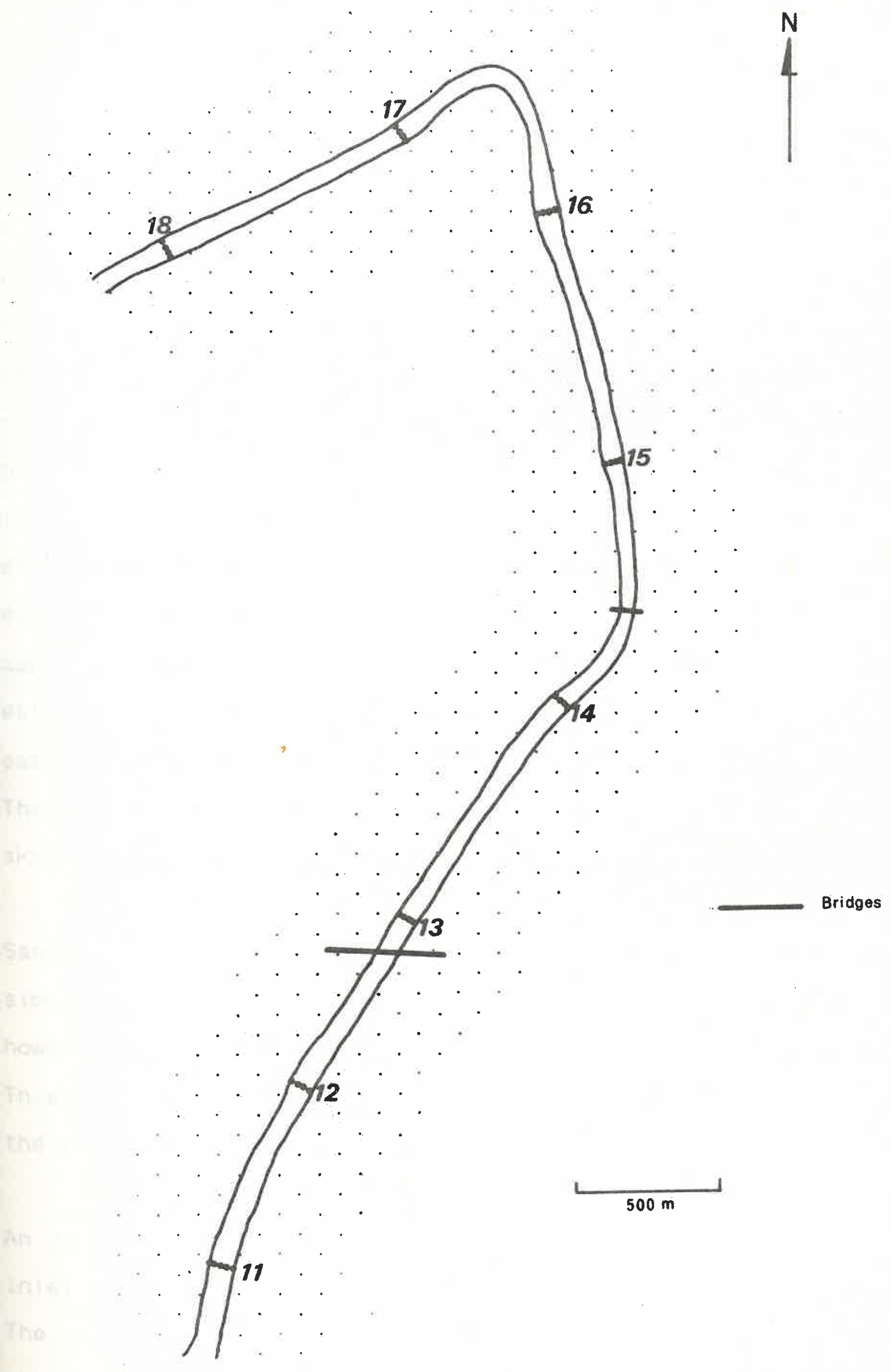


FIG 3.1 CONT

3.2 Sand distribution (fig. 3.2 a and b)

Sand becomes progressively finer-grained up-estuary from the tidal inlet of the Gamtoos estuary. This is probably controlled by the nature of the source sand. Sand at the inlet contains a large fraction of coarse-grained skeletal carbonate material (APPENDIX I) which enters the estuary under the influence of tidal currents. Resulting from the high winds that frequently blow across the area the aeolian sand at the western inlet margin is relatively coarse-grained. Fluvial sand in the estuary, by contrast, is fine-grained and is mostly found in the upper estuary. Sand in the proximal part of the abandoned inlet approach channel is fine-grained and similar to that of the upper estuary. The source (section 3.5) is fluvial. In the distal, eastern end of this channel the sediment is of marine origin. The sand in the distal region is coarser-grained and contains skeletal carbonate fragments.

Sand distribution 50 cm below the bed surface (fig. 3.2 b) is similar to that at the sediment surface. In the upper estuary, however, the sediment below the bed surface is coarser-grained. This type of upward fining sequence is typically deposited during the waning stage of a freshwater flood.

An unusual tongue of fine-grained sand extends from the abandoned inlet channel into the present inlet channel (fig. 3.2 a and b). The shape of this sand tongue indicates that it was ebb-deposited whereas its grain size suggests a fluvial source.

