ATLANTIC ZONE PROGRAMME

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ISLAND-ARC VOLCANISM AND EPISODIC FLUVIAL SEDIMENTATION IN THE ATLANTIC ZONE OF COSTA RICA

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The Atlantic Zone Programme (CATIE-AUW-MAG) is the result of an agreement for technical cooperation between the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), the Agricultural University Wageningen (AUW). The Netherlands and the Ministerio de Agricultura y Ganadería (MAG) of Costa Rica. The Programme, that was started in April 1986, has a long-term objective multidisciplinary research aimed at rational use of the natural resources in the Atlantic Zone of Costa Rica with emphasis on the small landowner.

PREFACE

General description of the research programme on sustainable Landuse.

The research programme is based on the document "elaboration of the VF research programme in Costa Rica" prepared by the Working Group Costa Rica (WCR) in 1990. The document can be summarized as follows:

To develop a methodology to analyze ecologicaly sustainable and economically feasible land use, three hierarchical levels of analysis can be distinguished.

1. The Land Use System (LUS) analyses the relations between soil type and crops as well as technology and yield.
2. The Farm System (FS) analyses the decisions made at the farm household regarding the generation of income and on farm activities.
3. The Regional System (RS) analyses the agroecological and socio-economic boundary conditions and the incentives presented by development oriented activities.

Ecological aspects of the analysis comprise comparison of the effects of different crops and production techniques on the soil as ecological resource. For this comparision the chemical and physical qualities of the soil are examined as well as the polution by agrochemicals. Evaluation of the groundwater condition is included in the ecological approach. Criterions for sustainability have a relative character. The question of what is in time a more sustainable land use will be answered on the three different levels for three major soil groups and nine important land use types.

Combinations of crops and soils

	Maiz	Yuca	Platano	Piña	Palmito	Pasto	Forestal I II III
Soil I	x	x	x		x	x	x
Soil II						x	x
Soil III	x			x	x	x	x

As landuse is realized in the socio-economic context of the farm or region, feasibility criterions at corresponding levels are to be taken in consideration. MGP models on farm scale and regional scale are developed to evaluate the different ecological criterions in economical terms or visa-versa.

Different scenarios will be tested in close cooperation with the counter parts.

The Atlantic Zone of Costa Rica is an area which is being studied in detail in the scope of a project of the Agricultural University of Wageningen (AUW), the Centro Agronomico Tropical de Investigación y Enseñanza (CATIE) [centre for investigation and development in tropical agriculture] and the Ministerio de Agronomía y Ganadería (MAG) [ministry of agriculture] cooperate. Purpose of this project is to develop a database for this zone in various kinds of specialisms to improve sustainable landuse in the region. Special attention is paid to the small-scale farmers of the Atlantic Zone.

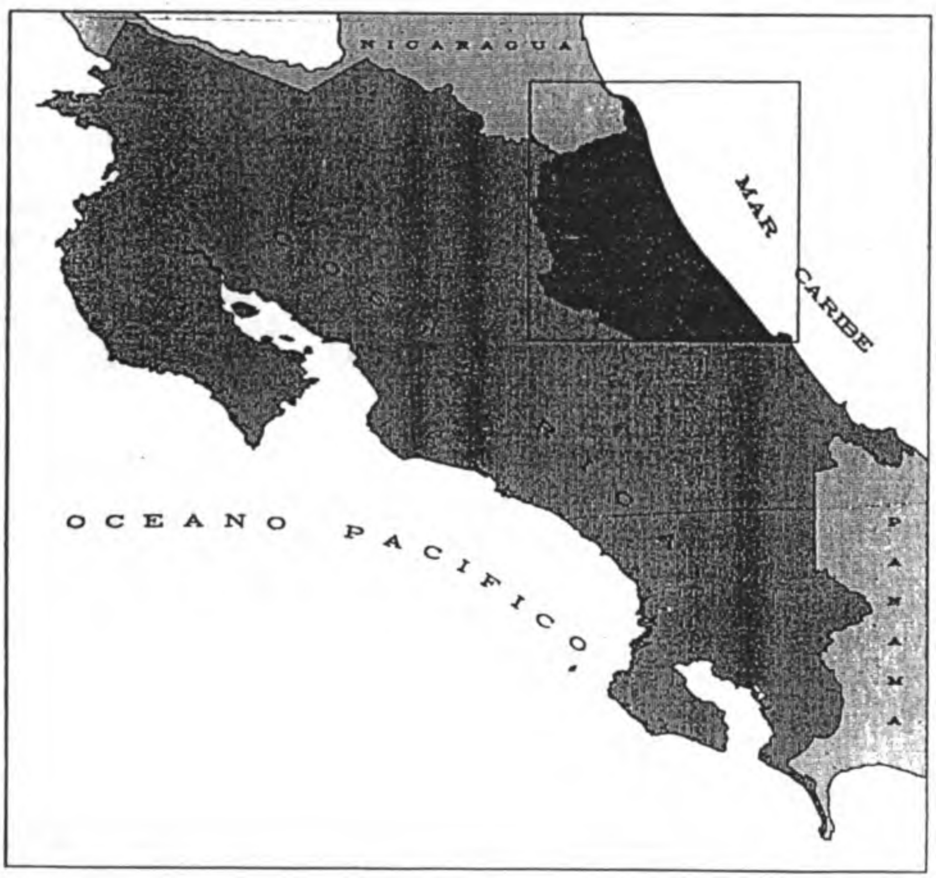

Fig 1.1 Costa Rica. The Atlantic Zone is indicated in black.

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ABSTRACT

Island-arc volcanism combined with the humid tropical climate of Costa Rica (rainfall 4000-7000 mm/y) causes episodic deposition of large amounts of sediments on the Caribbean alluvial plain, resulting in abundant elongated channel-fill sand bodies. Large crevasse splays also occur in this area.

Channel geometries in the alluvial plain show meandering patterns, which change into anastomosing systems in the swamp areas of the coastal plain. In one channel-fill sand body an amount of $\pm$ 6.10^6 to 24.10^6 m^3 of sand may be deposited. Channel width and depth strongly depend on the location on the alluvial fan. Both decrease towards the distal parts. Channel fills have widths varying from 20 to 70 m, and depths from 3 to 8-10 m. The channel fills laterally grade into wing-shaped floodplain deposits over 100-200 m from the main channel. The mean texture of the sediment ranges from fine gravel to fine sand and silt. The sedimentary structures are dominated by trough-cross bedding.

For some of the deposits ^{14}C datings have been carried out. They show a direct correlation with major eruptional phases of the volcanoes in the adjacent island arc.

Main factors causing channel infill turned out to be:

* Eruption of volcanic ashes followed by a short period of heavy downpour within few years after the eruption, washing down-fan high amounts of sediments from the mountain slopes.
* A decrease of the gradient and the change in river geometry at the transition of alluvial fan (braided streams) to the alluvial plain (meandering patterns).
* The extremely high sediment loads during high discharge periods leading to choking of the meandering channels.

Considering the character of the fining upward sequence in the channels, channel infill appears to occur in one rapid continuous process. Three phases can be distinguished:
Phase 1 is the initiation period with high amounts of rainfall in the whole area, leading to highly sediment loaded rivers and inundations in the lower parts of the area. In **phase** 2 deposition of the sediment takes place in the meandering and anastomosing river parts under normal flow conditions. This leads to chocking of the old river beds and changing of the river course. **Phase** 3 represents the period after deposition. In the first weeks the river occupies both old and new channels. After some years, a new vegetation cover has developed on the filled channels and clay compaction occurs.

I. INTRODUCTION

This study concerns volcanic-induced episodic fluvial sedimentation processes in the alluvial plain of the Atlantic Zone of Costa Rica (fig 1.1).

River systems in humid tropical areas are very dynamic. Rivers are characterized by high and variable discharges and the sedimentary basins show high sedimentation rates. When sediments are derived from an active volcanic mountain range sedimentation processes are very irregular due to the (episodically) abundant availability of fresh volcanic sediment. This is the case for the back arc basin, in which the Atlantic zone of Costa Rica is situated (fig 2.1). Volcanic eruptions irregularly supply ashes into the basin and into its surrounding area. After eruptions sediment loads of the rivers draining the volcanic arc increase considerably.

Costa Rica is a Central American country situated between Nicaragua and Panamá (fig 1.1). Costa Rica and Panamá are parts of a still active island arc. The Atlantic Zone is situated in the northeast of Costa Rica. It can be subdivided into three morphological units based on fluvial characteristics (fig 1.2): river channels deeply incise in the mountain area and change into braided river at the footslopes and at the alluvial fan. They change into meandering rivers on the alluvial plain, and show anastomosing[1] patterns in the swamps of the coastal plain.