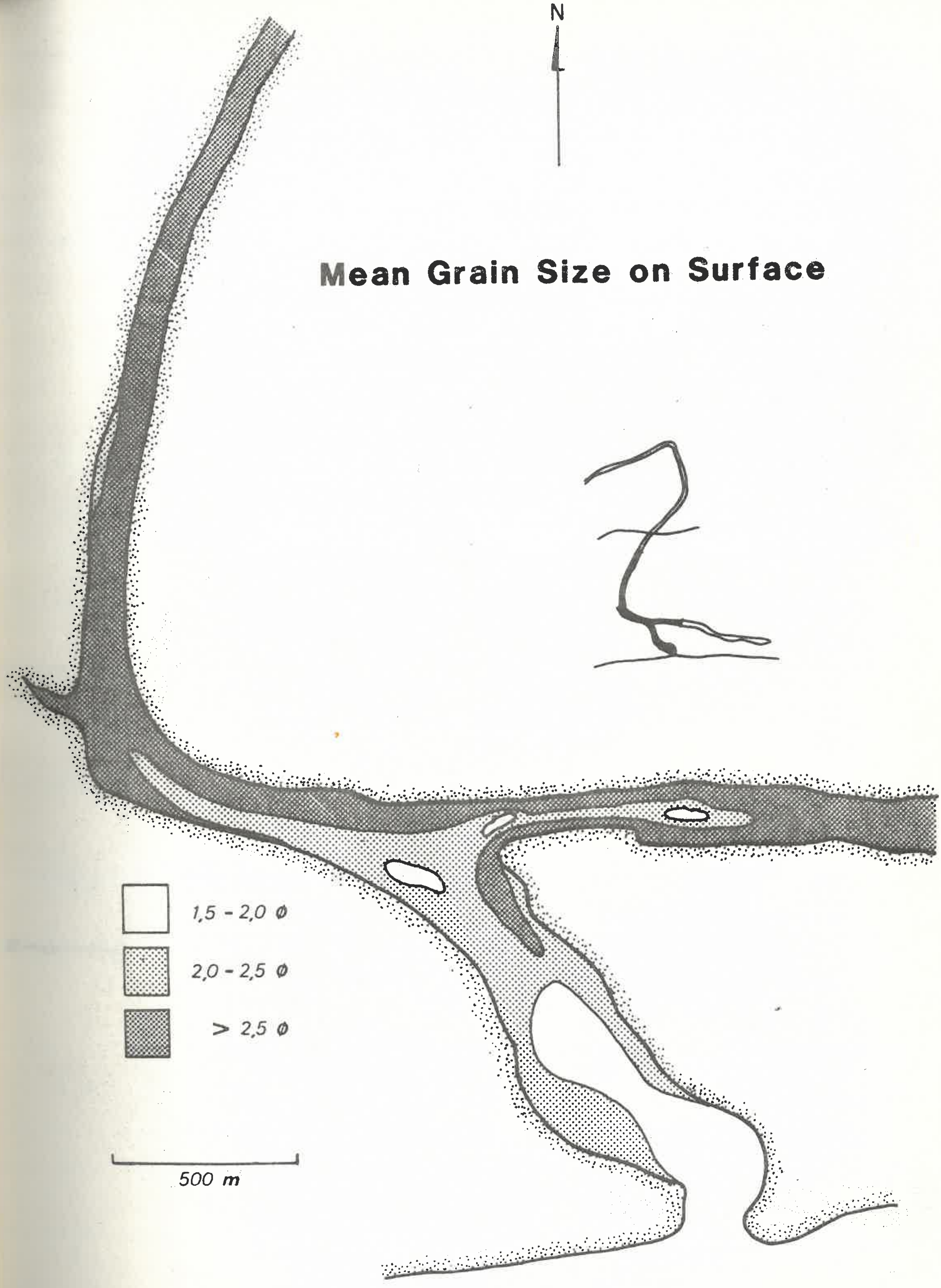


FIG 3.2A

Mean Grain Size on Surface

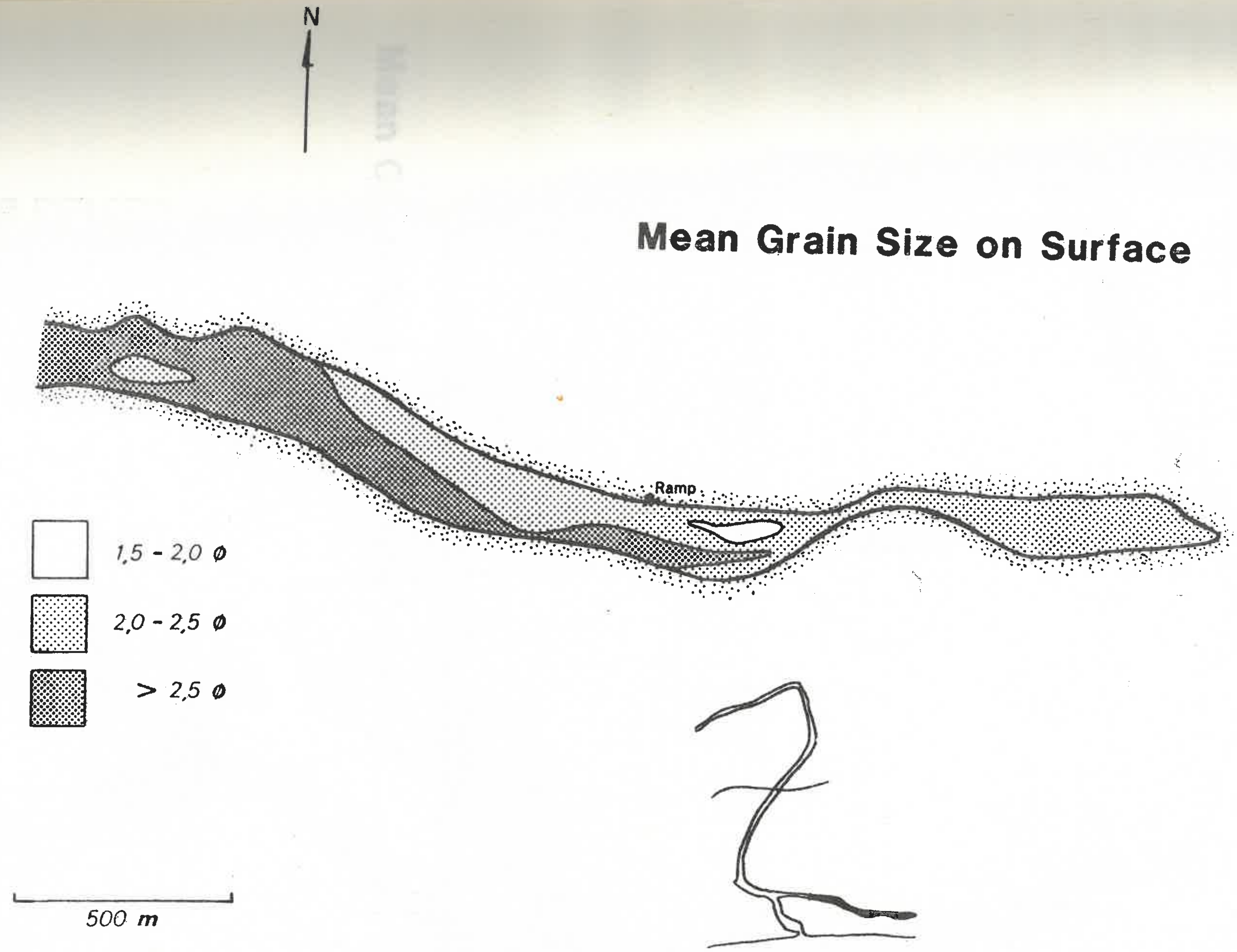


FIG 3.2A CONT

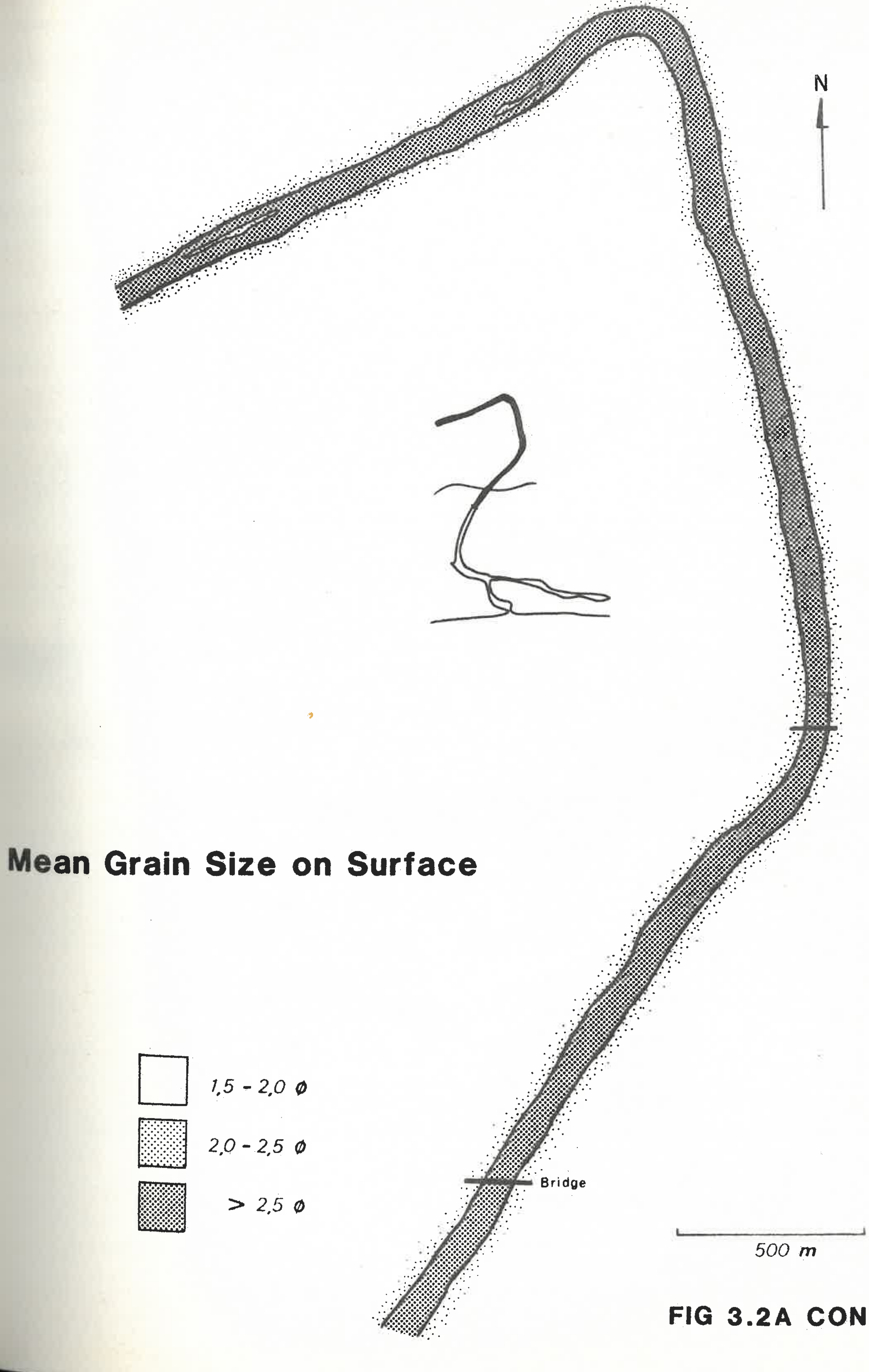


FIG 3.2A CONT

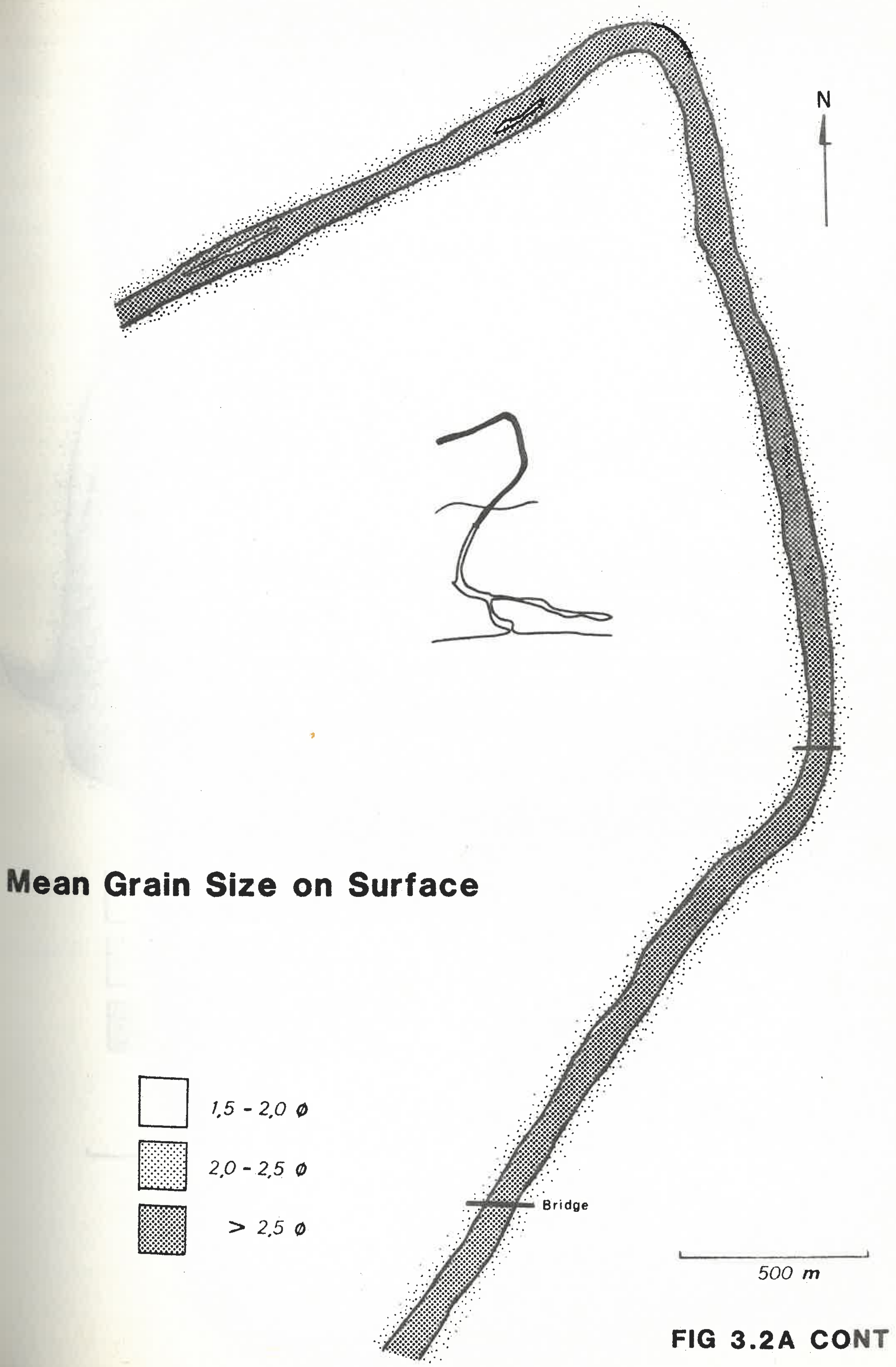


FIG 3.2A CONT

Mean Grain Size at -0,5m

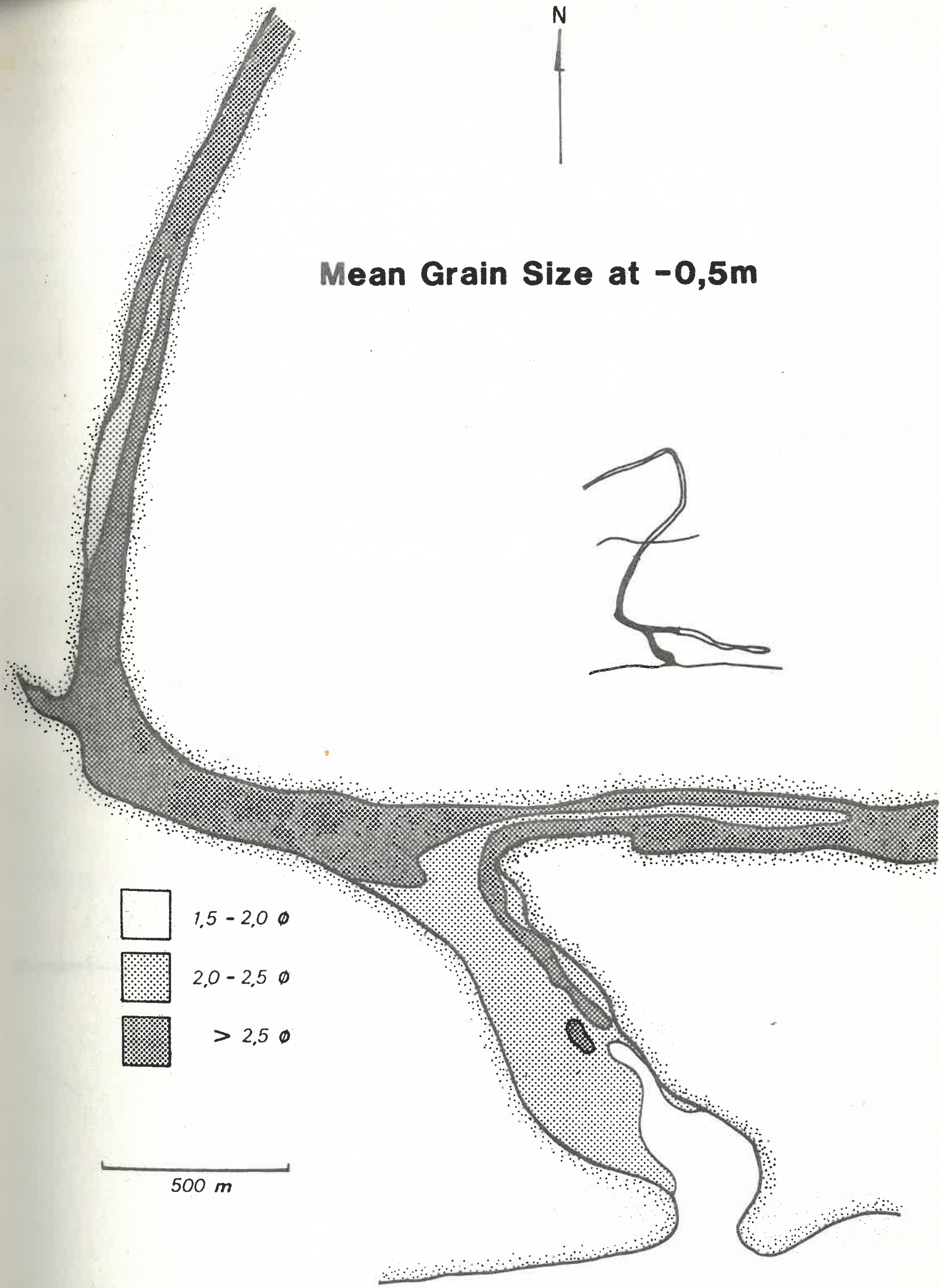


FIG 3.2B

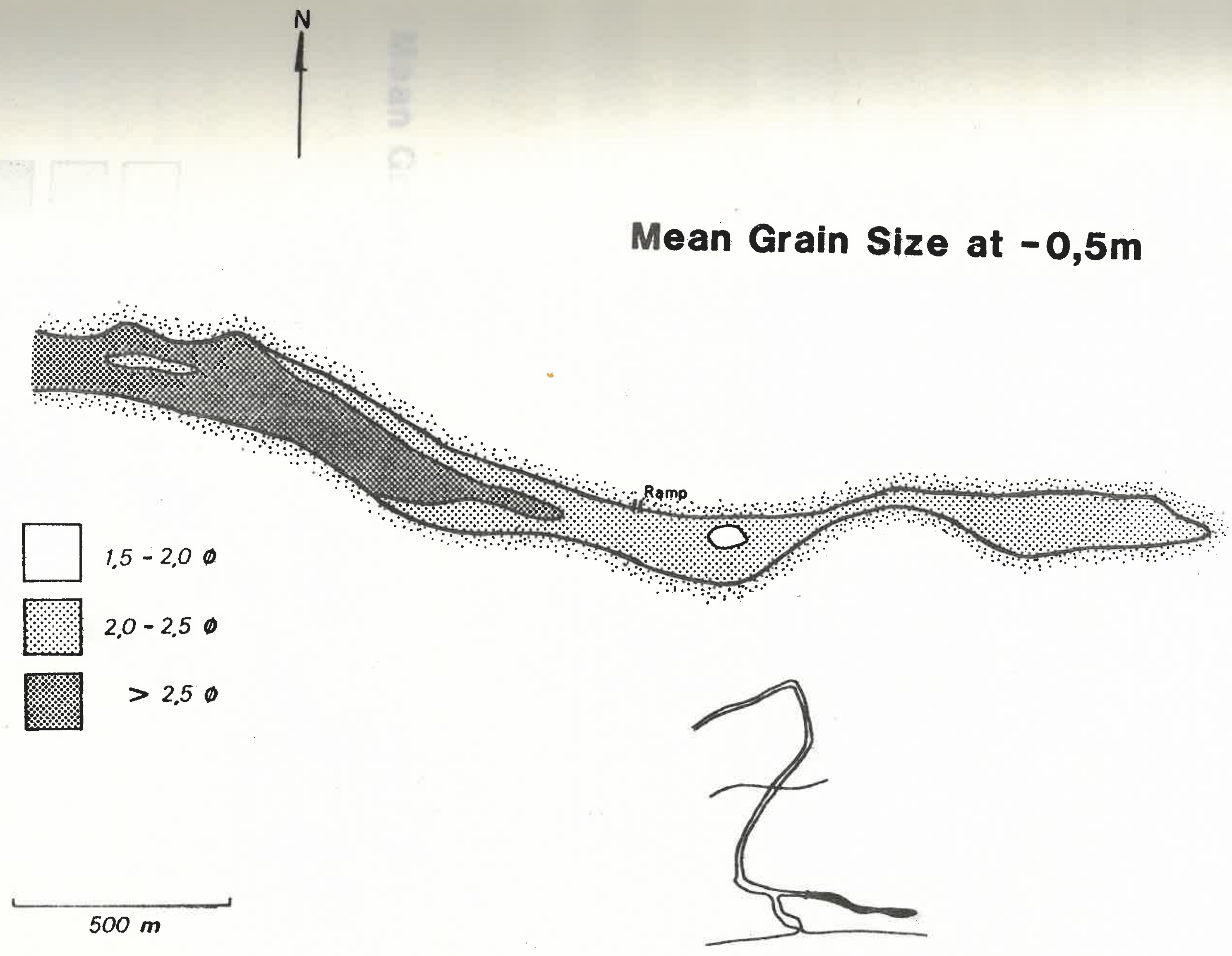


FIG 3.2B CONT

Mean Grain Size at - 0,5m

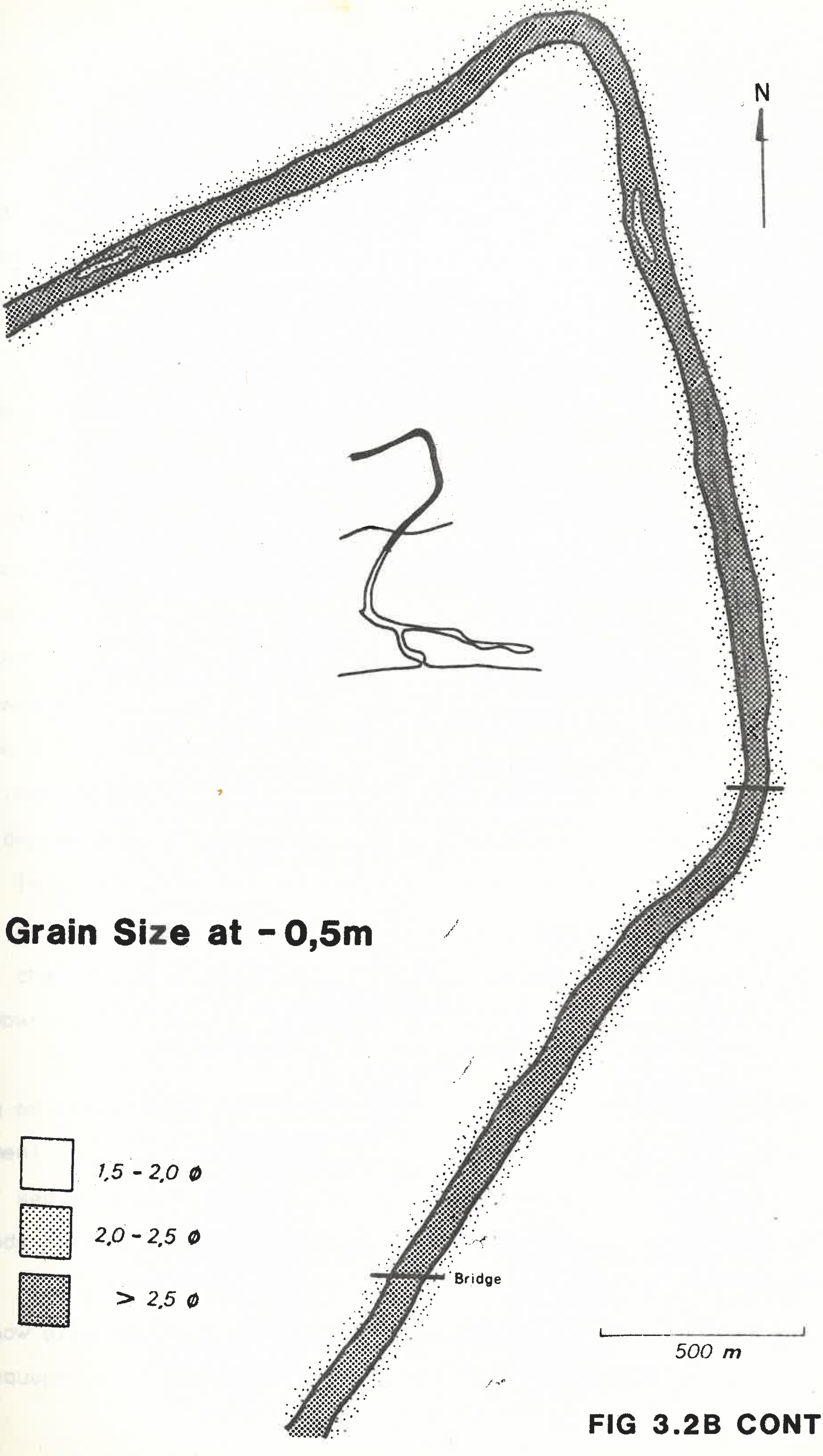


FIG 3.2B CONT

The tongue probably originates from fluvial sand which was initially deposited in the abandoned channel and subsequently transported to the present ebb channel during ebbing tides. This phenomenon has no special significance.

3.3 Mud distribution (fig. 3.3 a and b)

Clastic mud in the estuary originates largely in the catchment. The mud content in the surface sediment increases up-estuary from the inlet for about 3 km but decreases farther up-estuary. This probably results from flocculation of the freshwater mud suspension when it comes into contact with salty estuarine water. Floccules form by electrostatic attraction and settle faster than individual mud particles. This causes an increased rate of mud deposition in the area where fresh water and saline waters mix. This depositional pattern of mud also occurs in the Great Fish estuary (Reddering and Esterhuysen, 1982). The abandoned inlet channel has a relatively high surface mud content as it is a comparatively quiet water area where mud readily accumulates.

Being an essentially quiet water process, mud deposition at the sediment surface causes an upward increase of mud content of the upper sediment layers (compare fig. 3.3 a with b) during the periods between freshwater floods.

Mud now present below the bed surface was probably introduced subsequent to sand accumulation and the mud could have entered

Surface Distribution of Mud

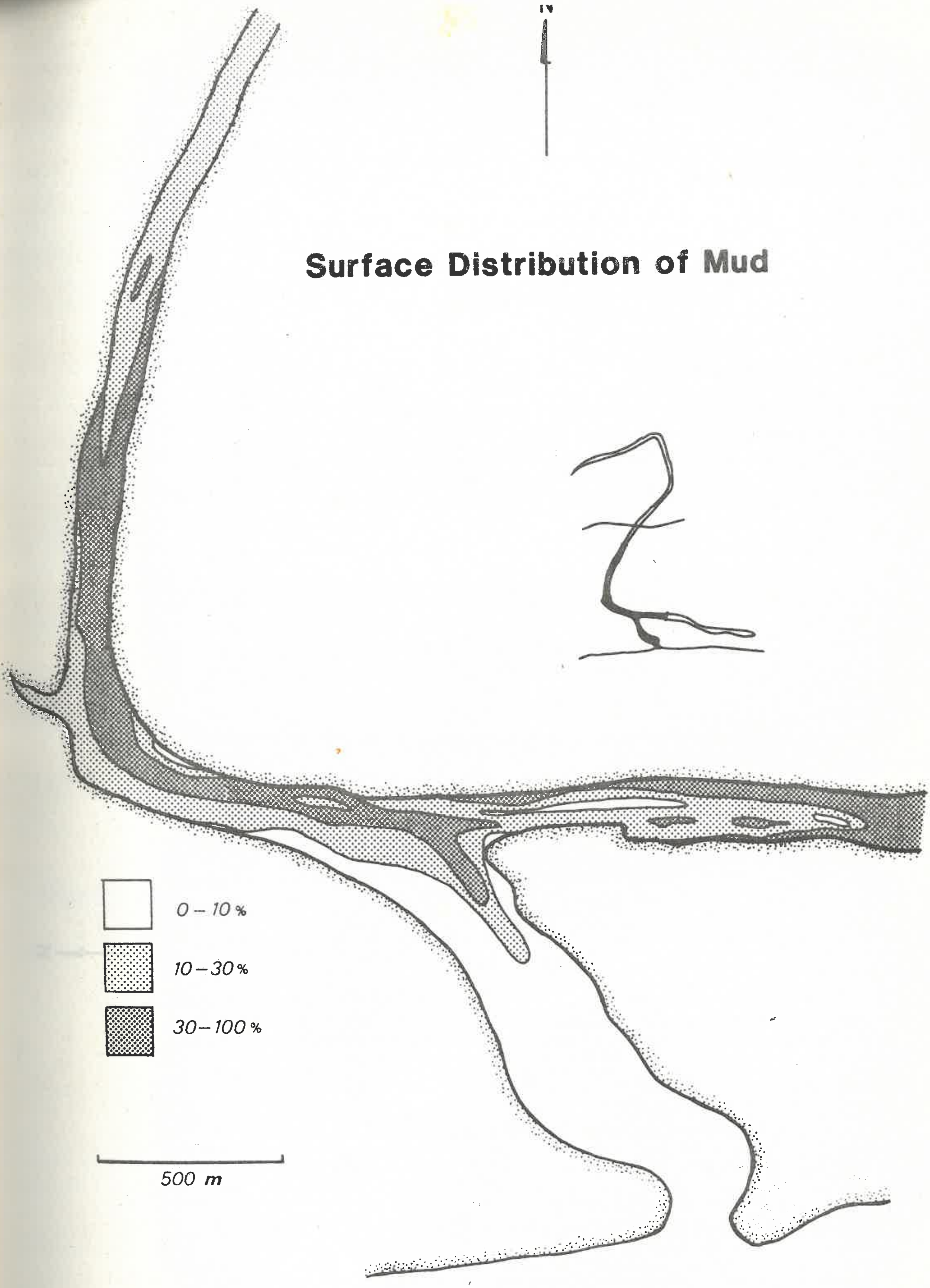


FIG 3.3A

Surface Distribution of Mud

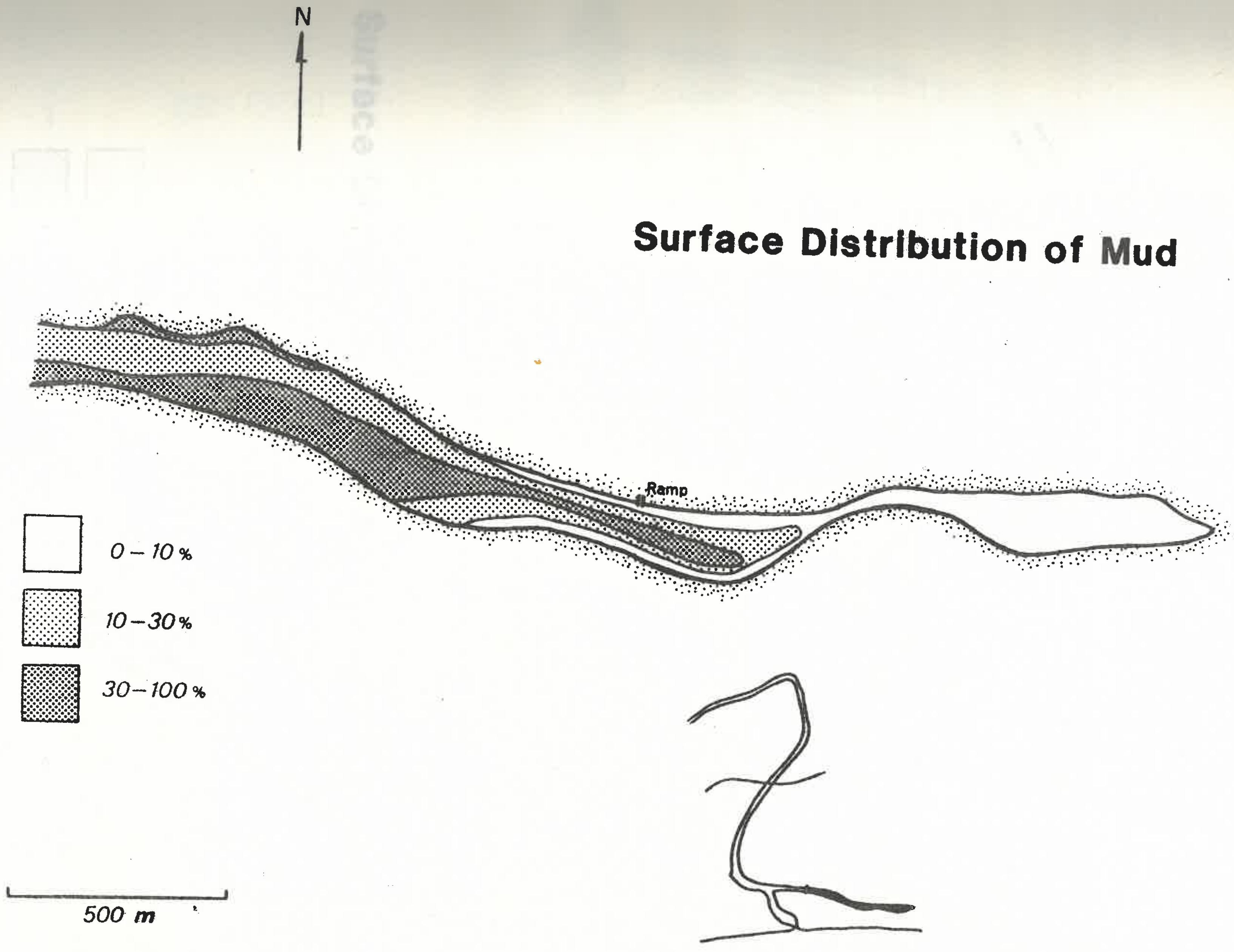


FIG 3.3A CONT

Surface Distribution of Mud

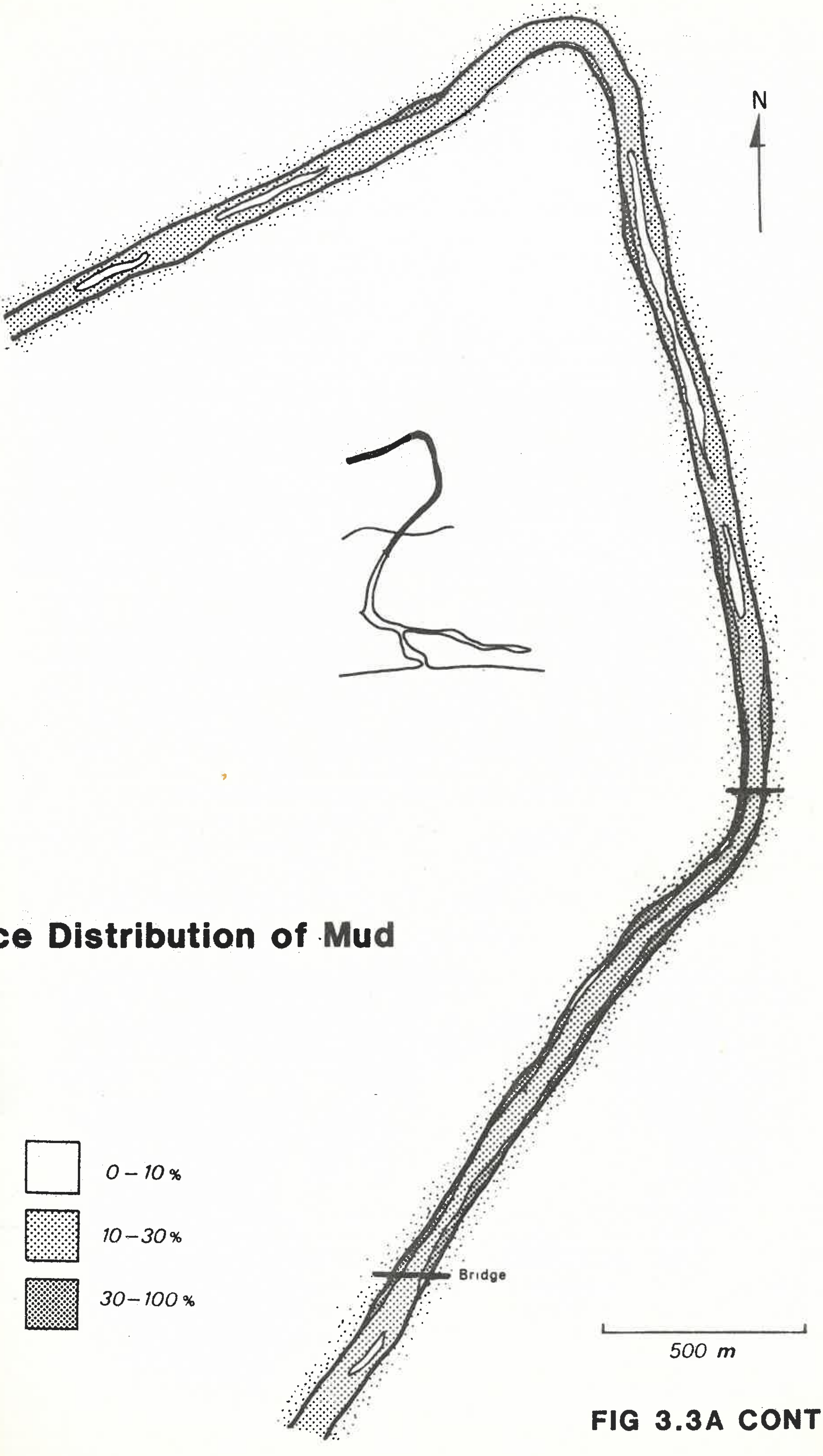


FIG 3.3A CONT

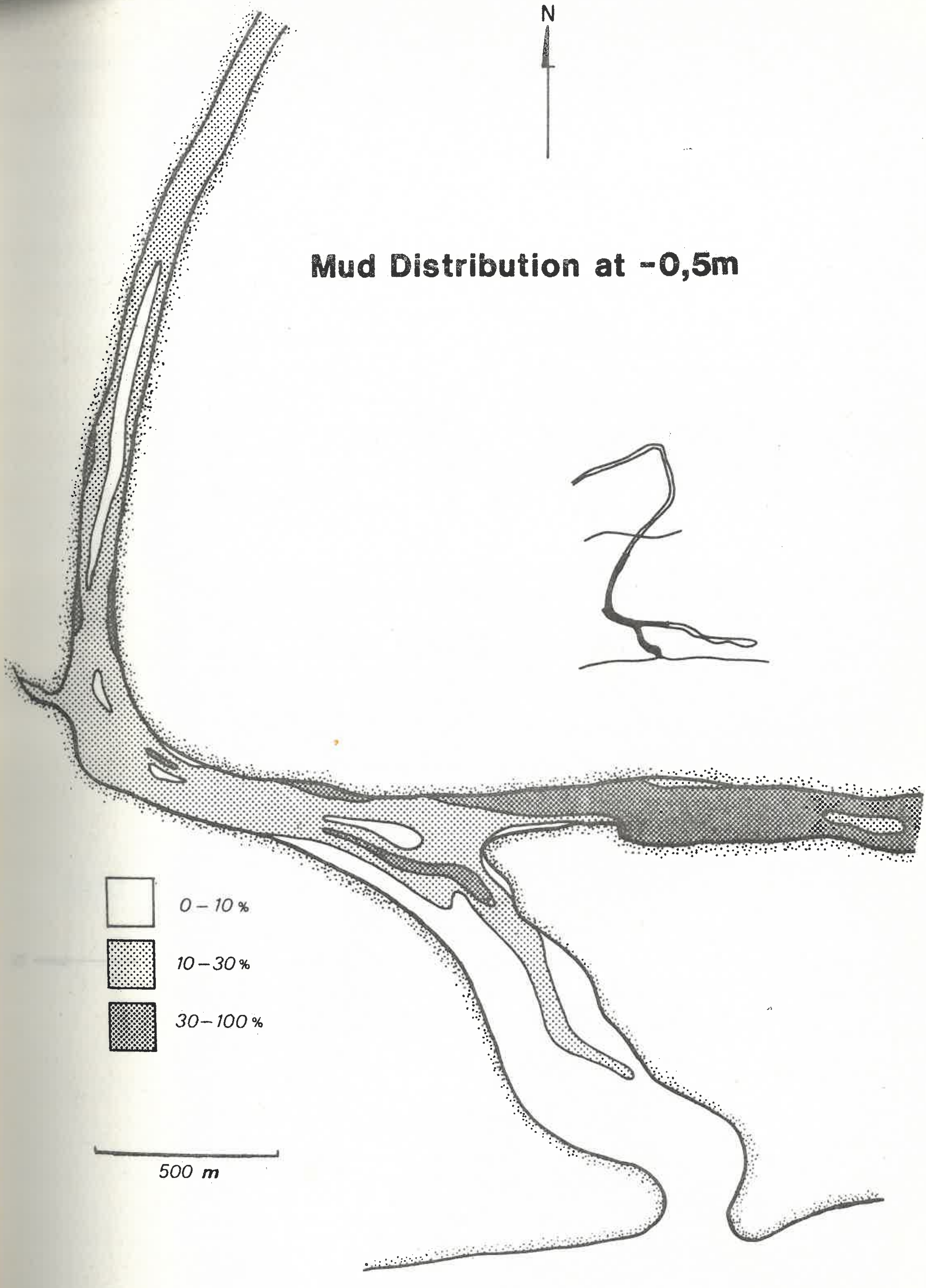


FIG 3.3B

Mud Distribution at – 0,5m

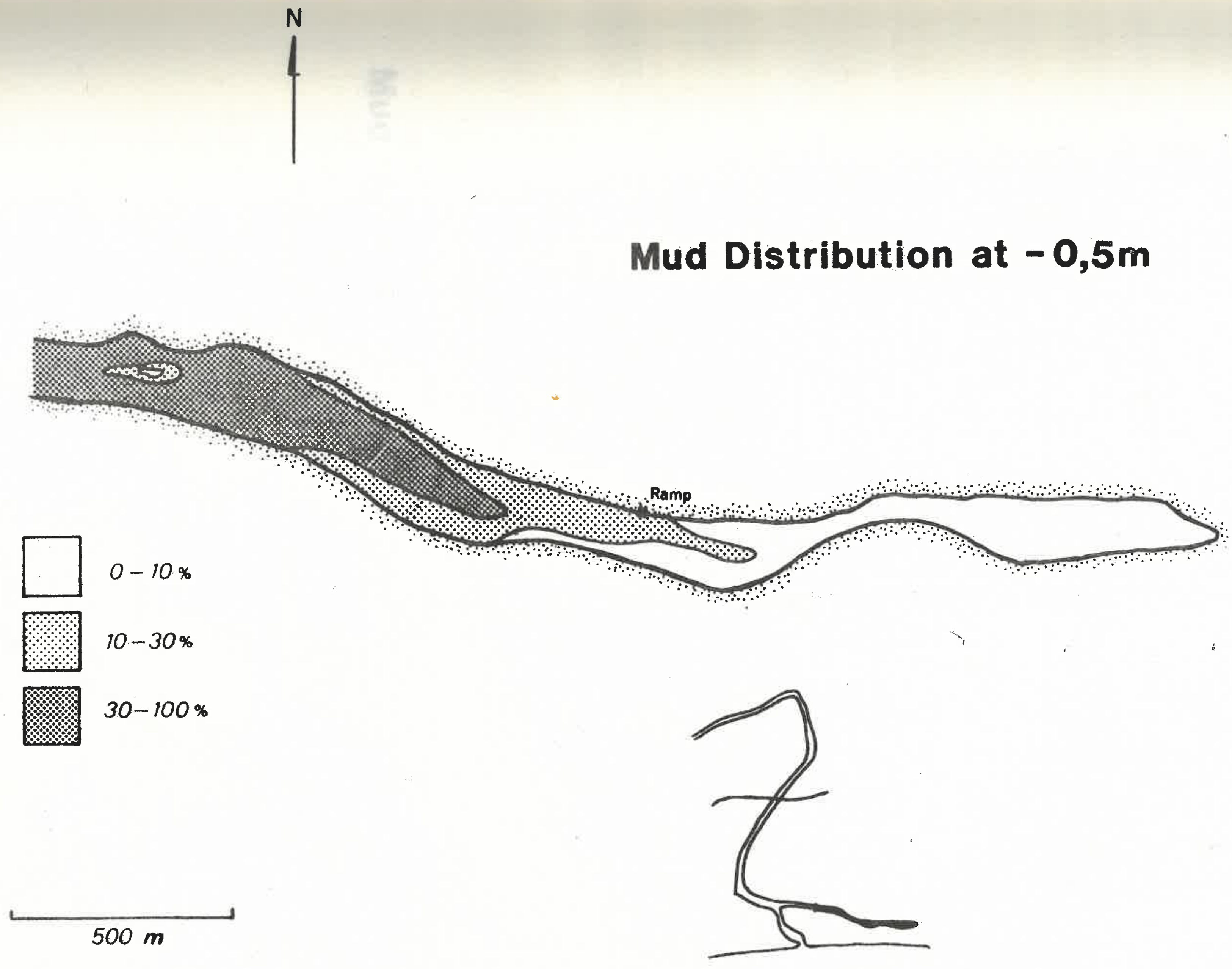
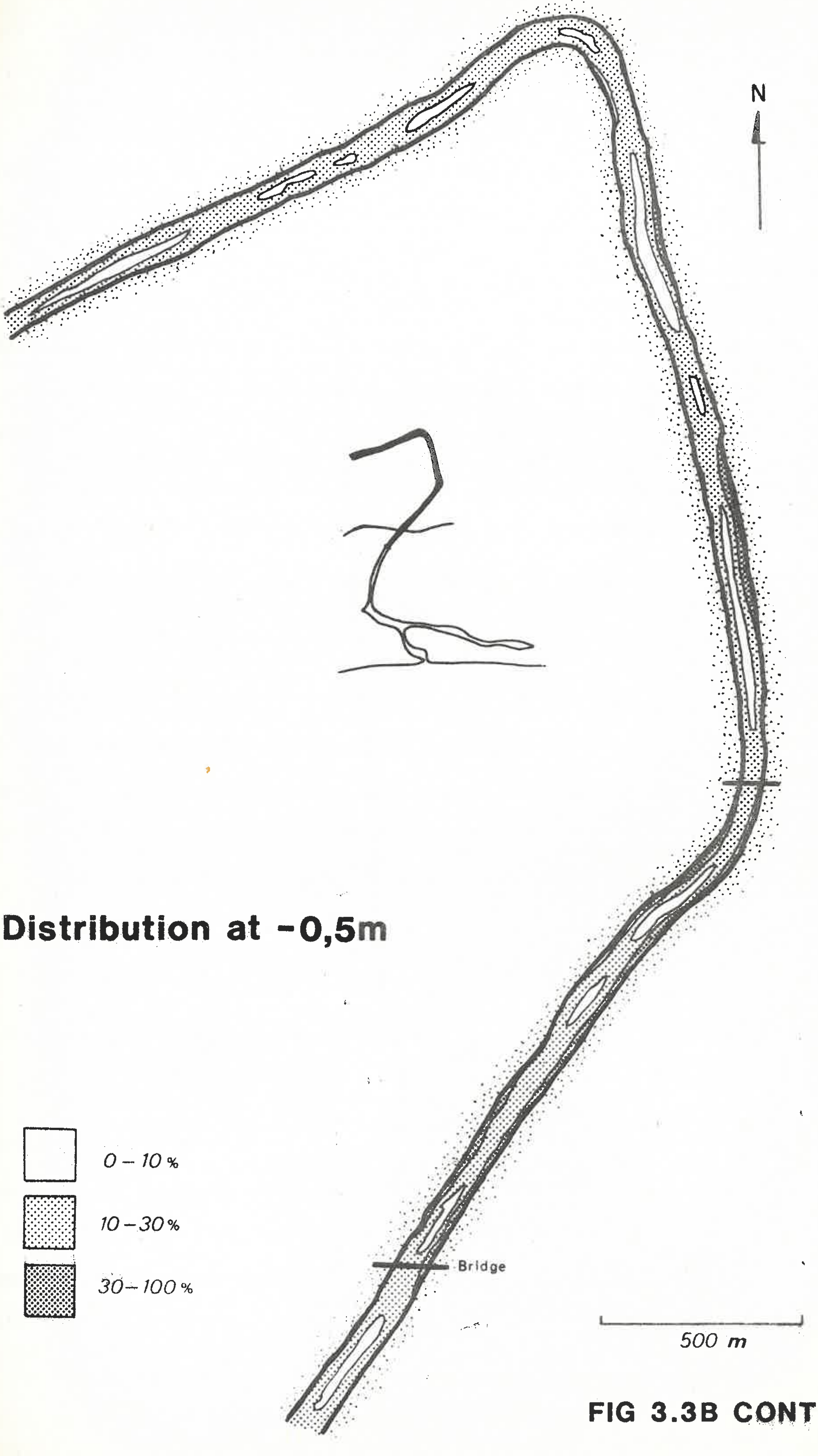


FIG 3.3B CONT



Mud Distribution at -0,5m

FIG 3.3B CONT

the sand interstices by at least two mechanisms. Firstly, it could have filtered into the sediment interstices under the combined influence of gravity and tidal ground water flow. The second possible mechanism for mud burial is by bioturbation. Burrowing organisms of various sizes disturb the sediment and in the process some surface mud is inevitably buried in the upper sediment column.

The high mud content of the sediment causes the channel banks to be cohesive. The prevailing tidal current is unable to erode these banks and as a result the intertidal areas are very narrow. Such narrow intertidal areas are also evident in the muddy Sundays (Reddering and Esterhuysen, 1981) and Great Fish (Reddering and Esterhuysen, 1982) estuaries. By contrast, mud-depleted estuaries such as the Kromme estuary (Reddering and Esterhuysen, 1983) and the Keurbooms estuary (Reddering, 1981; Rust and Reddering, 1983), generally have well developed intertidal flats.