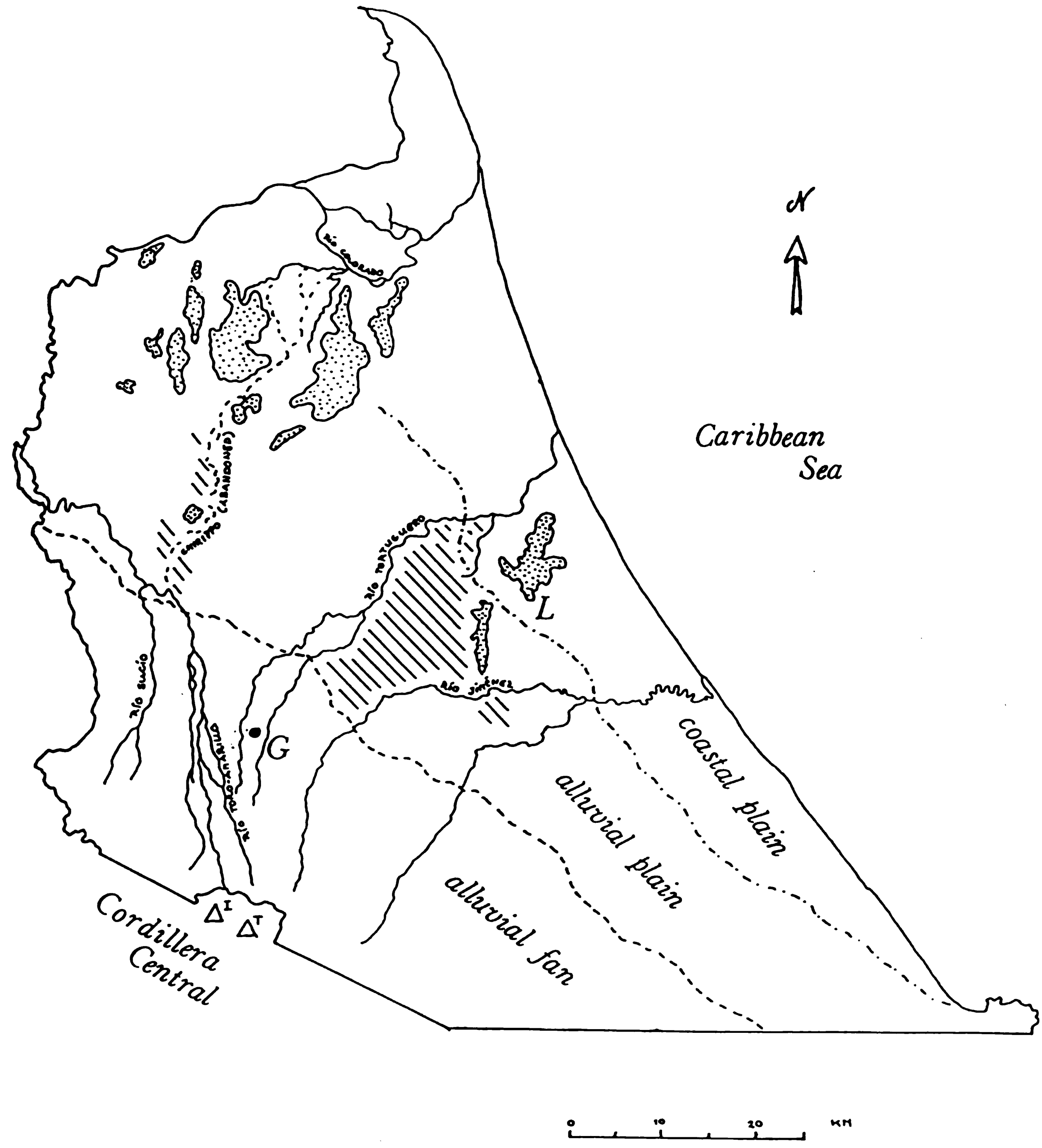
The study was carried out in the alluvial plain in the area near the hills of "Lomas de Sierpe" (fig 1.2), where elongated channel-fill sand bodies are abundant.

This study is a continuation of a previous study by van Ruitenbeek (1993), who studied similar deposits on the Yucatica farm (fig 3.1 gives the locations of the studied outcrops) in the same area. Other work on fluvial sedimentation in the area was done by Hartman (1991), who studied landslide risks in the Cordillera Central and the relation between processes in the mountains and the abandoned river course of the Río Chirripó; and by Kesel and Lowe (1987) who studied the fan processes in the braided area of the Río Toro Amarillo.

This study involves field observations, textural analysis and a literature study.

[1]According to Smith and Smith (1980): an *anastomosing river* is an interconnected network of low gradient, relatively deep and narrow straight to sinuous channels with stable banks, composed of fine grained sediment (silt/clay) and vegetation.

ZONA ATLANTICA



⁘	PLEISTOCENE BASALTIC VOLCANO
L	LOMAS DE SIERPE [HILLS]
I	IRAZÚ VOLCANO
T	TURRIALBA VOLCANO
G	GUAPILES
\\\\\\	STUDY AREA

Fig 1.2 The Atlantic Zone with study area.

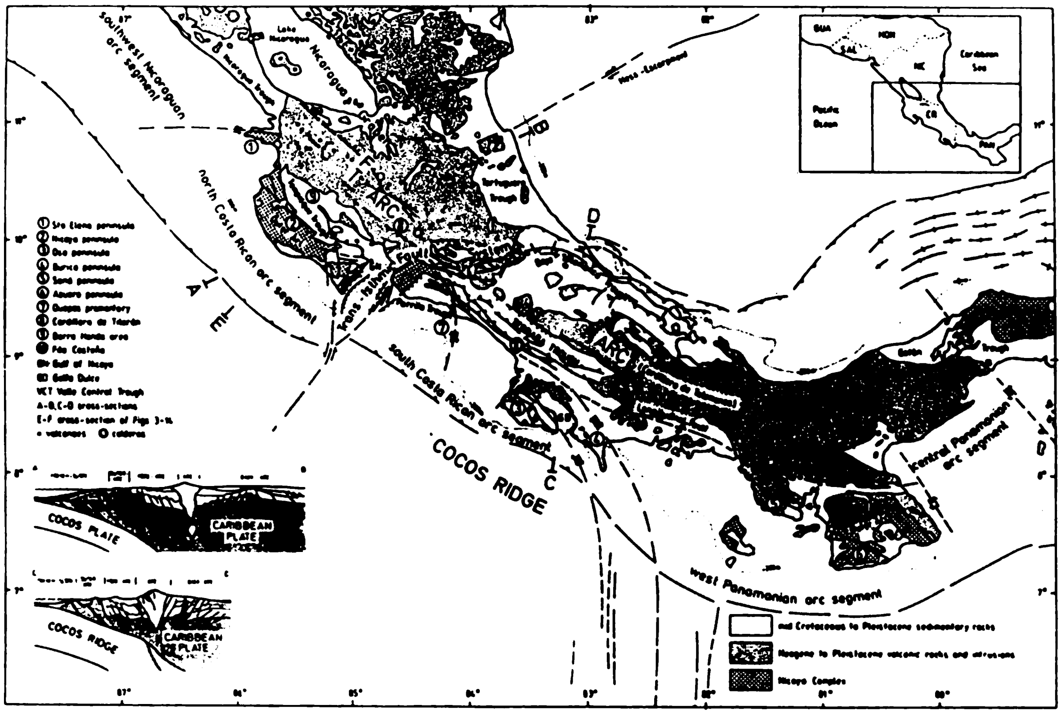


Fig 2.1 Structural map of southern Central America, showing major tectonic elements, main tectonostratigraphic units, large sedimentary basins, and localities mentioned in text. Synthesized after Case & Holcombe (1980), Dengo (1962), Campos (1987), Fernandez (1987), Gardner *et al.* (1987), Berrangé & Thorpe (1988), de Boer *et al.* (1988), Denyer & Montero (1989), Astorga *et al.* (1989), Berrangé *et al.* (1989), and unpublished mapping by the authors.

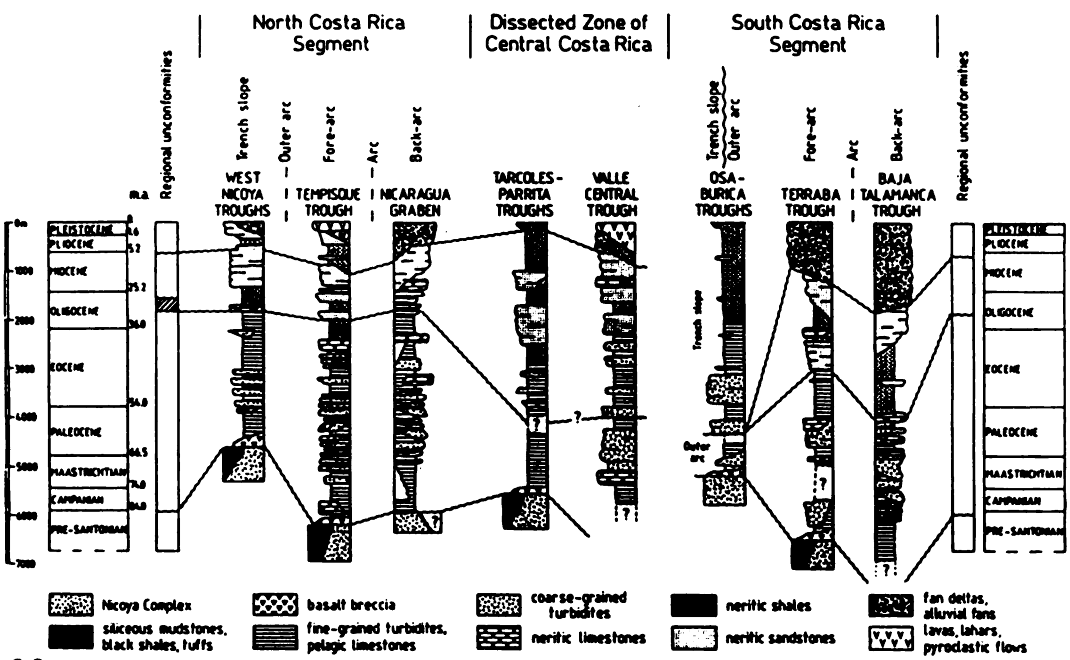


Fig 2.2 Generalized stratigraphic sections along and across the Costa Rican part of the south Central American isthmus. For location, compare with Fig. 2. Compiled after Astorga *et al.* (1989), Rivier & Calvo (1988), Corrigan (1986), and unpublished data from the authors.

II. GEOLOGICAL SETTING

The Southern part of the Central American isthmus is part of an island arc. This island arc was developed by subduction of the Cocos and Nazca plates beneath the Caribbean plate, which started in the Albian-Santonian (Seyfried *et al,* 1991) (fig 2.1). Costa Rica is situated on the northern part of this island arc.

The present Limón Basin was developed from the Tertiary Limón Trough and is situated in the southernmost part of the Nicaragua graben (Weyl, 1980). This graben started to subside in the Late Miocene and may still have been active at the beginning of the Late Pliocene (Seyfried *et al*, 1991). The Tortuguero Trough (fig 2.1) is situated in the Limón basin.

Since the Late Cretaceous the Limón Basin has been filled with a shallowing upward sedimentary sequence with a thickness of about 8 km thick. The final transition from marine to terrestrial deposition took place in the middle Miocene. However, marine ingressions continued until the early Pliocene (Seyfried *et al*, 1991). The Quaternary deposits in the eastern part of the basin reach up to 500 m thickness, which indicates a mean subsidence rate of 0.25 mm/yr (Nieuwenhuyse/RECOPE, 1991).

The sediments in the Tortuguero Trough, which is the northern continuation of the Limón basin, are largely undeformed (fig 2.1 and 2.2). The southern part of the Tortuguero Trough is bounded by the Trans-Isthmic Fault system. The northern part of the trough is dissected by the Hess Escarpment, a strike-slip fault which may have been active until the Pliocene.

At the western side the study area is bordered by volcanoes of the Cordillera Central, which were mainly built up during Pleistocene times (Seyfried *et al*, 1991). Earthquakes frequently occur in the basin and the area that surrounds the basin.

Fluvio-volcanic Pleistocene deposits cover an area of 390 km² in the present landscape of the study area (fig 2.3). The deposits were dissected by the last glaciation (8000 yrs B.P.) and weathered to a depth of several meters. Because of their red color they are known as "Tierras Rojas" ("Red Hill deposits"). Radiocarbon datings indicate that these deposits are older than 50000 yrs, because they fall beyond the ^{14}C resolution range (van Ruitenbeek, 1993).

The Holocene infill of the Limón basin is, like the Pleistocene sediments, mainly composed of fluvio-volcanic sediments derived from the Central-American arc. In the southern part the sediments are derived from the Cordillera de Talamanca, which is composed of Tertiary volcanic and plutonic rocks and Late Cretaceous and Tertiary marine sediments.

Several rivers draining the slopes of the volcanoes of the Cordillera Central (see fig 2.4) supply sediments in the studied (northern) part of the basin. These sediments mainly consist of andesitic and lati-andesitic volcanic rock fragments of the still active Central American arc.

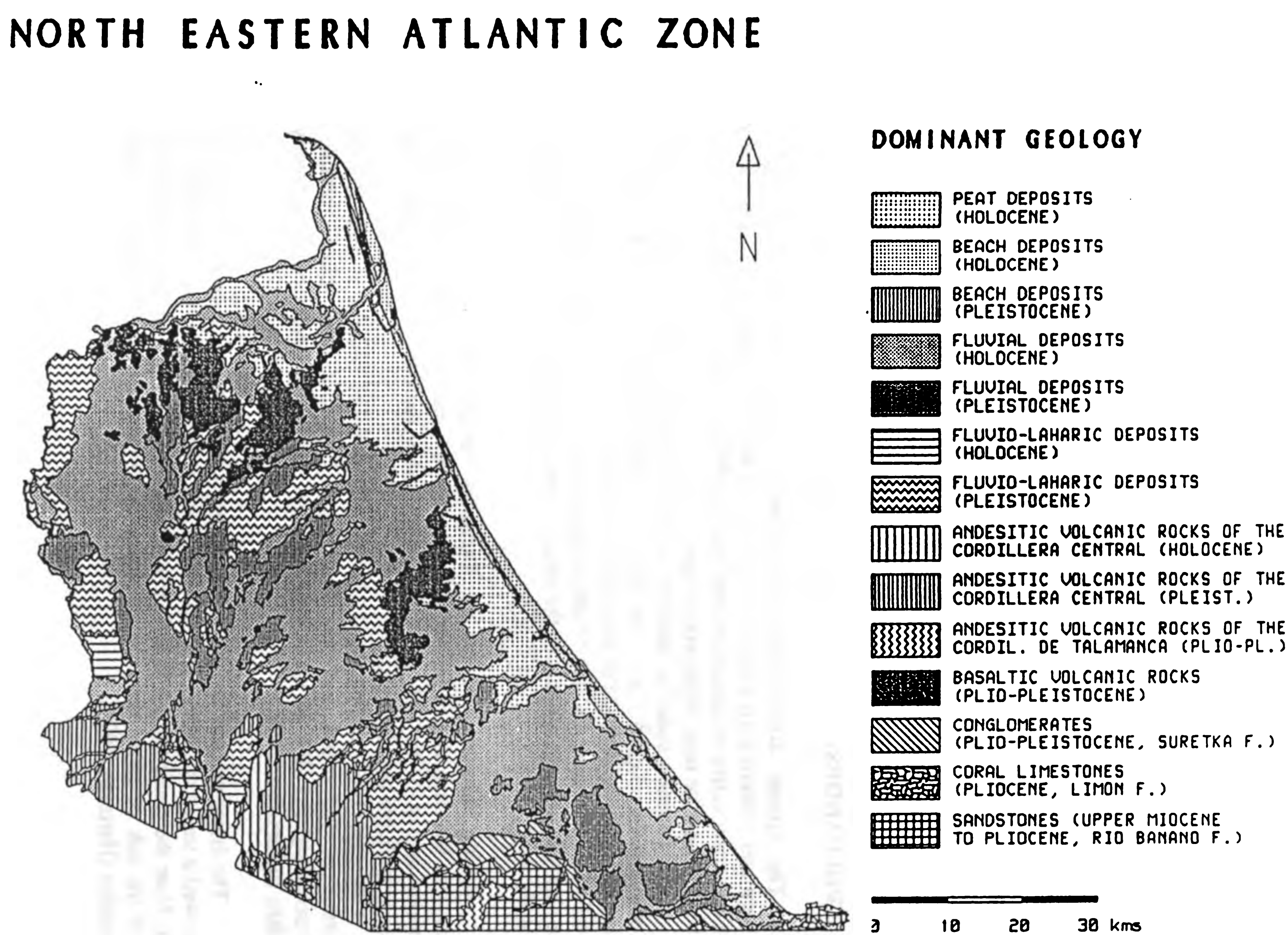


Fig 2.3 Geology of the Atlantic Zone.

The Holocene fluvial deposits cover an area of 2800 km^2 and were found not to be older than 6000 yrs. The Holocene sea-level rise caused the infill and covering of the older (Pleistocene) landscape.

In the northeastern part of the basin remnants of small basaltic volcanos crop out, reaching a height up to 300 m (black in fig 2.3). They were still active within the Pleistocene and were assumed to have erupted through small fissures as a result of back-arc extension (Weyl, 1980). They have been strongly weathered like the fluvial, Pleistocene deposits. One of the lavas was dated at 1.2 ± 0.4 Ma.

The cones consist of lapilli and bombs and the composition according to the Rittmann-Streckeisen definition is olivine hawaiite (Weyl, 1980). On the landward side of these hills lagoons with tidal influence have formed as revealed by shells found in the sediments of this zone. The shells were dated by ^{14}C methods which gave an age of 34,000 yrs B.P and were found at a depth of 26 m below the recent surface.

II.a VOLCANOES

The Atlantic Zone is bordered by the volcanoes of the Cordillera Central in the southern and western parts (fig 2.5 and 2.6). For the sedimentary infill of the study area the most important active volcanoes are the Irazú (3432 m) and the Turrialba (3328 m) (fig 1.2). Both are composite large strato volcanoes.

The Turrialba shows an andesite to rhyodacite composition according to the definition of Rittmann-Streckeisen, and the Irazú a quartz-latiandesite, quartz-latite to dacite composition (Weyl, 1980). The Poás, the Cacho Negro, the Barba and other volcanoes of the Cordillera Central may also have been of importance for the sedimentary infill of the Atlantic Zone, but the drainage systems of the rivers draining the slopes of these volcanoes are outside the study area.

During the past 2000 yrs the **Turrialba** volcano explosively erupted at least four times. The last time was in the period between 1864 and 1866. The volcanic deposits of the Turrialba consist of air fall, pyroclastic flow and pyroclastic surge deposits. The clasts in these deposits are usually angular.

Reagan (1987) distinguished 13 stratigraphic units, whereas at least 16 eruptions are recorded in the crater and summit region. Combined with older volcanic deposits approximately 2.1 Ma of arc-related volcanic activity is represented. Currently it only exhibits fumarolic activity.