3.4 Distribution of carbonate fragments and organic material

Carbonate components in the estuary are almost exclusively of marine origin. Carbonate is practically absent in the fluvial sand that enters at the head of the estuary. Possible limestone sources in the catchment area are the Pre-Cape Kaan Limestone Formation near Patensie and calcrete associated with the Karoo dolerite. Carbonate fragments are practically restricted to areas where marine sand enters the estuary through the inlet and by barrier overwash. Carbonate also enters from the coastal dune field. The original source of this windblown beach sand is also marine.

Distribution of carbonate (APPENDIX I) is limited to the inlet area and the abandoned inlet channel. At sample line 6 (fig. 3.1) carbonate is restricted to the western channel edge where sand is deposited by wind action. The carbonate content varies from about 30 percent at the inlet to zero in mid-channel at line 6. In the abandoned inlet channel carbonate material is concentrated on the channel floor and on the far barrier-ward shore of the channel. The channel floor carbonate is concentrated in lag deposits, particularly near the confluence with the main channel. Sand with a high carbonate content on the barrier-ward channel edge was deposited during barrier overwash and by wind action. Carbonate content is highest at the eastern end of the channel where these processes are most effective, owing to low relief on the barrier surface.

The organic content of the sediments in the Gamtoos estuary is generally low (APPENDIX I). The upper estuary is particularly depleted with respect to organic material, whereas the abandoned inlet channel has higher than average concentrations. Unlike the Great Fish estuary (Reddering and Esterhuysen, 1982) the organic material does not follow the depositional trend of mud. This indicates that the water column of the Gamtoos estuary has an inherently low content of fine-grained suspended organic material.

3.5 Sediment source (fig. 3.4)

The source of the sediment in the lower estuary near the inlet is marine (section 3.1) and sand enters the estuary by tidal currents, wind action and barrier overwash. Up-estuary of line 6 (fig 3.1) the sediment is fluvial in origin. Carbonate material in the estuary is marine (section 3.4) whereas the mud is fluvial. Both the catchment area and the sea introduce quartz sand into the estuary.

The marine sand which enters near the inlet consists of two components: wind-blown and tidally transported sand. Both components originate on the adjacent beach or in the shallow surf zone. It is consequently difficult to tell these apart unless the grain size parameters are distinctly different.

The inlet area is very dynamic and as a result the sediment distribution pattern there (fig. 3.4) changes continually.

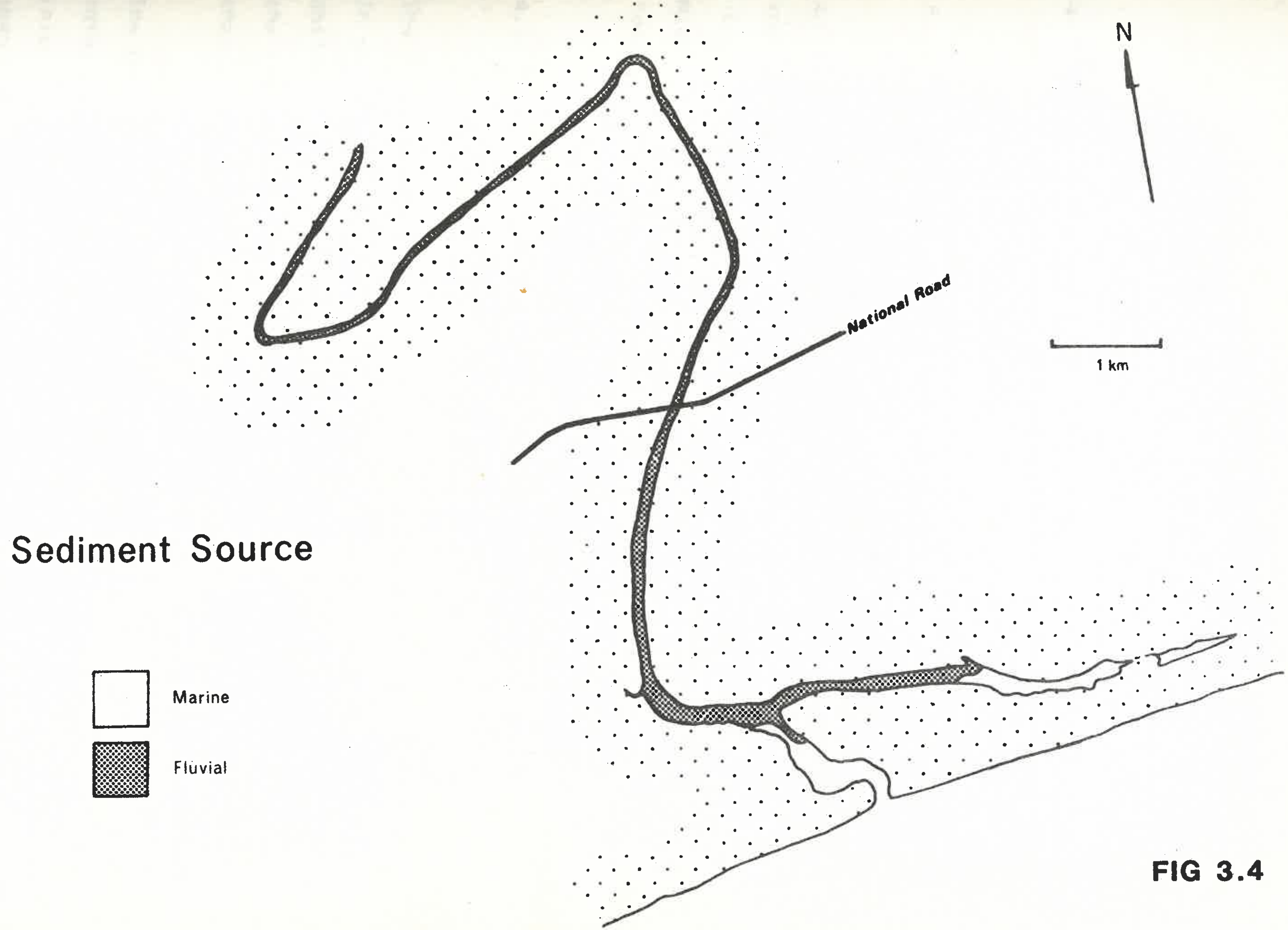


FIG 3.4

4. AERIAL PHOTOGRAPH INTERPRETATION

4.1 Introduction

Aerial photographs taken between 1960 and 1978 (fig. 4.1) indicate two aspects of the behaviour of the Gamtoos estuary: the inlet area has undergone many recent changes and the upper and middle estuary channel has meandered, leaving abandoned channel remnants on its floodplain.

4.2 Tidal inlet behaviour (fig. 4.1)

The inlet is very mobile and has a tendency to migrate eastward. In earlier aerial photographs (1960 to 1969) the inlet approach channel was parallel to the coast and the inlet channel entered the sea about 3 km east of the 1978 position. The approach channel was separated from the sea by a 3 km long sand barrier.

The photograph of September, 1960 (fig. 4.1 a) shows a blocked inlet with no free tidal access to the sea. By August, 1961 the inlet was open again and had migrated farther eastward. In May, 1969 the inlet was also open and had migrated even farther. A freshwater flood in August, 1971 (fig. 4.1 d) breached the

Inlet Configuration

SEPTEMBER 1960

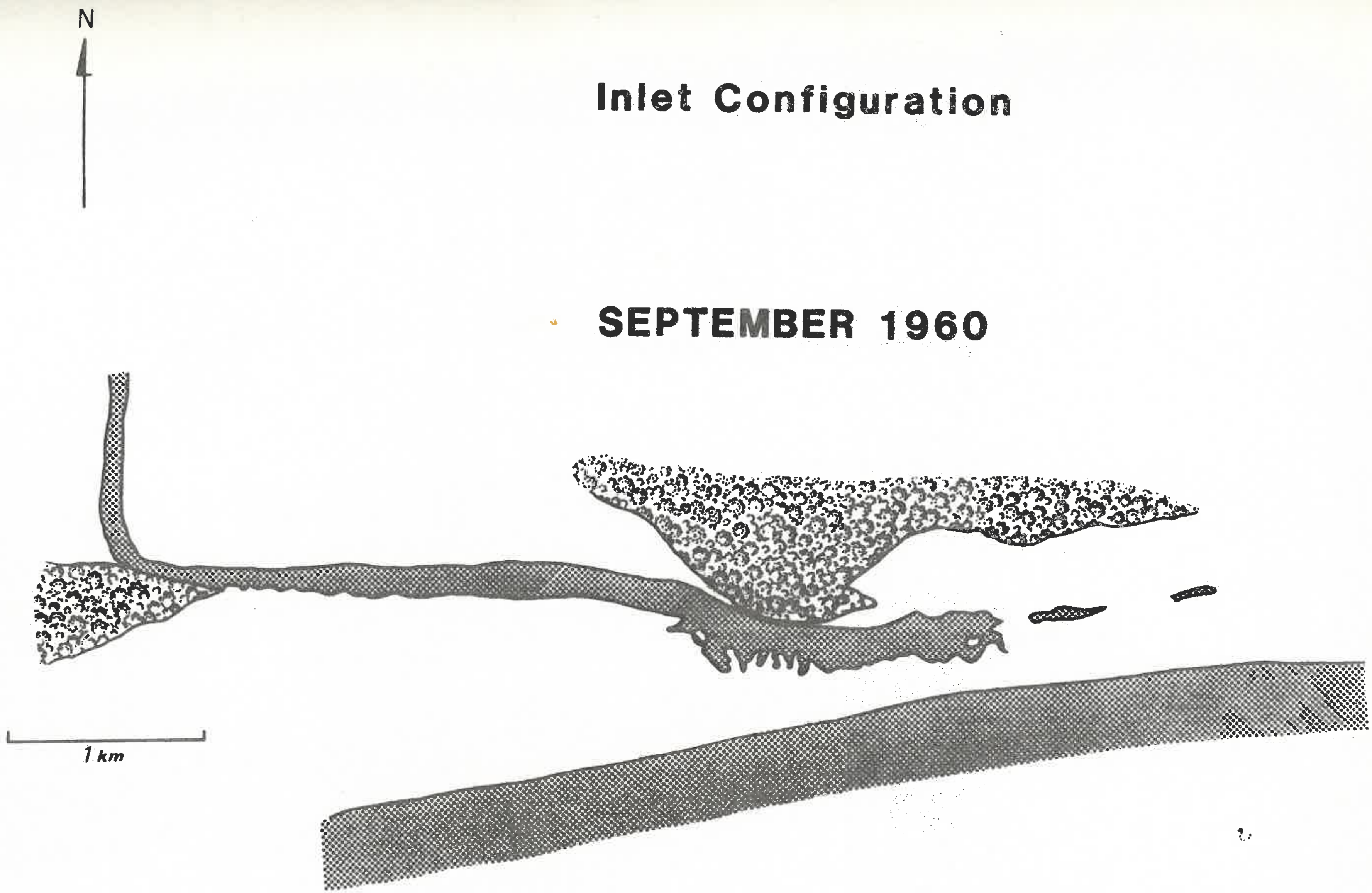


FIG 4.1A

Inlet Configuration

AUGUST 1961

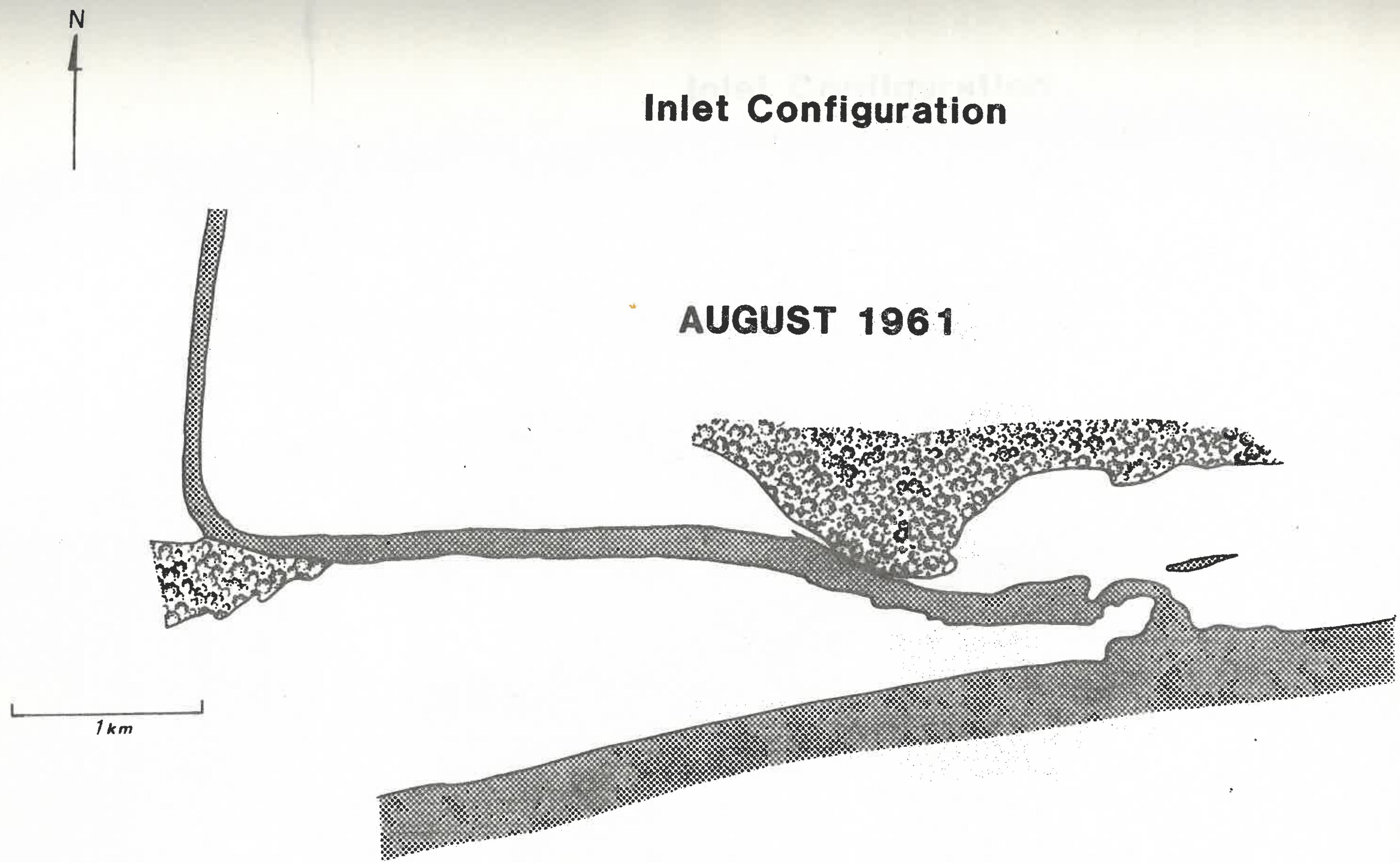


FIG 4.1B

Inlet Configuration

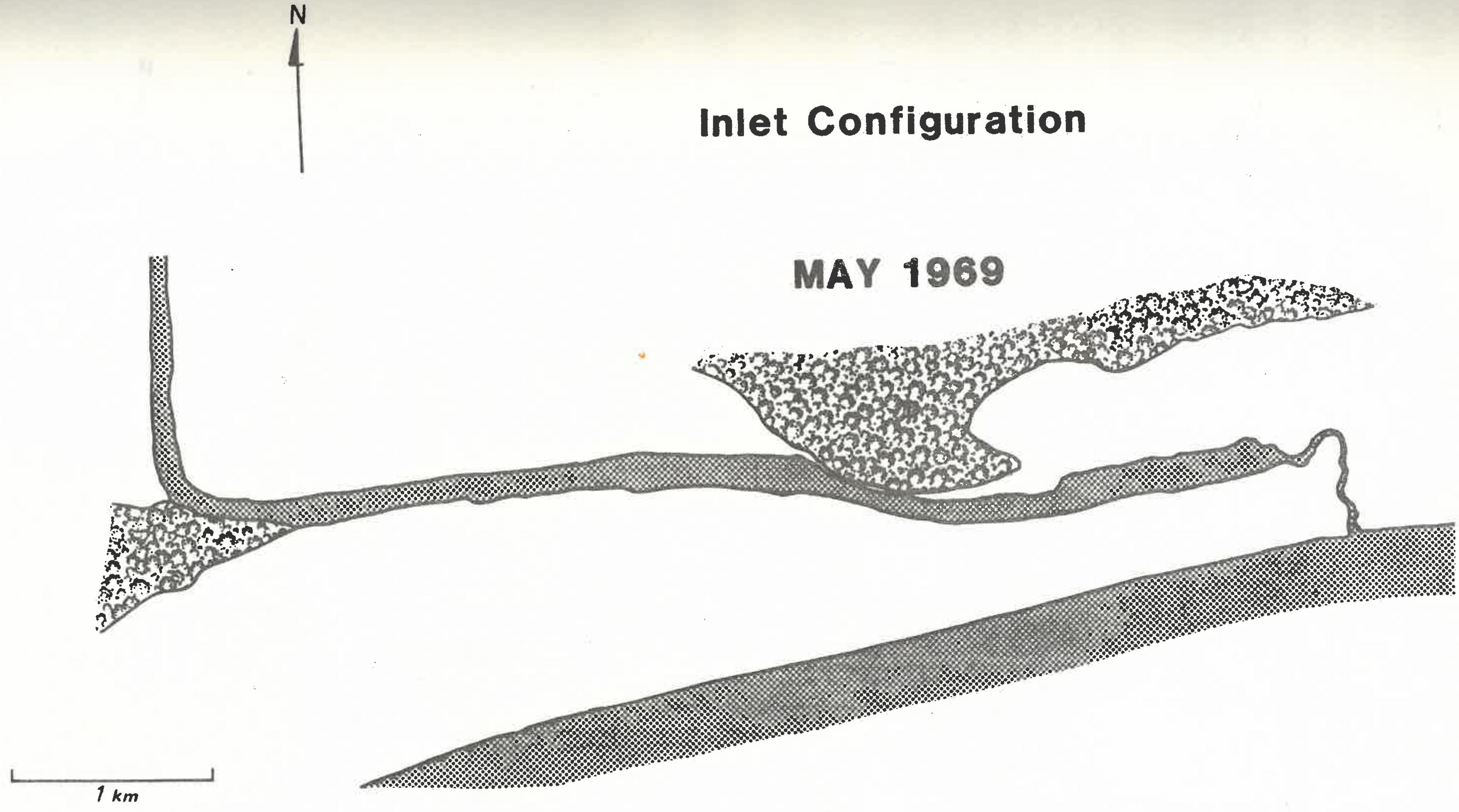


FIG 4.1C

Inlet Configuration

(After major flood of August 1971)

NOVEMBER 1971

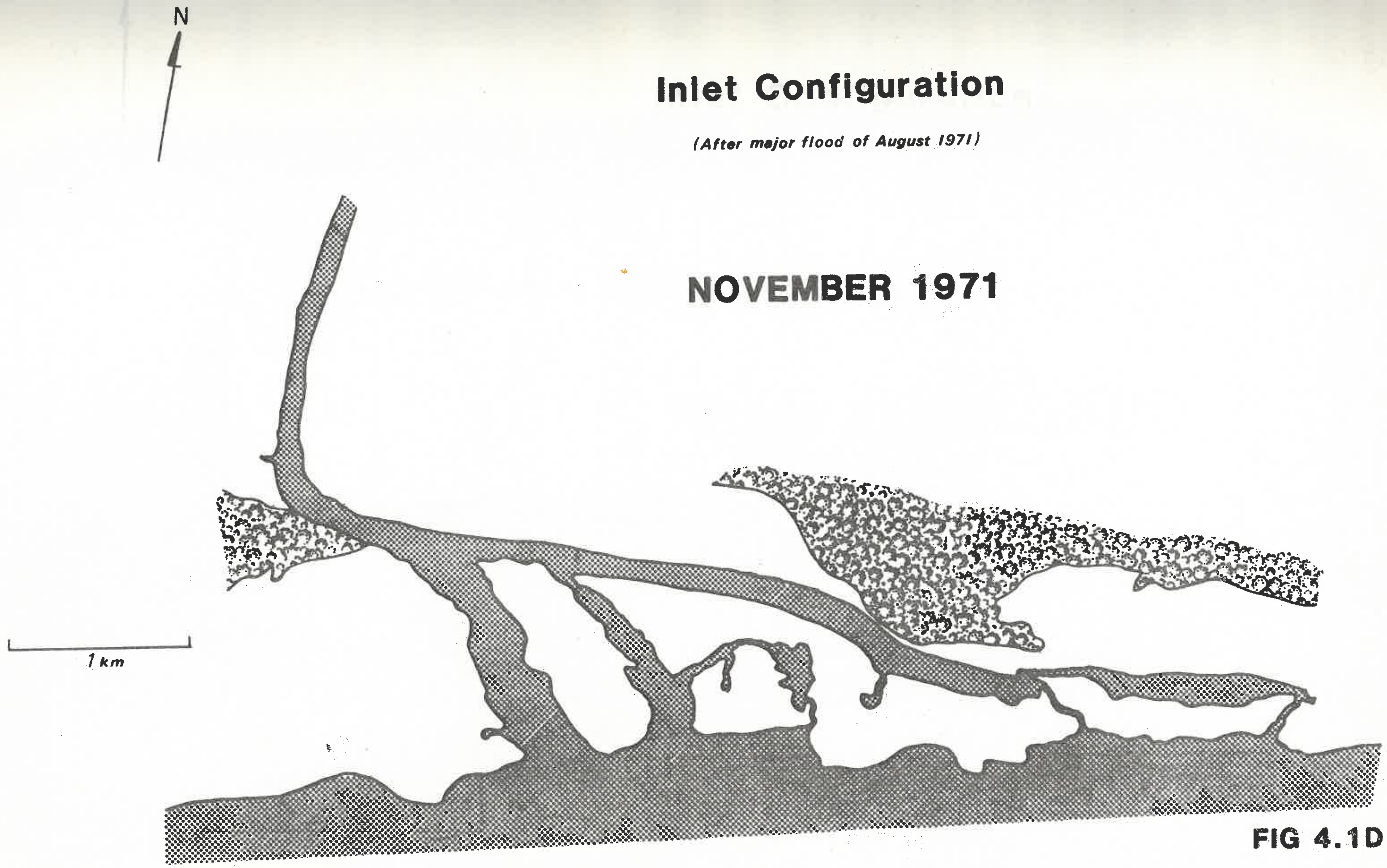


FIG 4.1D

Inlet Configuration

MAY 1978

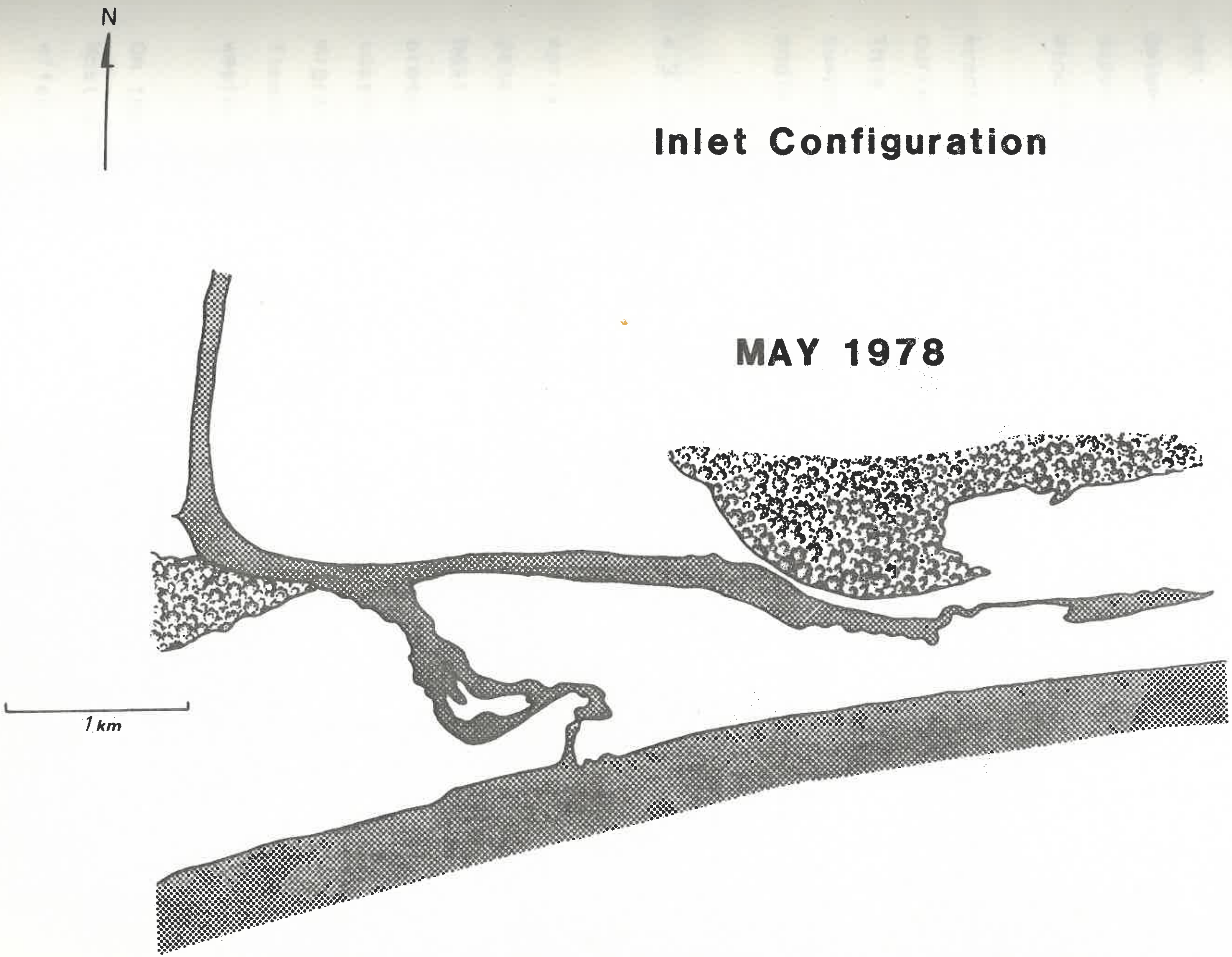


FIG 4.1E

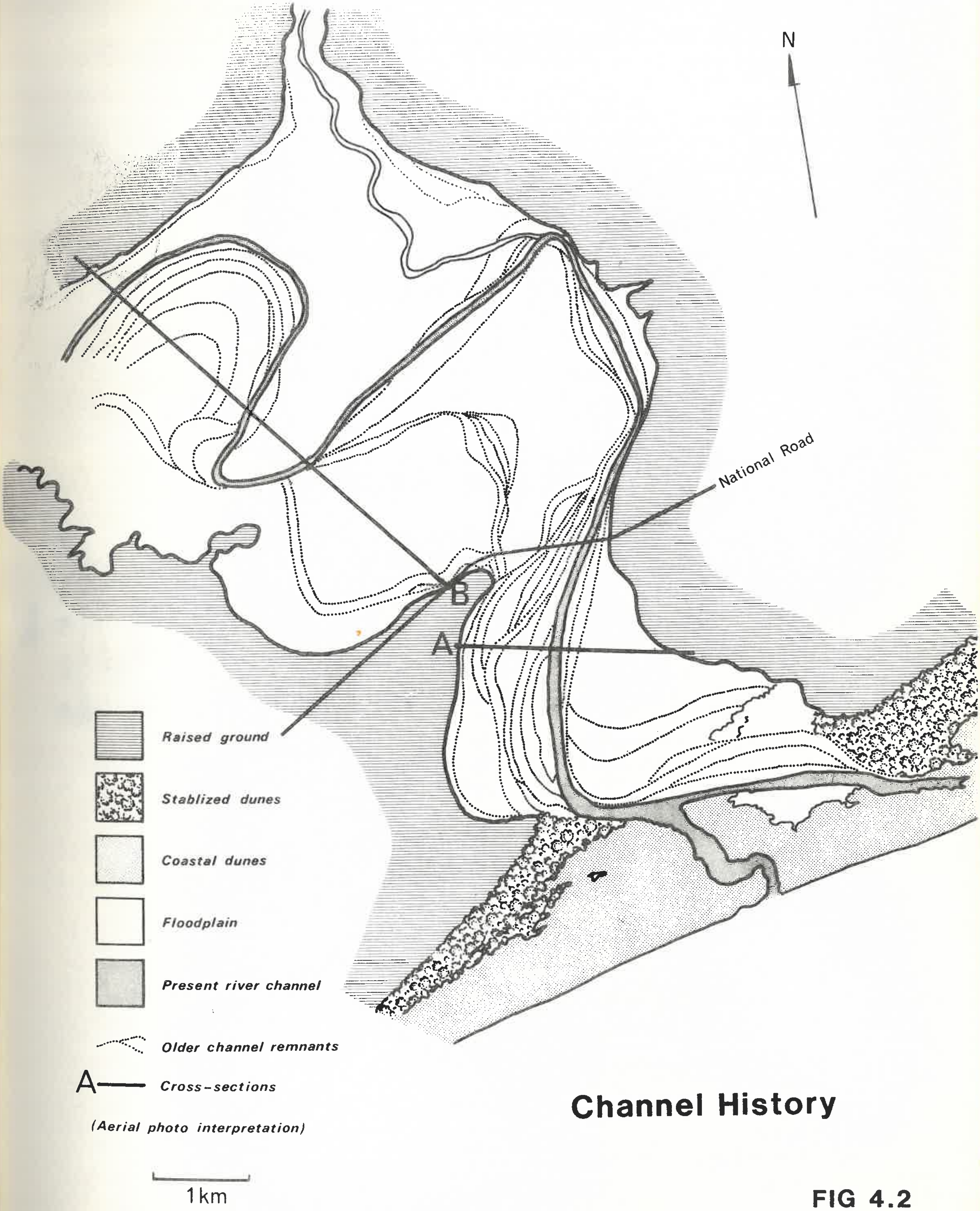
barrier in several places. By May, 1978 all inlet channels, except the most westward, had closed up. This western channel had resumed its eastward migration and had moved about 800 m. Between 1971 and 1978 storm waves washed across the barrier, depositing sand into the abandoned channel behind the barrier. Wind blown sand also entered there.

According to Heydorn and Grindley (1981) the prevailing longshore current as deduced from aerial photographs is from east to west. This is confirmed in this study by the dispersal pattern of suspended sediment plumes emanating from the inlet and by the angle between wave fronts and the beach.

4.3 Channel remnants on the floodplain (fig. 4.2)

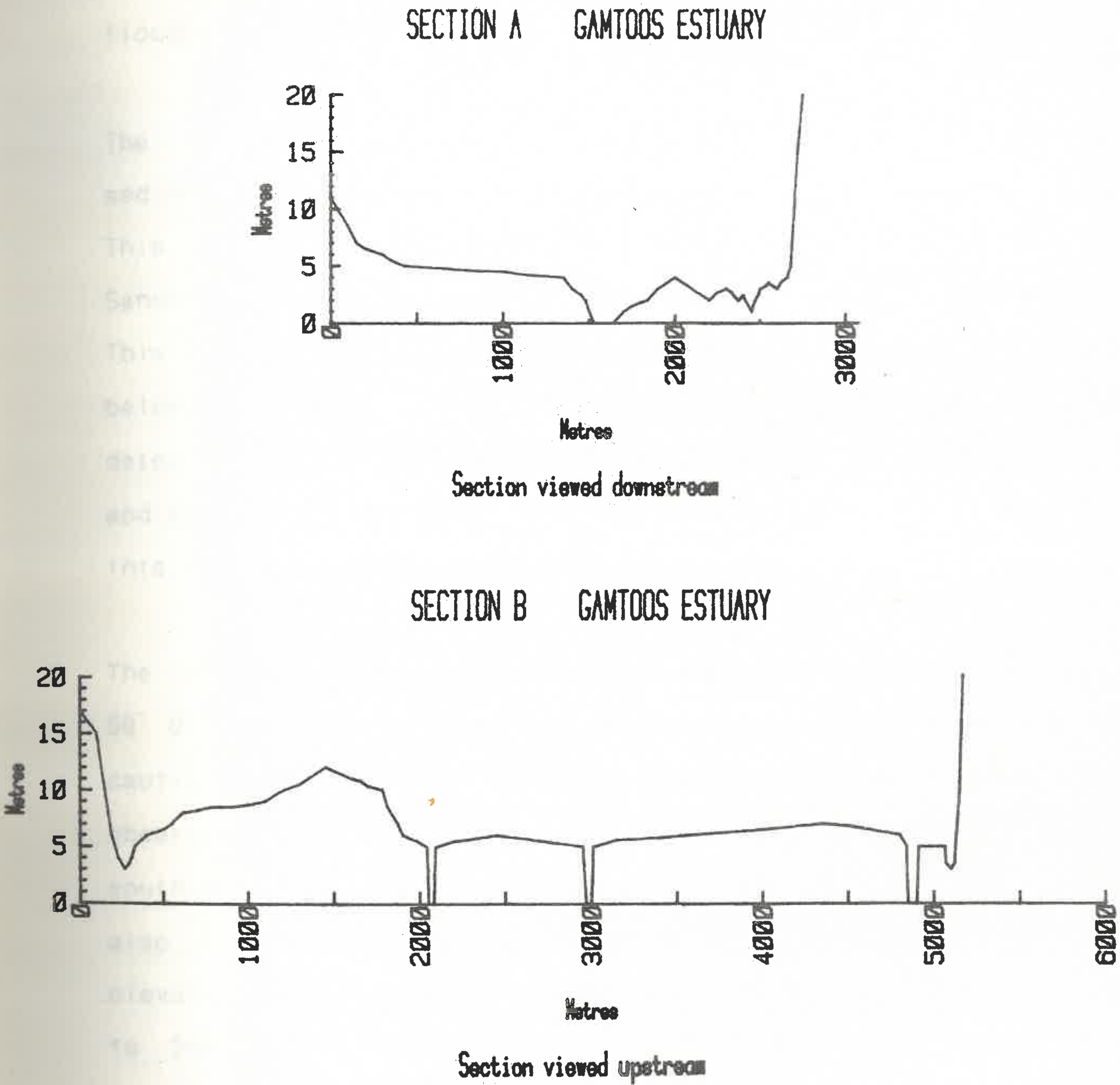
Aerial photographs clearly indicate several relict channel generations on the lower Gamtoos floodplain (fig. 4.2). The best evidence of the meandering behaviour of the channel is preserved on the western bank between the national road and the coastal dunes farther south. The remnant channels seem to have migrated eastward during a drop in sea level so that the floodplain is terraced with older, higher channel remnants on the western floodplain edge (fig. 4.3; section A).

On the rest of the floodplain the relationships are more complex. Most evidence of terraces has been obliterated by the combined effects of freshwater floods that regularly inundate the



Channel History

FIG 4.2



Sections across the lower Gamtoos floodplain
(positions on Fig. 4.2)

FIG 4.3

floodplain, and by ploughing of the fields.

The ages of these channel remnants are not known but underlying sediment, excavated during bridge construction, has been dated. This could be used to indicate a maximum age for the channels. Sandstone bedrock lies 47 m below river level (Davies,1972). This is respectively overlain by sand, and a boulder bed at 32 m below river level. Wood fragments collected 9 m below MSL were dated at 1170 +- 50 B.P. Shell fragments of Turritella capensis and Crassostrea sp. were also obtained from -9 m. The sand is intercalated with mud layers at higher levels.

The information indicates the terraces to be younger than 1170 +- 50 B.P.. This information must, however, be regarded with some caution because this age is inconsistent with other field observations. Beach rock outcrops underlying the dunes to the south of the bridge are exposed at about 3m above MSL. This is also the approximate elevation of the younger channels. This elevation is consistent with a high sea level, dating about 6000 to 2000 years B.P. along the South African coast (Flemming, 1977). The terraces may thus have an age of up to 6000 years B.P. but could be younger than 1170 years B.P. The weight of the evidence favours the older age.

The age of the prominent terrace at an elevation of 6 m (fig. 4.3) is in the order of 30 000 years B.P. (Davies, 1972). An even older terrace, 18 m above MSL, is cut into the surrounding hillside (Davies, 1972).

5. TIDAL INLET AND COASTAL DUNE FIELD CONFIGURATION

5.1 Introduction

The coastal dune field, longshore currents, freshwater floods and tidal action all interact to shape the inlet and its environs into an "equilibrium outline". Short term variations, such as freshwater floods, can temporarily change this state but when left to equilibrate, the equilibrium outline returns to "normal".

5.2 Tidal inlet migration

The inlet clearly migrates in the opposite direction to that of the prevailing longshore current. Such migration, although rare, is not unusual. Some inlets along the Natal coast also have this tendency (G.A.W. Fromme, pers. comm.) as does the Keurbooms inlet at Plettenberg Bay (Reddering, 1981; 1983). The migration mechanism is generally complex (Reddering, 1983). In the case of the Gamtoos, inlet migration is almost certainly aided by the westward movement of the coastal dune field (Heydorn and Grindley, 1981).

Inlet migration takes place by erosion of one inlet bank while the opposite margin grows by lateral accretion. Bank erosion generally takes place during the ebbing tide. Accretion at the opposite bank must take place both above and below the high water mark before the inlet can migrate. For this to happen several conditions must be met (Meistrell, 1966; Reddering, 1983): a shallow subtidal sand bar must be present adjacent to the growing margin; a subaerial headland must be present; and appropriate wave action is required. Details of the accretory process on the growing inlet margin of the Gamtoos are not known.