The **Irazú** erupted two times this century: in 1920 and between 1963 and 1965 when it showed a series of earthquakes and violent ash eruptions. Ashes were deposited towards the west. Near the crater the ash layers show a thickness of up to 2 m, but it is estimated that 50 % of the ash or more was washed down by erosion during the first rainy period after deposition (Hartman, 1992).

Fig 2.4 Overview of the Drainage Pattern of the Atlantic Zone.

II.b THE ALLUVIAL FAN

The Río Toro Amarillo (fig 2.5) is the most important river that drains the slopes of both the Turrialba and Irazú volcanoes. The catchment basin has an area of 138 km². The fan including its active and inactive parts, covers an area of 162 km² and merges seaward into a broad coastal plain with a minimum width of slightly more than 20 km (Kesel and Lowe, 1987).

The alluvial fans in this area are dominated by episodic eruptive, tectonic and climatic events, which cause short periods of high sediment discharge separated by longer inactive periods. These inactive periods are characterized by weathering, erosion and reworking of the fan sediments.

Radiocarbon datings yielded that this fan has been active for more than ± 10,500 yrs (Kesel and Lowe, 1987).

In periods of high discharge other, now smaller, rivers, which have their courses into the Atlantic lowlands like the Río Tortuguero and Río Suerte, may have been activated again and (re)connected with the Río Toro Amarillo. The Río Tortuguero was, according to the 1952 aerial photographs of the area, previously a major branch of the Río Toro Amarillo. The 1960 photos show only a connection during flood stages and recently its source is situated ± 10 km down-fan of the Río Toro Amarillo and the small river is now reworking and transporting its own sediments (van Seeters, 1992).

The eruptions of the Irazú during the period between 1963 and 1965 resulted in an increase in sediment yield in the Toro Amarillo and produced major changes in fan characteristics over a ten-year period.

Fan architecture resembles that of the Donjek River distinguished by Williams and Rust (1969). Between the fan apex and the intersection point the river consists of one single channel (100 m wide during flood stage). Downstream of the intersection point the river shows a braided pattern, but at low discharges only one channel is occupied (maximum width of 400 m during flood stage). An indication of the discharge during normal circumstances and during flood stages is given in table II.1.

Since the last eruption of the Irazú Volcano an increase in width of the active channel has been observed, locally to 200 m or more, by erosion and removal of high proportions of vegetation. The river pattern has changed from anastomosing into braided, and the main channel showed a fivefold increase in channel width. Large amounts of new sediment were deposited on the new fan surface, but the bulk of this sediment consists of older lithic debris and not of newly formed ash or eroded fresh lavas (Kesel and Lowe, 1987).

All debris found on the recent fan represents volcanic and volcani-clastic rocks of the northern slopes of the Irazú.

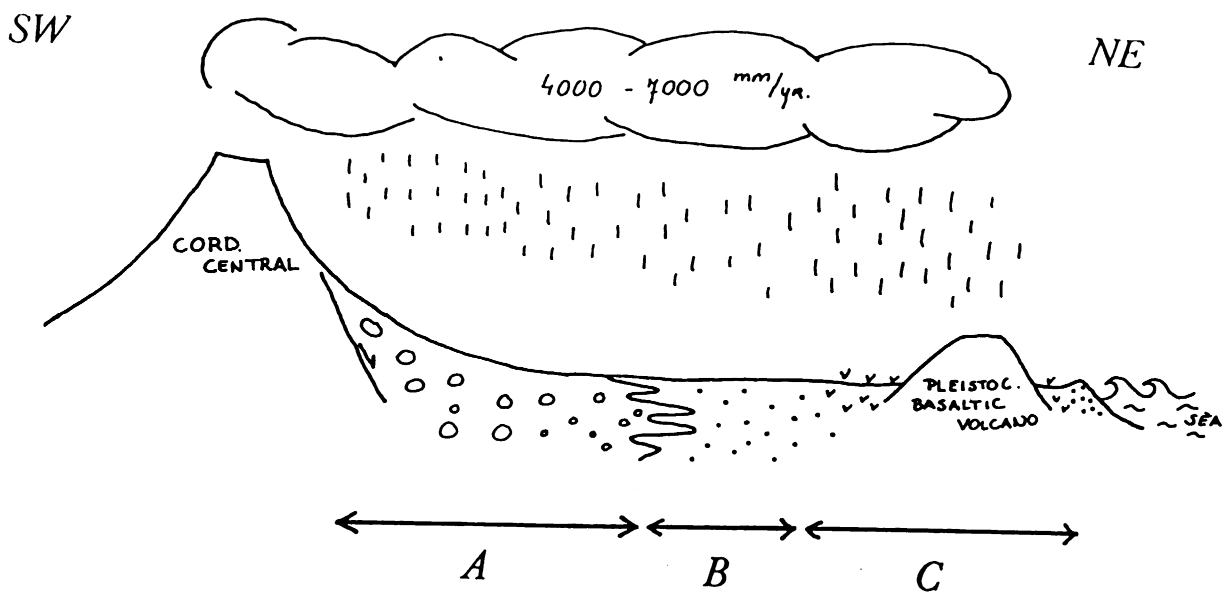


Fig 2.5 Schematic cross section of the Atlantic Zone.
Characteristic river patterns:

A. Alluvial fan - Braided rivers
B. Alluvial plain - Meandering rivers
C. Coastal plain - Anastomosing rivers

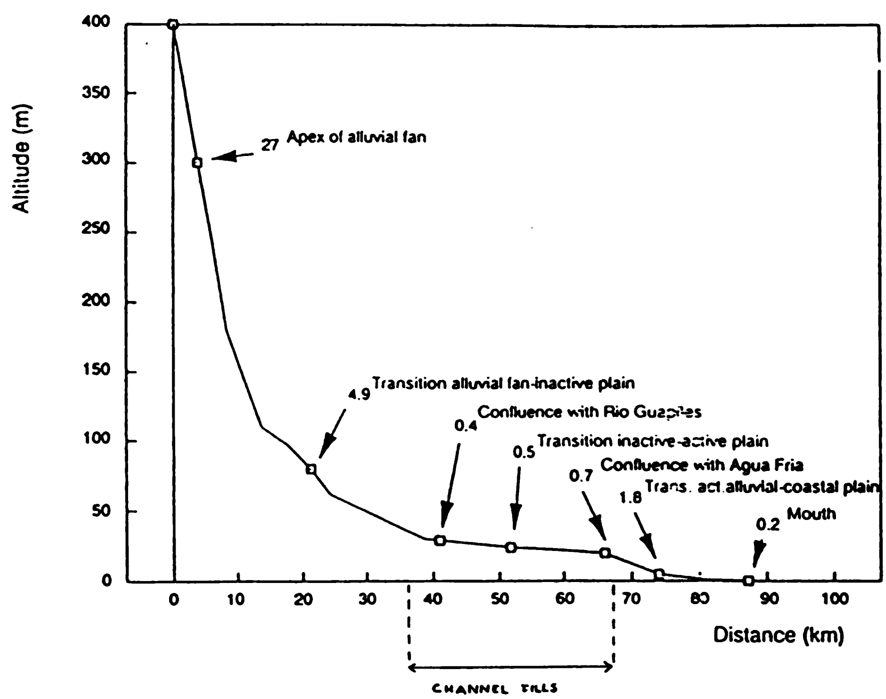


Fig 2.6 Cross section of the Atlantic Zone with gradient changes along the Río Tortuguero (after Van Seeters, 1991). Channel infill only occurs in the area which is characterised by a low gradient (alluvial plain).

Table II.1 River discharges of the Toro Amarillo-Tortuguero river system (Van Seeters, 1991).

River	Location Nr[a]	Suspended load (g/m3) Normal	High	Flood (Aug-91)
Toro Amarillo	1	35	400	7000
Tortuguero	3	30	70	-

Characteristics	Toro Amarillo-Tortuguero
Watershed[a]	400 km^2
Catchment area[a]	160 km^2
River length	
Total	112 km
Erosion[b]	31 km
Deposition[c]	81 km

[a] Depicted on fig 2.2.
[b] Length of river in part of drainage area where net erosion takes place.
[c] Length of river in part of drainage area where net deposition takes place.

II.c ALLUVIAL PLAIN

Downstream of the alluvial fan the rivers tend to have a meandering course (oxbow lakes in abandoned meanders are visible on aerial photographs of 1984), which changes into an anastomosing pattern (see footnote Chapter I) in the area where the coastal swamps are reached. The rivers incise into the Holocene fluvial, floodplain and swamp deposits and the Pleistocene "Tierras Rojas".

The sediment load of the rivers mainly consists of coarse sand. Towards the coastal swamps the grainsize decreases to medium-to-fine sand interbedded in muddy swamp deposits, containing abundant organic matter.

The Holocene deposits in this area show an alternation of sandy and clayey layers in beds of variable thicknesses, up to 1 m.

Extremely thick crevasse-splay sediments (coarse-to-medium sand up to 1.2 m in thickness) are found in this area. Sometimes they are interbedded between the swamp and floodplain deposits.

The elongated channel-fill sand bodies, which were subject of study, are only found in the alluvial plain. The total area covered by these sediments is 300 km^2.

II.d COASTAL PLAIN

A sandy beach ridge plain is situated along the Caribbean coast. The geochemistry of these coastal sands corresponds to the geochemistry of the different eruptions of the volcanos in the Cordillera Central during the last 2000 yrs (Nieuwenhuyse en Kroonenberg, 1993) and also indicates the large influence of episodic volcanic sediment supply in this region.