5.3 Freshwater floods

Freshwater floods passing through the inlet have considerably higher discharge than that produced by normal tidal exchange. The high inertia of a flood tends to straighten a pre-existing meandering channel. The jet of flood water emerging from the middle estuary is directed at the westernmost edge of the barrier. The current has considerable eroding power and it tends to breach a channel straight to sea. If the barrier is breached the eastern channel section is abandoned by the main current. When the flood subsides the old and new inlets will compete for dominance, but the one scoured by the freshwater flood will generally be deeper and more efficient. The old inlet will usually be abandoned by tidal currents; the inlet is then soon blocked by sand delivered through wave action (next section).

5.4 Tidal action versus wave action; tidal inlet stability

The term "inlet stability" refers to whether an inlet remains in one stable position and is suitable for navigation by ships (Bruun, 1978). South African inlets are mostly unstable. In concept it is useful to consider the factors which influence inlet stability.

Tidal currents usually flow sufficiently vigorously through an inlet in order to scour sediment from the inlet. Under the influence of tidal currents alone, most inlets would be stable. On the wave-dominated South African coast waves, longshore currents and the prevailing tide in an inlet interact to cause a far more complex situation than in a simple tide-dominated system.

Wave action has three important influences on an inlet. It generates longshore currents when wave fronts obliquely approach a beach or when there is a longshore variation in breaker height (Komar, 1975). Secondly, surf can cause sediment to be entrained in the surf zone. The longshore current is normally incapable of entraining sand as its velocity is too low, but sand kept in suspension by surf turbulence can easily be transported by the longshore current. Where this current flows past an inlet, part of its sand load can be deposited in the inlet channel where wave turbulence is reduced. Wave oscillation reworks such sediment to form a shallow bar across the inlet in the surf zone. Longshore sediment transport can then largely by-pass the inlet along this bar (Bruun, 1978). Thirdly, wave action can lead to blockage of an inlet. When tidal currents are too feeble to scour wave-deposited sand from the inlet, a bar will soon form across the inlet. This bar can be developed from landward migration of an existing bar in the surf zone or can result from longshore drift initiated spit growth. Without wave action such a bar cannot emerge above the water surface because flowing water cannot deposit sand at a level higher than its own. Sand transport by seawater to above high water level can thus only occur by the influence of waves. Wave action is consequently an integral part of inlet closure.

Stability of a tidal inlet depends on the balance between the respective effects of the tide and waves. The Gamtoos estuary is generally considered to have a permanent inlet; however the aerial photographs of September, 1960 (fig. 4.1 a) show a blocked inlet. Barrier overwash also blocked the approach channel behind the barrier and this probably contributed toward inlet closure by restricting tidal flow in the channel. The inlet could be closed again under conditions of reduced tidal exchange and increased wave action.

5.4.1 Significance of inlet behaviour

From a management view it is important to consider the possible effects of inlet closure. The dune ridge on the barrier is very active and the inlet depression in the barrier would rapidly be filled in by wind-deposited sand, should the inlet be blocked.

To breach a channel through the barrier, the water level in the estuary would have to rise to the level of the lowest dune depression. If this depression is high enough, the floodplain would be inundated before an inlet were breached. The floodplain is an intensively cultivated area and such flooding will destroy crops and cause damage to property.

Should the inlet be blocked, damage on the floodplain could be minimized. A subaerial channel could artificially be maintained on the barrier surface so that rising water would breach a channel to the sea. The level of the channel would have to be between about 0,5 m and 1,5 m above MSL.

5.5 The coastal dune field

The dune field to the west of the Gamtoos tidal inlet covers an area of about 2,5 km^2. Vegetated, stabilized dunes cover a further 0,5 km^2. Dune heights range between about 2 and 25 m. The dunes were clearly deposited by south-westerly and south-easterly winds. Interaction between the dunes causes an interference pattern whereby the subordinate south-easterly wind deposited dunes occupy the troughs between the dominant south-westerly wind deposited dunes. The angle between the crests is about 90 degrees giving rise to large "ladderback" dunes.

Dominant sand transport on this dune field is toward the north-east but north-westward transport by south-easterly winds also occurs. This causes sand to be deposited into the seaward end of the estuary. Freshwater floods periodically scour this sand from the estuary. A similar situation exists in the Sundays estuary (Reddering and Esterhuysen, 1981).

Other smaller drainage systems have had their estuaries obliterated by migratory dunes. Examples include blind rivers in the Bushmans River area, the coastal dunes between Sundays estuary and Woody Cape, and small streams behind the Gamtoos dune field. Flood water remains in the troughs of the Gamtoos dune field for weeks, slowly seeping through the dune sand, presumably towards the sea.

Dune migration probably aids eastward migration of the Gamtoos inlet (section 5.2). Aeolian sand is deposited on the western inlet margin whereas the eastern margin is eroded; in this way the inlet migrates eastward.

5.6 Inlet response to environmental factors - summary

The Gamtoos inlet migrates eastward under fairweather interplay of tides, waves and longshore currents. As tidal action is practically invariable, storm wave action will tend to bar the inlet. Storm waves occasionally wash across low-lying areas of the barrier to deposit sediment into the back-barrier approach channel. Eastward aeolian sand transport assists the inlet migration process. Conversely, freshwater floods tend to erode a channel through the barrier after flowing from the middle estuary.

6. FLOOD BEHAVIOUR OF THE LOWER ESTUARY

The flood during late July, 1983 made a useful final field excursion to the estuary impossible. It did however provide an opportunity to view flood effects from the air. A flight was chartered on 29th of July, two days after the main flood.

Oblique aerial photographs taken during the flight provide useful images of the flood results (figs. 6.1 to 6.6).

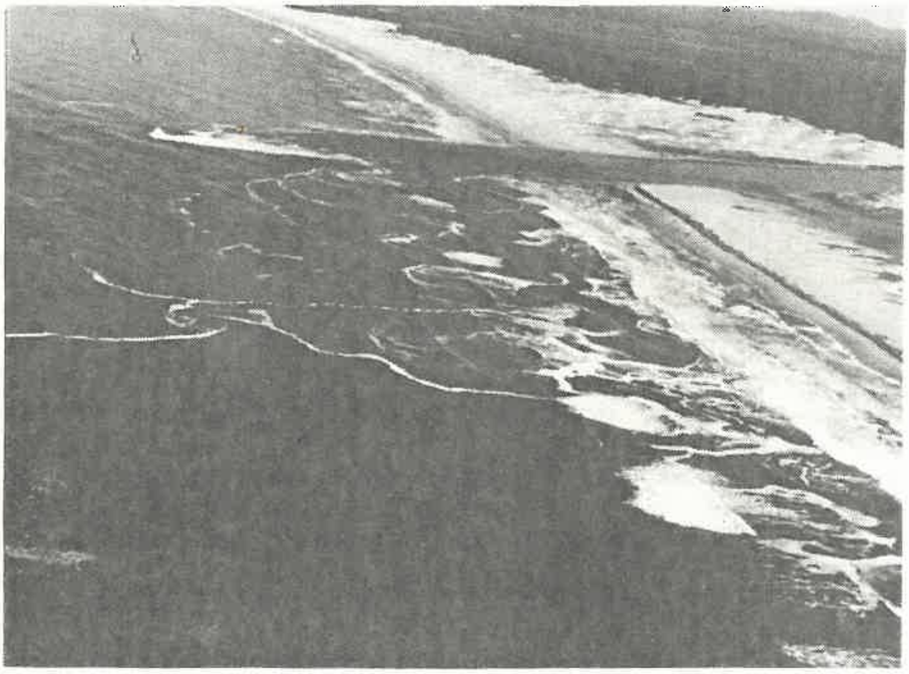


Fig. 6.1 The inlet viewed from the sea. The lighter coloured water is a plume of suspended sediment. The darker water is part of a less concentrated plume that stretched several kilometres across. Note the jet of flood water extending out to sea.

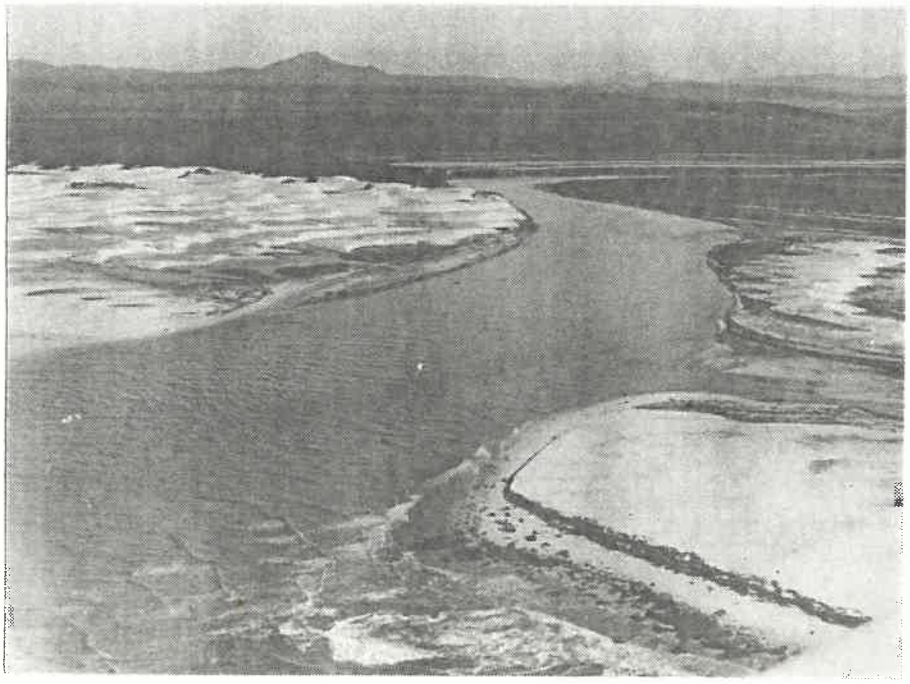


Fig. 6.2 Flood water flowing through the inlet along straight edges eroded through the dune field. The inlet was about 150 to 200 m wide at the time. Dune troughs to the left (west) are filled with water (section 5.5). The amount of debris on the beach gradually decreased toward the east.

Fig. 6.3 A seaward view of the inlet shows water-filled dune troughs, and the freshwater jet in the surf zone. The light-coloured patch in the background indicates the size of the plume.

Fig. 6.4 Water on the lower floodplain was concentrated in the abandoned river channels (section 4.3).

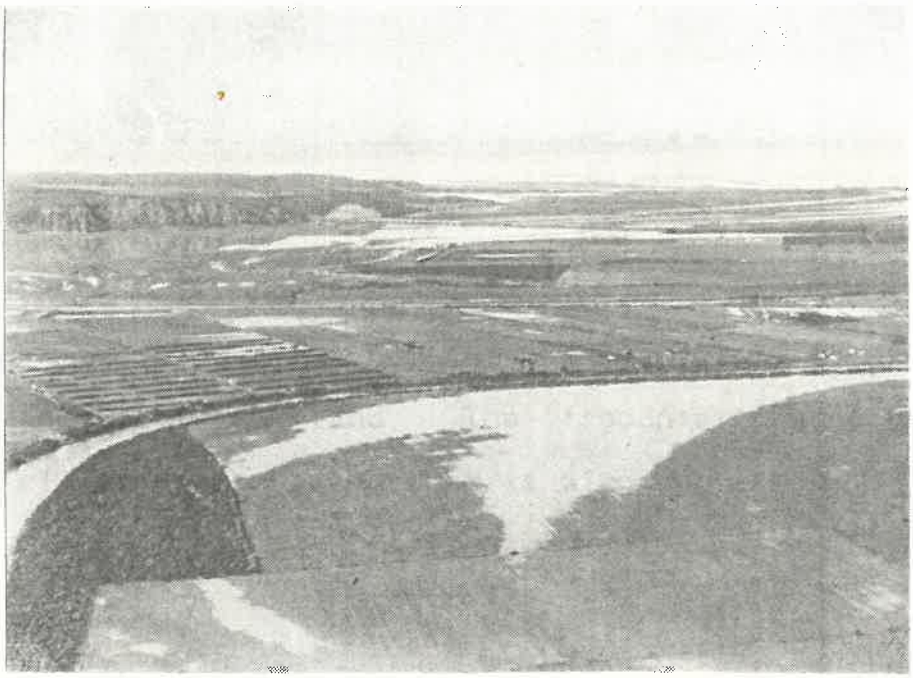


Fig. 6.5 Floodwater standing in an abandoned point bar depression. Note how ploughing tends to subdue the existing topography.

Fig. 6.6 The meandering course of Loeriespruit and partly submerged agricultural land. The floodplain adjacent to the sandstone cliffs in the background is also submerged.

7. CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

7.1 Environmental and recreational considerations

The Gamtoos estuary accumulates a considerable volume of sand in the periods between freshwater floods. This sediment originates from the coastal dune field to the west of the inlet and from the adjacent beach. Natural sediment removal during periodic freshwater floods efficiently clears accumulated sediment from the estuary. Ecologically undesirable sediment accumulation in the estuary is improbable if the present fluvial flood discharge regime continues unaffected.

The present shoaling, particularly in the abandoned inlet channel, is ecologically not undesirable. It is nevertheless recreationally unpopular because the shoals interfere with pleasure boating. Should recreational considerations warrant the removal of sediment from that part of the estuary, three aspects should be considered. (i) Cost would be the foremost concern as dredging is generally expensive. (ii) Spoil disposal requires planning and, (iii) such sediment removal will probably have to be repeated because shoaling is likely to continue. In the Gamtoos estuary shoaling is unpredictable because it is unfluenced by freshwater flooding which occurs at random intervals. As a result it is difficult to estimate how often dredging will have to be repeated and what sediment volume will have to be removed.

7.2 Suggestions for further study

The Gamtoos estuary has a dynamic sediment turnover. Details of the interaction between fluvial, marine and aeolian effects fall outside the scope of this report. The reaction of sediment dispersal and accumulation under the combined effect of the variables will increase the general understanding of such interaction.

The Gamtoos estuary is dominated by freshwater floods. The sedimentary record would consequently be fluvial rather than tidal. The estuarine biogenic overprint on such a sediment pile would result in an incongruous geological record. The interaction between episodic fluvial deposition and its fairweather, tidal-biogenic overprint is worth investigating.

The behaviour of the coastal dune field to the west of the inlet directly and indirectly influences the estuary. An understanding of the sediment movement by wind is essential to the overall understanding of inlet dynamics. Questions that require scrutiny are: What volume of sand is moved from the beach onto these dunes? As the dune field is probably less than 6000 years old, and the beach profile does not appear to suffer under aeolian sand removal, from where is the sand replenished? What is the age of the beach conglomerate underlying large areas of the dune field?

The stratigraphic sequence produced by a migratory tidal inlet is poorly understood. Migration of the Gamtoos inlet is aided by deposition from the coastal dune field. This aspect is unique and should be investigated. As coring would be an integral part of such a study it may be hampered by the presence of pebble layers that are intercalated with the lower inlet sand.

The middle and upper estuary is incised into a floodplain which has older channel remnants preserved on its surface. The underlying deposits are probably well preserved. The depositional history of the estuary and the lower river system can probably be deciphered by studying these channels and the underlying sand with the aid of detailed surface surveys and by vibracoring.

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REFERENCES

Bruun, P. (1978) Stability of Tidal Inlets. Developments in Geotechnical Engineering, Vol. 23. Elsevier, Amsterdam. 510 pp.

Buller, A.T. and McManus, J. (1979) Sediment sampling and analysis. In Dyer, K.R., Ed., Estuarine hydrography and sedimentation. Cambridge University Press. 230pp.

Davies, O. (1972) Pleistocene shorelines in the southern and south-eastern Cape Province (Part 2). Ann. Natal Mus., 2, 225-279.

Flemming, B.W. (1977) Distribution of recent sediments in Saldanha Bay and Langebaan Lagoon. Trans. R. Soc. S.Afr., 42, 317-340.

Heydorn, A.E.F. and Grindley, J.R. (1981) Estuaries of the Cape. Part II. Synopses of available information on individual systems. Report no. 7, GAMTOOS (CMS48). CSIR res. rep. no. 406, 40 pp.

Komar, P.D. (1975) Nearshore currents: Generation by obliquely incident waves and longshore variations in breaker height. In Hails, J. and Carr, A., Eds., Nearshore Sediment Dynamics and Sedimentation. Wiley and Sons, New York. 316pp.

McCave, I.N. (1979) Suspended sediment. In Dyer, K.R., Ed., Estuarine hydrography and sedimentation. Cambridge University Press. 230pp.

Meistrell, F.J. (1966) The spit-platform concept: laboratory observations of spit development. M.S. Thesis. Univ. of Alberta. 58pp. In Schwartz, M.L. (1972), Ed., Spits and Bars. Benchmark series. Dowden, Hutchinson & Ross, Stroudsberg. 452pp.

Reddering, J.S.V. (1981) The sedimentology of the Keurbooms Estuary. Unpubl. M.Sc. Diss., Univ. of Port Elizabeth. 131 pp.

Reddering, J.S.V. (1983) An inlet sequence produced by migration of a small microtidal inlet against longshore drift: the Keurbooms Inlet, South Africa. Sedimentology, 30, 201-218.

Reddering, J.S.V. and Esterhuysen, K. (1981) Sedimentation in the Sundays estuary. R.O.S.I.E. rep. no. 3., Dept. Geol., Univ. of Port Elizabeth. 48pp.

Reddering, J.S.V. and Esterhuysen, K. (1982) Fluvially dominated sedimentation in the Great Fish estuary. R.O.S.I.E. rep. no. 4, Dept. Geol., Univ. of Port Elizabeth. 62pp.

Reddering, J.S.V. and Esterhuysen, K. (1983) Sedimentation in the Kromme Estuary. R.O.S.I.E. rep. no. 6, Dept. Geol., Univ. of Port Elizabeth. 92pp.

Rust, I.C. and Reddering, J.S.V. (1983) Sedimentology of Keurbooms Estuary and Robberg Formation. (Guidebook for SEDPLETT 83, a field seminar held at Plettenberg Bay in October, 1983), Dept. Geol., Univ. of Port Elizabeth. 73pp.

Schink, J.C., Stockwell, J.H. and Ellis, R.A. (1979) An improved device for gasometric determination of carbonate in sediments. J. sedim. Petrol., 49, 651-653.

APPENDIX I

This section lists the distribution data of sediment samples collected in the Gamtoos estuary. The sample lines are marked on fig. 3.1. The position of the sample stations can be found from the coded station numbers. For example G 5;4T originates from the from the Gamtoos ("G" in the code) and was collected on line number 5 ("5", see fig. 3.1). It was taken at the bed surface ("T" denotes TOP) at position 4 on that line. This sampling spot (indicated as a dot, fig. 3.1) is the fourth from the LEFT, looking up-estuary. Samples were also collected 0,5 m below the surface by coring. These samples are indicated by a "B" (for BOTTOM) in the code.

All grain sizes listed below are in PHI-units and NOT in mm. (PHI = - $\log_2$ (grain size in mm / 1 mm))

This appendix has three sections: A, B and C. Section A lists the grain size class distributions of the samples. Section B gives the corresponding statistical parameters and section C lists the respective contents of bioclastic carbonate and of organic material.

APPENDIX I A

This section lists the grain size class distributions.

The parameters listed below are as follows:

VCS - Very coarse sand (grain diameters 1 mm to 2 mm)

CS - Coarse sand (grain diameters 0,5 mm to 1 mm)

MS - Medium sand (grain diameters 0,25 mm to 0,5 mm)

FS - Fine sand (grain diameters 0,125 mm to 0,25 mm)

VFS - Very fine sand (grain diameters 0,063 mm to 0,125 mm)

Mud - Silt and clay (grain diameters less than 0,063 mm)

Sample no	%VCS	%CS	%MS	%FS	%VFS	%Mud
G 1;1T	0.00	0.93	64.19	33.02	1.40	0.47
1B	3.14	18.83	62.78	13.45	0.45	1.35
2T	0.46	4.17	55.56	31.02	7.41	1.39
2B	0.86	7.76	59.05	29.31	0.43	2.59
3T	2.79	11.55	63.35	19.92	1.20	1.20
3B	0.41	3.28	60.66	34.43	0.00	1.23
4T	2.17	18.48	70.11	7.07	0.54	1.63
4B	0.44	7.93	71.81	16.74	1.76	1.32
5T	0.00	1.17	50.39	44.53	2.73	1.17
5B	0.00	2.46	53.20	42.36	0.00	1.97
G 2:1T	0.00	1.46	38.35	54.37	4.85	0.97
1B	0.00	0.48	30.48	68.10	0.00	0.95
2T	0.00	0.45	37.95	60.27	0.00	1.34
2B	0.00	0.00	19.11	79.11	0.44	1.33
3T	0.00	0.00	15.82	74.58	7.91	1.69
3B	0.00	0.95	41.71	55.92	0.00	1.42
4T	0.00	1.33	56.64	40.27	0.00	1.77
4B	0.00	0.44	35.96	62.28	0.00	1.32
5T	0.00	0.00	24.80	69.29	4.33	1.57
5B	0.00	0.00	0.00	0.00	0.00	100.00
6T	0.00	0.00	35.75	63.13	0.00	1.12
6B	0.00	0.45	69.64	28.57	0.00	1.34
G 3:1T	0.00	1.03	51.28	46.67	0.00	1.03
1B	0.00	0.48	20.10	67.46	10.05	1.91
2T	0.00	1.12	46.44	50.94	0.00	1.50
2B	0.00	1.59	32.94	45.63	11.90	7.94
3T	0.43	4.70	56.84	36.75	0.00	1.28
3B	0.00	0.82	11.84	40.00	26.94	20.41
4T	0.00	1.09	62.91	33.45	1.09	1.45
4B	0.00	3.78	54.98	39.52	0.00	1.72
5T	0.00	0.91	19.09	61.36	13.64	5.00
5B	0.00	0.97	5.34	79.13	10.68	3.88
6T	0.00	2.13	37.02	56.17	2.55	2.13
6B	0.00	0.87	32.03	65.37	0.00	1.73
G 4:1T	0.00	3.37	38.46	53.85	2.40	1.92
1B	0.00	2.69	43.50	51.57	0.45	1.79
2T	0.00	1.46	39.32	51.94	3.40	3.88
2B	0.00	1.85	38.43	50.00	3.70	6.02
3T	0.00	1.08	38.92	46.49	8.65	4.86
3B	0.00	0.47	31.75	52.61	8.53	6.64
4T	0.36	0.36	17.92	25.81	29.39	26.16
4B	0.00	0.00	1.23	56.44	31.29	11.04
5T	0.48	0.48	15.31	69.86	10.53	3.35
5B	0.00	0.52	2.09	25.13	57.59	14.66
6T	0.00	0.87	30.30	66.67	0.43	1.73
6B	0.00	1.50	41.35	53.38	1.88	1.88

Sample no	%VCS	%CS	%MS	%FS	%VFS	%Mud
G 5;1T	0.00	0.96	33.17	62.98	0.96	1.92
1B	0.00	1.06	34.75	57.80	2.48	3.90
2T	0.00	1.04	28.50	60.62	3.63	6.22
2B	0.00	1.20	22.75	53.29	11.98	10.78
3T	0.00	0.86	28.33	54.51	7.30	9.01
3B	0.00	1.42	41.28	45.91	6.05	5.34
4T	0.00	0.70	14.74	26.67	21.40	36.49
4B	0.00	0.60	1.20	12.57	41.92	43.71
5T	0.00	0.32	1.59	20.06	34.08	43.95
5B	0.00	0.53	4.81	27.81	5.35	61.50
6T	0.00	0.59	18.64	74.85	2.96	2.96
6B	0.00	1.09	37.59	56.93	2.92	1.46
G 6;1T	0.00	0.44	48.23	50.00	0.00	1.33
1B	0.00	1.45	49.76	47.34	0.00	1.45
2T	0.00	7.69	62.90	17.65	2.26	9.50
2B	0.00	0.00	4.11	28.08	7.53	60.27
3T	0.00	0.35	45.64	36.59	5.23	12.20
3B	0.00	0.00	37.04	53.97	4.76	4.23
4T	0.00	0.00	1.27	51.59	25.48	21.66
4B	0.00	0.00	17.75	75.15	3.55	3.55
5T	0.00	0.00	0.75	4.51	20.30	74.44
5B	0.00	0.00	0.00	0.00	0.00	100.00
6T	0.00	0.00	0.00	42.93	45.11	11.96
6B	0.00	0.00	0.49	29.13	57.28	13.11
G 7;1T	0.00	0.00	38.27	47.45	13.27	1.02
1B	0.00	0.00	37.68	13.04	47.10	2.17
2T	0.00	0.44	44.25	17.70	14.16	23.45
2B	0.00	0.00	0.00	0.85	1.69	97.46
3T	0.00	0.00	0.99	0.50	52.97	45.54
3B	0.00	0.00	0.00	24.91	66.67	8.42
4T	0.00	0.00	0.53	0.00	73.40	26.06
4B	0.00	0.00	0.00	2.71	68.33	28.96
5T	0.00	0.00	0.00	0.00	40.88	59.12
5B	0.00	0.00	0.00	0.00	21.71	78.29
G 8;1T	5.05	1.38	7.34	16.06	42.66	27.52
1B		Solid	substrate			
2T	0.00	0.53	1.05	0.00	2.63	95.79
2B	0.00	0.00	0.00	0.00	0.00	100.00
3T	0.00	0.00	2.42	5.45	39.39	52.73
3B	0.00	0.00	4.65	6.98	83.72	4.65
4T	0.00	0.00	11.21	3.02	65.52	20.26
4B	0.00	0.00	0.69	0.00	54.33	44.98
5T	0.00	0.00	1.34	58.39	33.56	6.71
5B	0.00	0.00	0.52	35.60	57.59	6.28

Sample no	%VCS	%CS	%MS	%FS	%VFS	%Mud
G 9;1T	0.00	0.00	4.17	44.70	36.74	14.39
1B	0.00	0.00	0.41	4.94	16.05	78.60
2T	0.00	0.89	20.89	5.33	36.00	36.89
2B	0.00	0.00	8.47	25.40	57.14	8.99
3T	0.00	0.00	2.49	0.41	73.86	23.24
3B	0.00	0.00	0.00	0.60	0.60	98.80
4T	0.00	0.00	0.48	1.92	54.81	42.79
4B	0.00	0.00	0.00	0.00	0.00	100.00
5T	0.00	0.00	0.65	9.15	33.99	56.21
5B	0.00	0.46	1.37	24.20	24.66	49.32
G 10;1T	0.00	2.91	27.83	19.42	12.94	36.89
1B	0.00	3.79	45.11	0.95	30.91	19.24
2T	0.00	0.00	15.51	18.78	25.31	40.41
2B	0.00	0.00	0.00	0.00	0.00	100.00
3T	0.00	0.00	11.58	0.35	57.19	30.88
3B	0.00	1.38	59.52	31.14	4.50	3.46
4T	0.00	0.00	5.36	21.07	49.81	23.75
4B	0.00	0.00	42.86	53.66	1.74	1.74
5T	0.00	0.32	1.62	10.68	56.31	31.07
5B	0.00	0.00	1.65	26.45	45.45	26.45
G 11;1T	0.00	0.00	9.03	3.82	80.90	6.25
1B	0.00	0.00	1.37	14.61	31.05	52.97
2T	0.00	0.00	1.74	9.88	42.44	45.93
2B	0.00	0.00	2.94	40.44	45.22	11.40
3T	0.00	0.00	9.16	0.76	67.94	22.14
3B	0.00	0.00	25.36	52.45	17.00	5.19
4T	0.00	0.00	5.93	14.84	54.90	24.33
4B	0.00	0.00	24.00	70.77	2.77	2.46
5T	0.00	0.00	1.09	1.09	15.85	81.97
5B	0.00	0.00	0.00	16.86	65.10	18.04
G 12;1T	0.00	0.00	0.00	7.47	75.86	16.67
1B	0.00	0.00	0.00	15.16	48.38	36.46
2T	0.00	0.00	0.38	42.59	43.73	13.31
2B	0.00	0.00	0.00	56.61	38.10	5.29
3T	0.00	0.00	3.86	30.88	53.68	11.58
3B	0.00	0.00	1.59	78.49	16.33	3.59
4T	4.62	3.36	28.99	4.62	55.46	2.94
4B	0.00	0.00	0.00	0.51	2.55	96.94
G 13;1T	2.03	3.55	15.74	33.50	10.66	34.52
1B	0.00	0.00	0.00	0.70	4.20	95.10
2T	0.00	0.00	3.97	73.02	13.49	9.52
2B	0.00	0.00	2.04	75.92	16.33	5.71
3T	0.00	0.00	1.59	52.78	35.71	9.92
3B	0.00	0.00	1.70	59.66	28.98	9.66
4T	0.00	0.00	1.40	21.96	31.78	44.86
4B	0.00	0.00	0.00	1.83	18.29	79.88

Sample no	%VCS	%CS	%MS	%FS	%VFS	%Mud
G 14;1T	0.00	0.00	0.00	1.00	2.00	97.00
1B	0.00	0.00	0.00	0.56	1.13	98.31
2T	0.00	0.00	0.00	55.56	24.44	20.00
2B	0.00	0.00	2.20	67.40	26.01	4.40
3T	0.00	0.00	1.30	57.58	22.51	18.61
3B	0.00	0.00	5.88	64.22	24.02	5.88
4T	0.00	0.00	0.00	2.82	2.82	94.37
4B		Solid	substrate			
G 15;1T	0.00	0.00	0.41	0.00	53.47	46.12
1B	0.00	0.00	0.00	0.00	0.00	100.00
2T	0.00	0.00	1.99	57.77	24.30	15.94
2B	0.00	0.00	5.02	44.80	46.59	3.58
3T	0.00	0.00	8.00	70.91	12.00	9.09
3B	0.00	0.00	10.37	13.70	71.85	4.07
4T	0.00	0.00	2.25	40.54	34.68	22.52
4B	0.00	0.00	2.17	5.43	16.30	76.09
G 16;1T	0.00	0.00	0.00	2.05	1.03	96.92
1B	0.00	0.00	0.00	0.00	0.00	100.00
2T	0.00	0.00	1.79	60.00	29.85	8.36
2B	0.00	0.00	4.04	83.46	9.19	3.31
3T	0.00	0.00	50.79	17.06	28.97	3.17
3B	0.00	0.00	39.25	57.74	1.51	1.51
4T	0.00	0.00	1.80	9.71	61.51	26.98
4B	0.00	0.00	0.00	6.85	29.84	63.31
G 17;1T	0.00	0.00	0.00	0.00	0.00	100.00
1B	0.00	0.00	0.00	0.00	0.00	100.00
2T	0.00	0.00	18.90	47.64	17.32	16.14
2B	0.00	0.00	26.34	64.29	7.14	2.23
3T	0.00	0.00	10.49	44.06	32.87	12.59
3B	0.00	0.00	35.37	60.13	3.22	1.29
4T	0.00	0.00	1.66	6.22	46.06	46.06
4B	0.00	0.00	0.35	28.13	43.75	27.78
G 18;1T	0.00	0.00	0.00	0.00	0.00	100.00
1B	0.00	0.00	0.00	0.00	0.00	100.00
2T	0.00	0.00	14.29	43.25	29.37	13.10
2B	0.00	0.00	19.23	67.83	9.79	3.15
3T	0.00	0.37	38.20	38.95	15.36	7.12
3B	0.00	0.34	50.00	46.55	1.72	1.38
4T	0.00	0.66	8.25	31.35	37.29	22.44
4B	0.00	0.00	1.29	29.61	43.35	25.75
G A;1T	0.00	0.00	4.69	34.38	55.73	5.21
1B	0.00	0.00	5.35	48.66	36.90	9.09
2T	0.00	0.56	3.91	3.35	48.60	43.58
2B	0.00	0.00	0.76	24.33	60.46	14.45
3T	0.00	4.03	70.97	24.19	0.81	0.00
3B	0.00	0.00	0.44	2.20	5.73	91.63
4T	0.00	0.00	0.57	5.11	26.14	68.18
4B	0.00	0.00	0.00	1.55	46.39	52.06

Sample no	%VCS	%CS	%MS	%FS	%VFS	%Mud
G B; 1T	0.00	0.00	10.70	43.62	18.11	27.57
1B	0.00	0.00	3.75	15.83	22.50	57.92
2T	0.00	0.00	5.36	5.36	0.00	89.29
2B	0.00	0.00	8.25	43.81	17.01	30.93
3T	0.00	0.97	65.53	31.55	0.97	0.97
3B	0.00	0.57	17.82	33.33	5.75	42.53
4T	0.99	0.49	1.48	16.75	33.00	47.29
4B	0.00	0.00	0.00	10.92	66.81	22.27
G C; 1T	0.00	0.55	3.31	18.78	13.26	64.09
1B	0.00	0.82	7.35	33.47	16.33	42.04
2T	0.00	0.00	14.74	64.74	15.26	5.26
2B	0.00	0.65	13.73	49.67	11.11	24.84
3T	0.00	0.44	4.85	34.80	29.07	30.84
3B	0.00	0.34	7.09	52.03	19.26	21.28
4T	0.00	0.48	2.39	11.48	33.01	52.63
4B	0.60	0.60	4.19	24.55	33.53	36.53
G D; 1T	0.00	0.00	1.38	22.58	21.66	54.38
1B	0.00	0.00	1.14	16.48	26.14	56.25
2T	0.00	1.85	45.83	38.43	6.48	7.41
2B	0.00	0.00	16.35	29.33	22.60	31.73
3T	0.00	0.00	0.56	15.73	55.62	28.09
3B	0.00	0.00	32.49	53.81	7.61	6.09
4T	0.00	0.00	1.64	8.20	17.21	72.95
4B	0.00	0.00	0.41	9.84	25.82	63.93
G E; 1T	0.00	0.00	10.08	35.08	10.48	44.35
1B	0.00	0.00	0.00	0.00	0.00	100.00
2T	0.00	0.83	2.50	7.50	9.17	80.00
2B	0.00	0.00	0.54	2.15	3.23	94.09
3T	0.00	0.00	3.01	30.12	18.07	48.80
3B	0.00	0.00	2.50	22.00	20.50	55.00
4T	0.45	1.79	45.29	45.29	0.45	6.73
4B	0.00	1.58	35.26	41.58	2.63	18.95
G F; 1T	0.00	0.45	31.22	66.97	0.45	0.90
1B	0.00	0.00	26.74	72.19	0.00	1.07
2T	0.00	0.00	0.00	0.00	0.00	100.00
2B	0.00	0.00	2.94	37.06	30.00	30.00
3T	0.00	0.00	6.90	7.76	6.03	79.31
3B	0.00	0.63	42.77	54.09	1.26	1.26
4T	0.00	0.52	29.84	63.35	1.57	4.71
4B	0.00	3.76	48.36	34.27	1.41	12.21
G G; 1T	0.00	0.00	21.72	77.83	0.45	0.00
1B	0.00	0.00	18.57	80.00	0.48	0.95
2T	0.00	0.00	6.28	27.75	30.89	35.08
2B	0.00	0.36	43.43	52.55	1.82	1.82
3T	0.00	4.79	51.50	23.35	2.99	17.37
3B	0.00	5.17	54.24	26.20	2.95	11.44
4T	0.00	4.35	51.38	37.94	2.37	3.95
4B	0.49	5.34	52.43	33.01	2.43	6.31

APPENDIX 1 B

This section lists the statistical parameters of the Gamtoos estuary sediments. NOTE that the statistical parameters only apply to the sand size classes. Silt and clay are EXCLUDED from these parameters. Lines without data consist of 100 % mud (see APPENDIX 1 A) and sand statistics cannot be evaluated.

Statistical formulae were obtained from Buller and McManus (1979). The parameters listed below are as follows:

Med. - The distribution median in PHI-units ($Md = P_{50}$) *

Mean - The mean grain size in PHI-units ($M = P_{16}+P_{84})/2$)

Sort - Grain sorting in PHI-units ($So = (P_{84}-P_{16})/2$)

Ske. - Distribution skewness in PHI-units ($Sk = (M-Md)/S$)

Kurt - Distribution kurtosis in PHI-units

$$(Ku = (((P_{95}-P_{5})/2)-S)/S)$$

* P_x is the xth percentile of the relevant distribution.