Near the Caribbean sea a swamp area has been formed. Coast parallel lagoons are found behind the beach ridges. As a result of the low gradient (< 0.3 m/km) and the dense vegetation in this area anastomosing river patterns occur (fig 2.7).

II.e CLIMATE

Climate is also a main factor causing episodic and irregular sediment supply in the Atlantic Zone.

The humid tropical climate includes considerable rainfall (200 to 250 days/yr) and a mean average temperature of 25° (Nuhn *et al*, 1967). The mean annual precipitation in the area varies between 3500 and 5500 mm, and reaches a value of 7500 mm/yr in the mountains of the Cordillera Central (van Seeters, 1993). Of the annual precipitation 60% is caused by "temporales", heavy rainfall, which frequently occurs during the last months of the year (Nuhn *et al*, 1967).

After the last glaciation 8000 years B.P. the climate remained stable and did not show many differences with the recent climate (Nieuwenhuyse, pers.comm.). Therefore long-term climate variations are considered not important in this study of Holocene sedimentation.

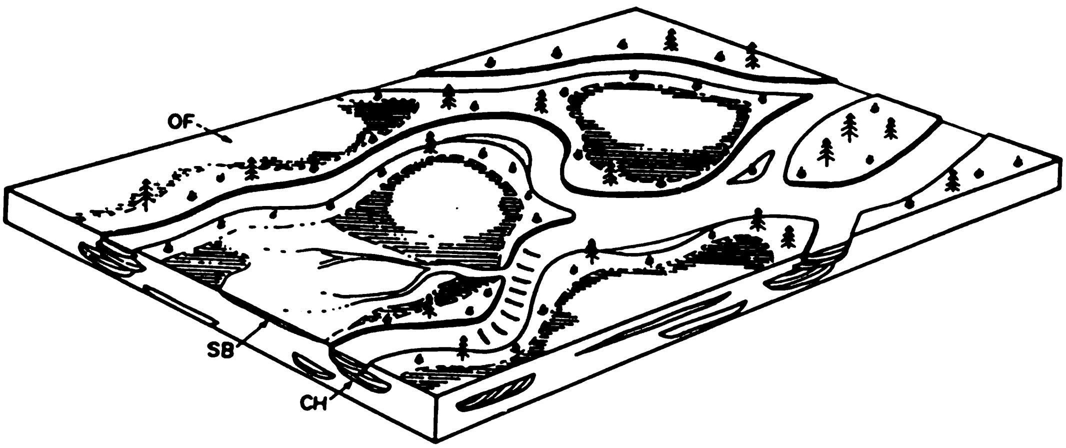


Fig 2.7 Example of an anastomosing river. Horizontal ruling on the top surface of the diagram indicates swamp vegetation, and encloses areas of open water comprising small, shallow, floodplain ponds. Channels are interconnected in a low gradient area. (CH channel; SB swamp bog; OF open water floodplain). [Diagram: Walker, 1991].

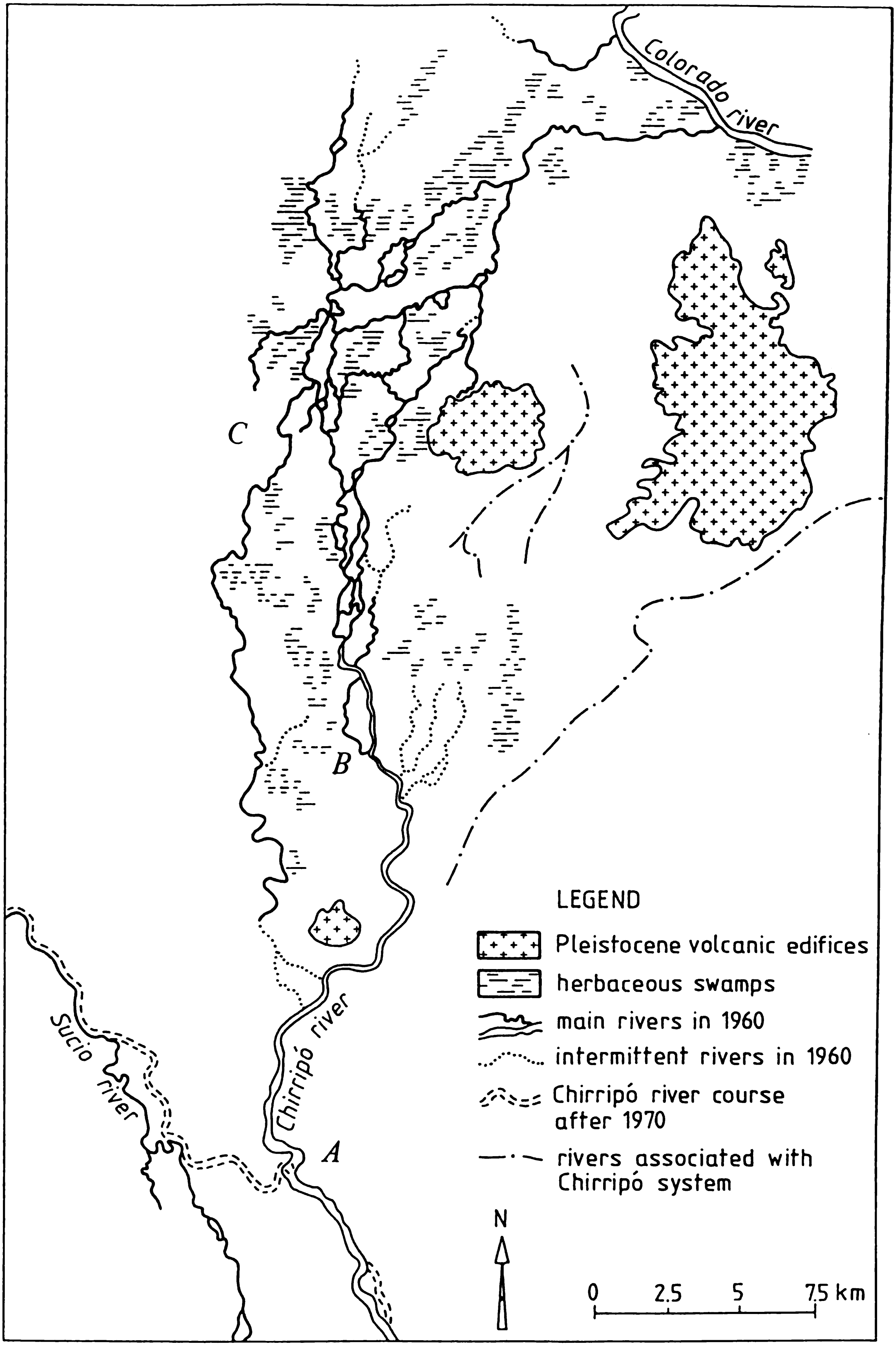
The high rainfall often causes landslides high up in the mountains. Because of the rapidly increasing discharges of the rivers during high rainfall, the landslide debris and some fan material can be transported into the lowlands, where inundations often occur.

II.f VEGETATION

The area is densely vegetated with humid tropical forest. The vegetation cover stabilizes mountain slopes and river banks and protects them against erosion. The relative stability of the river banks prohibits fast and large-scale lateral migration of the meandering channels in the alluvial plain.

During volcanic eruptions vegetation on the mountain slopes is covered by ashes and destroyed.

Since the 1950-ies cultivation of the Atlantic Zone has intensified, and large parts of the forest disappeared, mainly in the alluvial fan and in the alluvial plain. This is a recent development which did not influence on sediment deposition during earlier Holocene times.


Colorado river
C
B
A
Chirripó river
Sucio river
LEGEND
Pleistocene volcanic edifices
herbaceous swamps
main rivers in 1960
intermittent rivers in 1960
Chirripó river course after 1970
rivers associated with Chirripó system
N
0
2.5
5
7.5 km

Detailed study of the deposition of sand bodies in the alluvial plain of the Atlantic Zone

In the alluvial plain channels completely filled by sand are a very common phenomenon. From the transition of the alluvial fan to the alluvial plain downstream many elongated sandy channel fill deposits are found. The youngest of these channel fills, the Río Chirripó was deposited downstream from the transition from the alluvial fan into the alluvial plain after a period of very high rainfall in 1970, about five years after an eruption of the Irazú in 1963-1965 (see Chapter II.a). As can been seen on aerial photographs of 1961 and 1984 of the channel fill of the Río Chirripó (fig 3.1) the pre 1970 course is choked and filled with sediments, while the river has shifted its course towards the west, occupying an old, abandoned meander.

A channel may be filled by about 6.10^6 to 24.10^6 m^3 sediment, deposited during one catastrophic event, relating the high amounts of fresh sediments deposited after an eruption and the extremely high rainfall that regularly occur in the Atlantic Zone.

Ten of this kind of sand bodies were selected for a detailed description, although more sand bodies occur. Locations of the studied sand bodies are shown in fig 3.2. The Yucatica sand body has already been described by van Ruitenbeek, 1993.

Two of the sand deposits, La Guadalupe and Mola II, are situated in the distal part of the alluvial fan and show fan influences. At these locations remnants of sheet-flooding were found, consisting of coarse to very coarse sand and boulders of $\pm$ 25 cm. In this report they are called "proximal sand bodies", because they are situated most upstream of all sand bodies. The other sand bodies, which were less coarse and were interbedded in a swamp environment lacking hyperconcentrated flood flow deposits, are called "distal sand bodies". They are situated in the alluvial plain about 10 to 15 km downstream of La Guadalupe and Mola II.

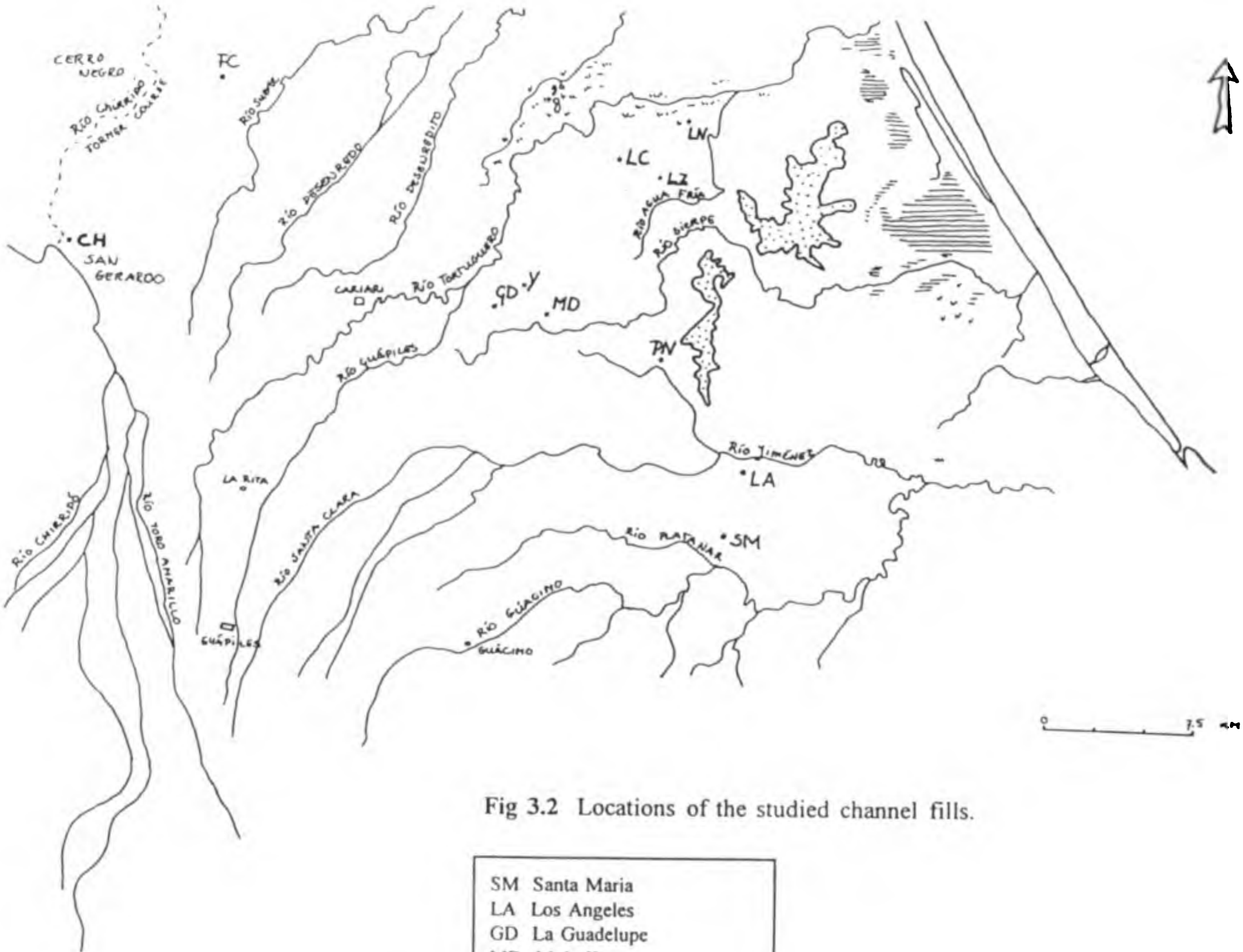


Fig 3.2 Locations of the studied channel fills.

SM	Santa Maria
LA	Los Angeles
GD	La Guadelupe
MD	Mola II
Y	**Yucatica**
PN	**Calinda**
LC	**Lomas I**
LZ	**Lomas II**
LN	**Lomas III**
CH	**Chirripó**
FC	**Finca Cobal**

Fig 3.1 **The former 1970 course of the Río Chirripó. The new course is also indicated. At the point of changing an unusual nick was present, and caused inundations and blocking of the course. The new course occupied an old oxbow lake.**

⟵

III. METHODS

Observations in this study were mainly based on studying outcrops. In these outcrops vertical profiles were drawn of the sand deposits and sometimes samples were taken for textural analysis and radiocarbon datings. Aerial photographs of the most recent channel fill were studied to give a better overview of the process of channel infill.

III.a Outcrops

The vegetated, humid tropical area hardly shows any (deep) outcrops. In most cases outcrops were studied in canals, dug in banana plantations. These canals[2] commonly have a depth of ± 2-4 m and a length between 100-200 m. Best outcrops were found in recently dug canals, because it takes only a few months in which the the canal walls become vegetated (fig 3.3). Thus, sedimentary structures could be best examined in the most recent canals. In most cases the upper metre of the studied profile was disturbed by pedogenesis.

When more information was needed about deposits deeper than the canals or when no canals were present at a specific place, auger borings were made. For the borings an "Edelman" hand-bore was used. These borings give only information about the texture of the sediment; sedimentary structures are disturbed by this method. Maximum depth reached by boring was about 8 m below the surface.

The sand deposits of Lomas Finca III (fig 3.2) were situated in a swampy and forested area and were poorly accessible. They were only studied by borings due to a lack of canals in this part of the banana plantation. In the youngest sand body, that was deposited in 1970 by the Río Chirripó, no canals had been dug either. These Chirripó deposits were studied along a river cutbank, borings, pits, and by means of aerial photographs.

[2] Mark the difference between the term canal, which is dug for drainage, and channel, which is a natural phenomenon caused by river flow.

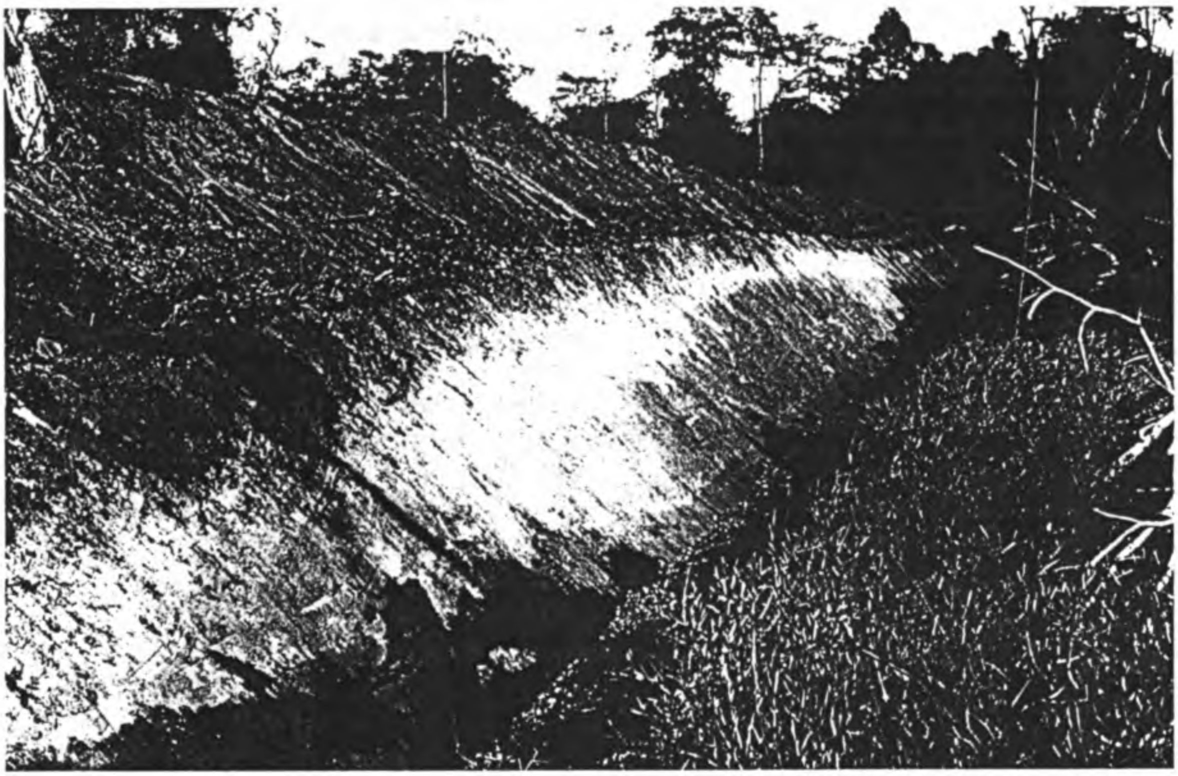


Fig 3.3 Example of an outcrop: canal 1 at Lomas II (App A, fig A.6). Light colours are from the sand of the channel fill, the swamp and overbank deposits are dark in the profile.

III.b Texture

Textural analyses of sediment from several locations were executed. Most samples were taken in the channel fills and channel infill associated deposits. However, a few samples were taken of the sand deposits of flooding events which had not lead to a channel choking, like thin crevasse splay and floodplain sediments. Bulk samples of trough beds, horizontal beds or other sedimentary structures or units were taken. Commonly the samples were taken at a depth of ± 2 m below the surface.
In the laboratory the samples were only dried. The following sieve fractions were analyzed:

2000, 1000, 500, 250, 100 and 53 μm.