Sample no	Med.	Mean	Sort	Ske.	Kurt
G 1; 1T	1.76	1.90	0.66	0.20	0.38
1B	1.44	1.32	0.65	-0.18	0.98
2T	1.80	1.97	0.76	0.21	0.52
2B	1.68	1.80	0.68	0.18	0.71
3T	1.55	1.64	0.62	0.15	1.11
3B	1.75	1.87	0.67	0.17	0.37
4T	1.41	1.31	0.57	-0.17	0.94
4B	1.57	1.63	0.53	0.12	1.12
5T	1.96	2.00	0.71	0.06	0.32
5B	1.88	1.94	0.69	0.09	0.33
G 2; 1T	2.18	2.09	0.71	-0.13	0.34
1B	2.27	2.14	0.63	-0.22	0.41
2T	2.18	2.07	0.67	-0.17	0.35
2B	2.38	2.32	0.49	-0.13	0.72
3T	2.45	2.44	0.45	-0.00	1.30
3B	2.12	2.04	0.68	-0.12	0.33
4T	1.84	1.93	0.68	0.13	0.34
4B	2.21	2.09	0.66	-0.18	0.36
5T	2.35	2.24	0.60	-0.20	0.49
5B	-	-	-	-	-
6T	2.22	2.10	0.65	-0.18	0.36
6B	1.70	1.83	0.61	0.22	0.44
G 3; 1T	1.95	1.97	0.69	0.04	0.32
1B	2.42	2.34	0.58	-0.15	0.98
2T	2.03	2.00	0.69	-0.04	0.32
2B	2.25	2.17	0.77	-0.11	0.64
3T	1.78	1.88	0.69	0.15	0.38
3B	2.68	2.76	0.76	0.11	0.69
4T	1.77	1.90	0.66	0.20	0.37
4B	1.83	1.91	0.69	0.12	0.34
5T	2.45	2.36	0.61	-0.14	1.00
5B	2.53	2.53	0.41	0.00	1.22
6T	2.17	2.07	0.70	-0.15	0.34
6B	2.25	2.11	0.65	-0.21	0.39
G 4; 1T	2.13	2.04	0.72	-0.14	0.34
1B	2.06	2.00	0.70	-0.08	0.33
2T	2.14	2.06	0.71	-0.11	0.33
2B	2.13	2.06	0.72	-0.11	0.33
3T	2.16	2.11	0.75	-0.07	0.58
3B	2.27	2.17	0.71	-0.15	0.63
4T	2.71	2.61	0.99	-0.10	0.37
4B	2.77	2.89	0.66	0.18	0.37
5T	2.46	2.44	0.49	-0.04	1.33
5B	3.26	3.10	0.66	-0.24	0.41
6T	2.27	2.13	0.64	-0.22	0.41
6B	2.12	2.04	0.70	-0.11	0.33

Sample no	Med.	Mean	Sort	Ske.	Kurt
G 5;1T	2.24	2.11	0.66	-0.20	0.38
1B	2.21	2.09	0.68	-0.17	0.36
2T	2.29	2.15	0.66	-0.20	0.40
2B	2.39	2.27	0.69	-0.18	0.80
3T	2.30	2.18	0.69	-0.18	0.62
3B	2.10	2.07	0.73	-0.05	0.45
4T	2.61	2.58	0.94	-0.03	0.43
4B	3.33	3.18	0.61	-0.25	0.53
5T	3.18	3.04	0.69	-0.19	0.35
5B	2.50	2.50	0.47	0.00	1.50
6T	2.39	2.32	0.52	-0.14	0.69
6B	2.19	2.08	0.69	-0.15	0.35
G 6;1T	2.01	2.00	0.68	-0.02	0.32
1B	1.96	1.98	0.69	0.02	0.32
2T	1.60	1.71	0.60	0.18	0.90
2B	2.56	2.62	0.54	0.11	1.09
3T	1.95	2.03	0.73	0.10	0.42
3B	2.20	2.11	0.70	-0.13	0.34
4T	2.73	2.86	0.64	0.20	0.39
4B	2.41	2.36	0.49	-0.10	0.76
5T	3.37	3.27	0.53	-0.19	0.72
5B	-	-	-	-	-
6T	3.02	3.01	0.68	-0.02	0.32
6B	3.24	3.11	0.65	-0.20	0.38
G 7;1T	2.24	2.18	0.77	-0.07	0.63
1B	2.86	2.54	1.13	-0.28	0.23
2T	1.85	2.20	0.93	0.37	0.42
2B	3.25	3.12	0.64	-0.20	0.39
3T	3.49	3.49	0.35	0.00	0.32
3B	3.31	3.18	0.60	-0.22	0.47
4T	3.50	3.50	0.34	0.00	0.32
4B	3.48	3.48	0.35	0.00	0.32
5T	3.50	3.50	0.34	0.00	0.32
5B	3.50	3.50	0.34	0.00	0.32
G 8;1T	3.15	2.72	1.01	-0.43	1.07
1B		Solid	substrate		
2T	3.20	2.44	1.30	-0.58	0.35
2B	-	-	-	-	-
3T	3.40	3.38	0.43	-0.06	1.27
3B	3.43	3.43	0.39	0.00	1.49
4T	3.39	3.16	0.65	-0.36	1.00
4B	3.49	3.49	0.34	0.00	0.32
5T	2.78	2.89	0.66	0.18	0.36
5B	3.19	3.07	0.67	-0.17	0.35

Sample no	Med.	Mean	Sort	Ske.	Kurt
G 9;1T	2.86	2.92	0.71	0.08	0.33
1B	3.33	3.20	0.59	-0.23	0.53
2T	3.12	2.58	1.14	-0.48	0.23
2B	3.20	2.99	0.75	-0.28	0.58
3T	3.48	3.48	0.35	0.00	0.32
3B	3.00	3.00	0.68	0.00	0.32
4T	3.48	3.48	0.35	-0.00	0.32
4B	-	-	-	-	-
5T	3.36	3.24	0.55	-0.20	0.61
5B	2.97	2.97	0.71	-0.01	0.32
G 10;1T	2.04	2.24	0.98	0.20	0.40
1B	1.81	2.39	1.19	0.49	0.20
2T	2.76	2.62	1.00	-0.14	0.34
2B	-	-	-	-	-
3T	3.40	2.88	0.93	-0.56	0.43
3B	1.79	1.94	0.71	0.22	0.37
4T	3.23	3.04	0.72	-0.27	0.55
4B	2.12	2.05	0.69	-0.09	0.33
5T	3.39	3.33	0.48	-0.13	0.89
5B	3.19	3.06	0.68	-0.19	0.36
G 11;1T	3.42	3.42	0.39	0.00	2.07
1B	3.24	3.09	0.67	-0.23	0.39
2T	3.36	3.25	0.55	-0.21	0.68
2B	3.02	2.98	0.70	-0.05	0.32
3T	3.43	3.43	0.39	0.00	2.23
3B	2.42	2.35	0.75	-0.09	0.68
4T	3.31	3.10	0.68	-0.31	0.68
4B	2.35	2.23	0.58	-0.20	0.51
5T	3.43	3.43	0.39	0.00	1.74
5B	3.37	3.29	0.51	-0.16	0.66
G 12;1T	3.45	3.45	0.37	0.00	0.86
1B	3.34	3.23	0.56	-0.20	0.54
2T	3.01	3.00	0.68	-0.01	0.32
2B	2.84	2.93	0.67	0.15	0.34
3T	3.18	3.03	0.70	-0.20	0.35
3B	2.59	2.62	0.44	0.05	0.89
4T	3.13	2.49	1.23	-0.52	0.56
4B	3.40	3.38	0.42	0.00	0.93
G 13;1T	2.34	2.16	0.85	-0.21	0.96
1B	3.42	3.42	0.40	0.00	1.01
2T	2.57	2.57	0.42	0.00	0.97
2B	2.59	2.62	0.45	0.07	0.85
3T	2.82	2.92	0.68	0.14	0.34
3B	2.73	2.86	0.64	0.20	0.40
4T	3.13	3.03	0.69	-0.15	0.34
4B	3.45	3.45	0.37	0.00	0.86

Sample no	Med.	Mean	Sort	Ske.	Kurt
G 14;1T	3.25	3.12	0.64	-0.20	0.39
1B	3.25	3.12	0.64	-0.20	0.39
2T	2.72	2.85	0.62	0.21	0.42
2B	2.68	2.80	0.61	0.21	0.46
3T	2.68	2.81	0.61	0.21	0.45
3B	2.64	2.76	0.62	0.19	0.63
4T	3.00	3.00	0.68	0.00	0.32
4B		Solid	substrate		
G 15;1T	3.50	3.50	0.34	-0.00	0.32
1B	-	-	-	-	-
2T	2.69	2.82	0.62	0.21	0.43
2B	2.96	2.95	0.72	-0.02	0.35
3T	2.53	2.53	0.44	0.00	1.35
3B	3.33	3.07	0.71	-0.36	0.74
4T	2.90	2.95	0.70	0.07	0.33
4B	3.27	3.03	0.73	-0.32	0.63
G 16;1T	2.75	2.88	0.64	0.20	0.39
1B	-	-	-	-	-
2T	2.73	2.86	0.65	0.20	0.39
2B	2.53	2.53	0.39	0.00	0.86
3T	1.95	2.39	1.08	0.40	0.27
3B	2.17	2.08	0.68	-0.14	0.34
4T	3.41	3.41	0.40	-0.00	1.17
4B	3.39	3.33	0.47	-0.12	0.76
G 17;1T	-	-	-	-	-
1B	-	-	-	-	-
2T	2.48	2.47	0.76	-0.02	0.67
2B	2.35	2.23	0.64	-0.19	0.67
3T	2.75	2.83	0.75	0.10	0.64
3B	2.23	2.12	0.67	-0.17	0.36
4T	3.41	3.41	0.40	0.00	1.23
4B	3.17	3.07	0.67	-0.16	0.35
G 18;1T	-	-	-	-	-
1B	-	-	-	-	-
2T	2.67	2.75	0.78	0.10	0.64
2B	2.43	2.36	0.56	-0.13	1.03
3T	2.20	2.21	0.83	0.00	0.56
3B	1.98	2.00	0.69	0.03	0.32
4T	2.95	2.89	0.78	-0.08	0.61
4B	3.14	3.04	0.68	-0.15	0.34
G A;1T	3.15	3.02	0.71	-0.19	0.34
1B	2.82	2.90	0.71	0.10	0.43
2T	3.42	3.42	0.39	0.00	1.99
2B	3.29	3.15	0.62	-0.23	0.44
3T	1.65	1.77	0.60	0.20	0.51
3B	3.27	3.09	0.68	-0.27	0.46
4T	3.39	3.34	0.46	-0.10	0.89
4B	3.48	3.48	0.35	0.00	0.32

Sample no	Med.	Mean	Sort	Ske.	Kurt
G B; 1T	2.58	2.69	0.67	0.16	0.84
1B	3.06	2.94	0.76	-0.16	0.55
2T	2.00	2.00	0.68	0.00	0.32
2B	2.60	2.71	0.64	0.17	0.85
3T	1.74	1.88	0.65	0.21	0.39
3B	2.31	2.19	0.71	-0.17	0.68
4T	3.20	3.04	0.71	-0.23	0.51
4B	3.42	3.42	0.40	0.00	1.00
G C; 1T	2.75	2.83	0.73	0.11	0.70
1B	2.62	2.73	0.70	0.16	0.82
2T	2.50	2.51	0.50	0.01	1.37
2B	2.47	2.41	0.58	-0.11	1.11
3T	2.84	2.89	0.73	0.07	0.55
3B	2.61	2.72	0.62	0.17	0.84
4T	3.28	3.09	0.68	-0.28	0.57
4B	3.05	2.95	0.75	-0.14	0.62
G D; 1T	2.95	2.96	0.70	0.02	0.32
1B	3.16	3.04	0.69	-0.17	0.35
2T	1.97	2.03	0.75	0.08	0.48
2B	2.61	2.59	0.92	-0.02	0.43
3T	3.35	3.24	0.55	-0.20	0.59
3B	2.27	2.16	0.70	-0.15	0.60
4T	3.21	3.04	0.71	-0.25	0.48
4B	3.30	3.16	0.62	-0.23	0.45
G E; 1T	2.51	2.52	0.63	0.02	0.94
1B	-	-	-	-	-
2T	2.89	2.80	0.85	-0.11	0.66
2B	3.08	2.95	0.76	-0.18	0.55
3T	2.75	2.86	0.69	0.16	0.46
3B	2.91	2.93	0.72	0.03	0.39
4T	1.98	1.98	0.70	-0.00	0.32
4B	2.09	2.04	0.71	-0.07	0.33
G F; 1T	2.27	2.13	0.64	-0.21	0.40
1B	2.31	2.19	0.59	-0.22	0.47
2T	-	-	-	-	-
2B	2.87	2.92	0.70	0.09	0.33
3T	2.44	2.47	0.99	0.02	0.36
3B	2.11	2.04	0.69	-0.10	0.33
4T	2.27	2.14	0.65	-0.21	0.40
4B	1.83	1.92	0.71	0.13	0.34
G G; 1T	2.36	2.27	0.53	-0.18	0.61
1B	2.39	2.33	0.48	-0.12	0.76
2T	2.94	2.91	0.76	-0.05	0.57
2B	2.10	2.04	0.69	-0.08	0.33
3T	1.71	1.86	0.70	0.22	0.49
3B	1.72	1.87	0.70	0.21	0.48
4T	1.85	1.94	0.72	0.12	0.34
4B	1.78	1.90	0.72	0.16	0.49

APPENDIX I C

This section lists the respective contents of $CaCO_3$ and of H_2O_2-leachable organic material.

Carbonate content of the samples was determined using a "carbonate bomb" (Schink et al., 1979). The organic content was determined by H_2O_2 leaching (McCave, 1979). This method does not determine all the organic material in the sediment but gives an approximation of the material that is likely to influence the redox potential of the sediment.

The parameters listed below are as follows:

%Carb. - The percentage (m/m) of carbonate in the sediment samples expressed as $CaCO_3$.

%Org C - The percentage organic material in the samples.

The "tr." occurring in some columns denotes trace amounts of carbonate. The sample effervesced when the acid was added but the carbonate content was too low to register a reading.

Sample no	%Carb.	%Org C
G 1;1T	26.20	0.50
1B	62.90	0.90
2T	31.90	1.10
2B	40.70	0.70
3T	44.40	0.40
3B	32.60	0.90
4T	40.80	1.00
4B	40.60	1.20
5T	33.00	1.10
5B	32.70	1.10
G 2;1T	36.90	0.50
1B	30.20	0.60
2T	27.00	1.00
2B	31.30	0.90
3T	30.30	1.00
3B	34.70	3.40
4T	41.50	1.80
4B	26.00	0.70
5T	26.90	0.90
5B	0.00	2.70
6T	30.20	0.60
6B	21.50	0.80
G 3;1T	26.30	0.80
1B	27.50	1.10
2T	25.10	0.80
2B	26.30	1.40
3T	30.80	0.70
3B	17.40	1.10
4T	30.40	0.70
4B	33.20	0.90
5T	27.80	1.50
5B	31.70	1.60
6T	34.50	1.00
6B	26.90	0.40
G 4;1T	38.50	0.80
1B	40.80	0.90
2T	17.80	0.70
2B	15.00	0.90
3T	tr.	1.50
3B	19.80	0.90
4T	6.60	1.60
4B	tr.	1.10
5T	21.30	1.40
5B	tr.	2.30
6T	36.20	0.90
6B	31.50	0.70

Sample no	%Carb.	%Org C
G 5;1T	38.10	1.30
1B	34.30	0.80
2T	29.00	1.10
2B	26.70	1.20
3T	9.80	1.00
3B	15.50	1.10
4T	tr.	2.10
4B	tr.	2.70
5T	tr.	1.80
5B	tr.	2.50
6T	39.00	0.70
6B	38.6	0.40
G 6;1T	34.90	0.00
1B	19.40	0.40
2T	9.60	0.30
2B	tr.	0.60
3T	tr.	0.30
3B	0.00	1.70
4T	tr.	0.00
4B	tr.	1.00
5T	0.00	1.20
5B	tr.	1.60
6T	0.00	1.10
6B	0.00	0.00
G 7;1T	35.90	0.50
1B	34.10	0.40
2T	tr.	1.10
2B	0.00	0.00
3T	0.00	1.00
3B	tr.	0.80
4T	0.00	0.40
4B	0.00	0.80
5T	0.00	1.30
5B	0.00	0.90
G 8;1T	0.00	0.30
1B	Solid substrate	
2T	0.00	1.10
2B	0.00	0.70
3T	tr.	1.80
3B	tr.	0.50
4T	tr.	1.10
4B	0.00	0.50
5T	tr.	0.90
5B	0.00	1.00

Sample no	%Carb.	%Org C
G 9;1T	tr.	0.40
1B	tr.	0.00
2T	tr.	1.10
2B	0.00	0.30
3T	0.00	1.10
3B	0.00	0.70
4T	tr.	1.20
4B	tr.	0.70
5T	tr.	0.70
5B	tr.	1.20
G 10;1T	0.00	0.70
1B	0.00	0.60
2T	tr.	0.80
2B	tr.	0.90
3T	tr.	0.40
3B	tr.	0.50
4T	0.00	0.40
4B	0.00	0.40
5T	0.00	0.30
5B	tr.	0.40
G 11;1T	tr.	1.00
1B	0.00	0.90
2T	0.00	2.20
2B	0.00	0.40
3T	tr.	0.70
3B	0.00	0.60
4T	tr.	0.90
4B	0.00	0.90
5T	0.00	1.00
5B	tr.	0.80
G 12;1T	tr.	1.60
1B	tr.	1.80
2T	tr.	0.90
2B	tr.	0.60
3T	tr.	0.00
3B	tr.	0.40
4T	0.00	0.60
4B	0.00	0.80
G 13;1T	tr.	0.00
1B	tr.	1.30
2T	tr.	0.50
2B	tr.	0.00
3T	0.00	0.50
3B	tr.	0.40
4T	tr.	0.00
4B	tr.	0.40

Sample no	%Carb.	%Org C
G 14;1T	0.00	0.80
1B	tr.	0.40
2T	0.00	0.60
2B	0.00	0.70
3T	0.00	0.60
3B	0.00	0.90
4T	13.80	0.00
4B	Solid substrate	
G 15;1T	tr.	0.40
1B	tr.	0.40
2T	0.00	0.60
2B	0.00	0.40
3T	0.00	0.40
3B	0.00	0.50
4T	0.00	0.50
4B	tr.	0.60
G 16;1T	tr.	0.50
1B	tr.	0.00
2T	0.00	0.30
2B	0.00	0.00
3T	0.00	0.30
3B	0.00	0.80
4T	0.00	0.40
4B	tr.	0.40
G 17;1T	tr.	0.00
1B	0.00	0.00
2T	tr.	0.00
2B	0.00	0.00
3T	0.00	0.00
3B	0.00	0.00
4T	0.00	0.00
4B	tr.	0.00
G 18;1T	tr.	0.40
1B	0.00	0.00
2T	tr.	0.30
2B	0.00	0.00
3T	tr.	0.00
3B	0.00	0.40
4T	tr.	0.00
4B	tr.	0.00
G A;1T	tr.	1.10
1B	10.90	0.00
2T	0.00	2.40
2B	0.00	0.70
3T	19.10	0.50
3B	0.00	0.30
4T	0.00	0.70
4B	tr.	1.00

Sample no	%Carb.	%Org C
G B;1T	16.20	0.90
1B	tr.	1.40
2T	tr.	3.20
2B	tr.	0.70
3T	22.60	0.60
3B	15.30	0.00
4T	0.00	1.00
4B	tr.	1.70
G C;1T	tr.	1.20
1B	tr.	1.70
2T	6.60	0.90
2B	11.60	1.40
3T	tr.	0.60
3B	tr.	1.10
4T	0.00	1.40
4B	tr.	2.50
G D;1T	tr.	0.80
1B	tr.	0.80
2T	28.80	0.80
2B	tr.	1.40
3T	0.00	0.80
3B	14.40	0.40
4T	tr.	0.40
4B	tr.	0.40
G E;1T	tr.	0.90
1B	tr.	1.10
2T	0.00	2.90
2B	0.00	0.90
3T	0.00	1.30
3B	0.00	1.00
4T	38.30	0.30
4B	29.60	0.40
G F;1T	33.20	0.40
1B	34.40	0.50
2T	0.00	4.80
2B	0.00	0.70
3T	tr.	0.60
3B	17.80	0.30
4T	28.80	0.60
4B	33.50	0.00
G G;1T	33.10	0.30
1B	29.60	0.30
2T	tr.	0.60
2B	22.80	0.00
3T	34.50	0.40
3B	34.20	0.40
4T	13.90	0.00
4B	34.30	0.30