When the term ***loam*** is used, a mixture of sand (>63 μm) [35%], silt (2-63 μm)[43%] and clay (<2 μm) [22%] is meant (according to FAO and USDA, 1951).

III.c ^{14}C-Datings

For some of the channel fills radio-carbon datings were carried out. This depended on the fact if organic matter was present directly below the channel fill and also on the interest for another research in soil sciences in the Atlantic Zone (Nieuwenhuyse, in prep).

Organic matter was collected from the clay layer below the channel fill. Preference was given to leave and leave fragments, because of the limited life time of leaves compared to wood and branch fragments.

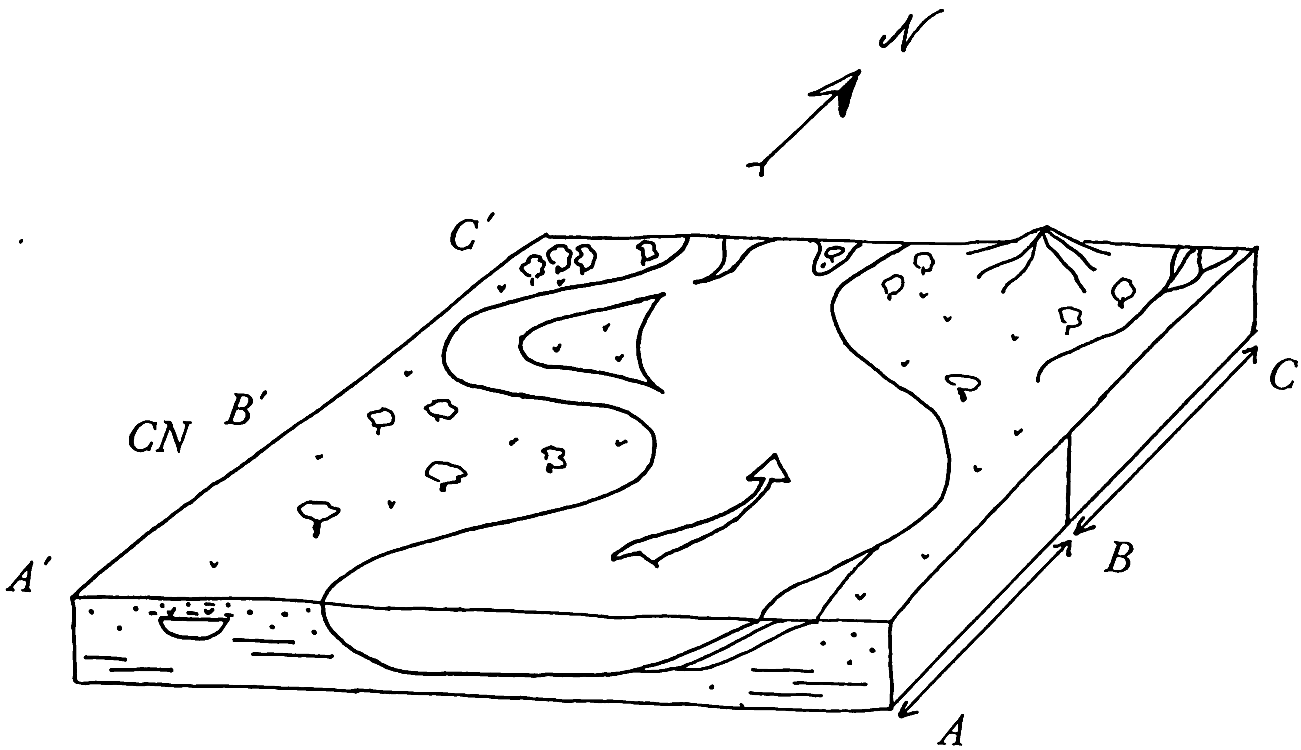


Fig 4.1 Schematic block diagram of the Río Chirripó. Compare with fig 3.2 for the locations.

IV. RESULTS

IV.a Aerial Photographs

Results of studying the 1961 and 1984 aerial photographs of the Río Chirripó are shown in figure 3.1. The 1961 photographs show the situation before the (1963-1965) eruption of the Irazú and before channel choking and course changing of this river in 1970. The 1984 photographs represent the situation after the channel blocking and resemble the recent situation. Gradient changes and a description of the Río Chirripó deposits are given in appendix A and table A.II.

1961 Situation:

In the transition area between braided and meandering river courses an unusual sharp meander bend is found. This bend is located at the place where the channel changed its course, and may be a major reason for changing at this place. Large amounts of sands have been deposited near this critical point.

In this transition area, up to 5 km upstream of the begin of the channel choking (at A in fig 3.1 and at San Gerardo in fig 3.2) the river already shows a tendency to form meanders and large amounts of sand have been deposited at the sides of the main channel along this transect.

At point B, before the area changes in to widespread swamps (fig 3.1 and 4.1), a sand plain can be seen. This place might be critical for the start of the infill process too, because large amounts of sands have been deposited at this place during former (before 1961) inundations.

Between B and C (fig 4.1), i.e. the swamp area, river course of the Chirripó is difficult to follow. Channel width has decreased considerably and the amount of channels has increased. No relicts of sand deposition can be found in this area.

1984 Situation:

On the 1984 aerial photos the abandoned river course of the Chirripó can be recognised. It is exposed as an elongated sand body in the landscape.

The post 1970 course has reoccupied an abandoned meander bend, which was situated just upstream of the sharp meander on the 1961 aerial photos. Recently it follows this old bend, until the river confluences with the Río Sucío. At present the Río Sucío is much wider than before 1970 from this point. Sinuosity of this new course is 1.45, which is much higher than the value of 1.26, which had the Río Sucío before channel changing.

At A (fig 4.1) the sands are deposited over a broader area than that of the former channel width of the river. A part of these sands was already deposited during other smaller scale inundations as mentioned in the description of the 1961 air photos. The newly (1970) deposited sands are distributed between 1 and 1.5 km from the old main channel in westward direction.

The sand plain at B can still be recognized.

Between B and C the abandoned channel has been filled with sands. Near the Río San Juan anastomosing channels drain the area and confluence in the most distal part of the former Río Chirripó that, as before 1970, flows into the Río Colorado. These anastomosing channels seem to be reoccupied by new streams or may never have been completely filled and choked with sands.

IV.b Channels

All sand bodies, except the crevasse splay like sand body found at Lomas finca III (See fig 3.2 for location), show the same sedimentary and morphological composition. Detailed descriptions of the sand bodies are given in Appendix A.

The sand bodies consist of a channel filled with sandy sediments and associated overbank and floodplain deposits (sheet). The channel width and depth vary, depending on the size of the original river bed in which the sediments were deposited.

The width of the channels varies between 40 and 60 m; depth varies between 8-10 m, downstream shallowing to a depth of 3 m towards the distal area (coastal plain), where at present shallow anastomosing rivers occur. The stream direction indicated by the direction of the channel fills is N-NE, which is similar to that of the recent rivers (fig 2.5).

The channel deposits are interbedded in a sequence of alternating clay and thin (5-70 cm) beds of sand (also sandy clay and clayey sand) deposits (a. in fig 4.2) and the deeply weathered remnants of fluvio-volcanic Pleistocene deposits ("Tierras Rojas")(i. in fig 4.2), which are abundant in the distal parts of the fluvial system (fig 2.3). In most cases the floodplain deposits related to the channel fills, pinch out against these "red hill" deposits. The floodplain and crevasse splay deposits often overlie swamp deposits, which can be recognised by their dark grey (reduction) colour and the presence of branches and complete leaves.

The channel fills are thickest in the proximal part of the alluvial plain (deposits of La Guadalupe and Mola II). The accompanying floodplain deposits have a sheet form and show a laterally wide extension. They can be followed over 50-200 m. In the distal swamp areas sheets and channel fills sometimes are covered by younger deposits (mainly clays).

On places where channel fills are not covered by younger sediments, the main channel can be recognized by an elevation of $\pm$ 1 m in the landscape due to relief inversion by clay compaction in the adjacent backswamps.

All channel fills show an overall fining-up in texture and sedimentary structures. The sand body at Lomas Finca III however, is interpreted as a crevasse splay by its lack of a main deep channel fill and its broad lateral distribution.

IV.c Sedimentary sequences in the channel fills

The sedimentary sequences in the channel fills show similar structures. They consist of:

*** Base/Lag deposits (b. in fig 4.2):***
Consisting of gravel and pebbles, or more downstream pebbly very coarse sand. No imbrication was observed. Sometimes horizontal lamination or dunes (up to 0.4 m high) were found. The base commonly has thicknesses of 0.50-1.25 m.
At the base flame structures were discovered, consisting of soft and unripened[1] swamp clay, probably formed by soft sediment deformation of the clay. Also clay clasts occur, with maximal sizes of 12 cm. They also consist of unripened clay and may be eroded and transported parts of the flame structures.

*** Large troughs (c. in fig 4.2):***
Consisting of very coarse sand and sometimes fine gravel, with pebbles up to 25 cm (measured along the a-axis). The width of the small channels varies and is ± 3 m; maximum height is 0.5 m. The sequence of large trough cross beds is in most cases up to ± 1 m thick.

*** Trough cross beds (d. in fig 4.2):***
The trough cross beds decrease in wavelength and thickness up in the sequence. Sizes vary from a wavelength of 120 cm at the lower part of the profile to a wavelength 25 cm in the upper part (fig 4.3). In the upper metre of the profile they change into current ripples which may indicate a decreasing flow velocity. This change into current ripples could only be seen in the youngest deposit, where the ripples had not been disturbed by soil-forming processes. Grainsize fines upward from very coarse to fine sand. Pebbles and gravel ranging from 8.0 to 0.5 cm are always abundant. Sometimes the troughs show mud drapes at their bases.
The trough-cross-bedded part is mostly 2-3 m thick.

*** Channel margins (f. in fig 4.2):***
Characterised by climbing ripples and small trough beds. Remarkable are clay wedges, which are sometimes found at the channel margins. The show lengths up to 1.2 m in the channel.
The wedges consist of unripened clay and are surrounded by gravel and very coarse sand or by small troughbeds (c. in fig 4.2).
Texture of the sand is mainly between medium and very coarse sand.

*** Soils in the floodplain sediments of the channel fill***
(e. in fig 4.2):
In the older deposits the upper 1.0-1.5 m has been disturbed by pedogenesis like bioturbation and growth of rootlets (fig 4.4). In the youngest deposits of the Río Chirripó (age 22 yrs) a soil of only 20 cm thick has developed. Texture of the soils fines up from medium to loamy- and fine sand.

[1] With ***unripened clay***, uncompacted and soft clay is meant. In this kind of clay no soil has been formed. In the area it commonly consists of smectites. Unripened clay is commonly deposited in swamp and poorly drained environments.

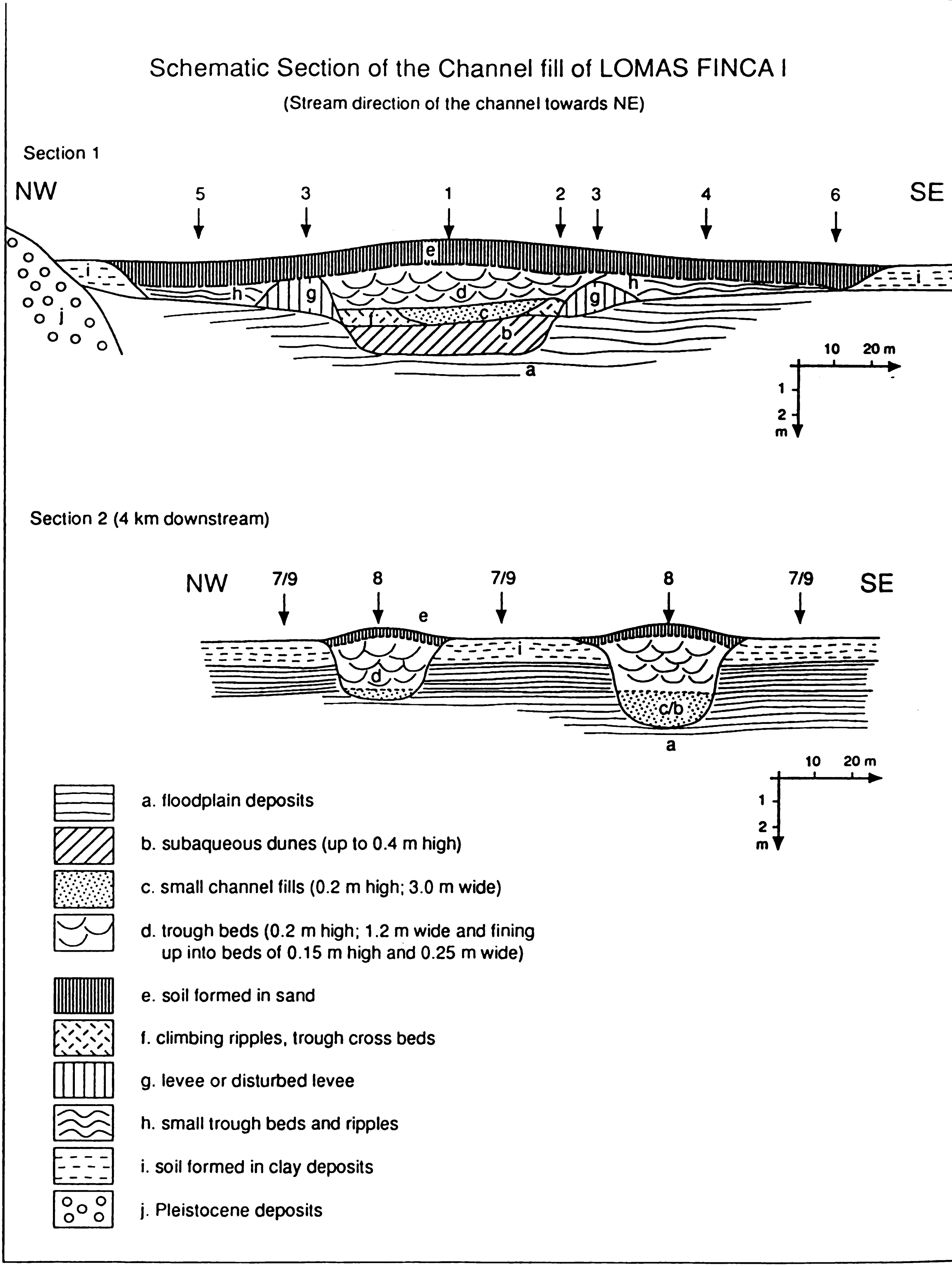
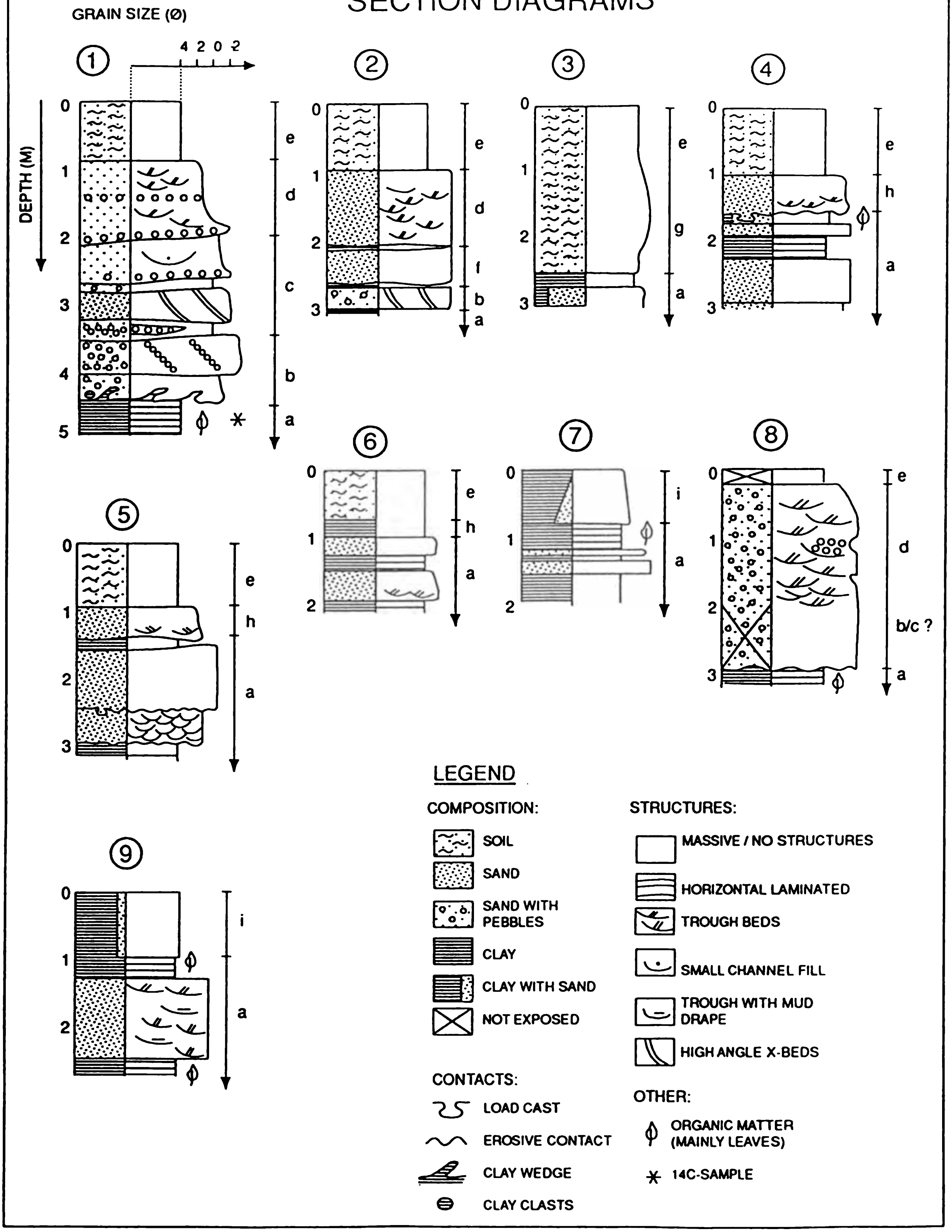


Fig 4.2 Sedimentary infill of a channel. Section 1 and 2 can be found on fig A.5, which shows the locations.

SECTION DIAGRAMS



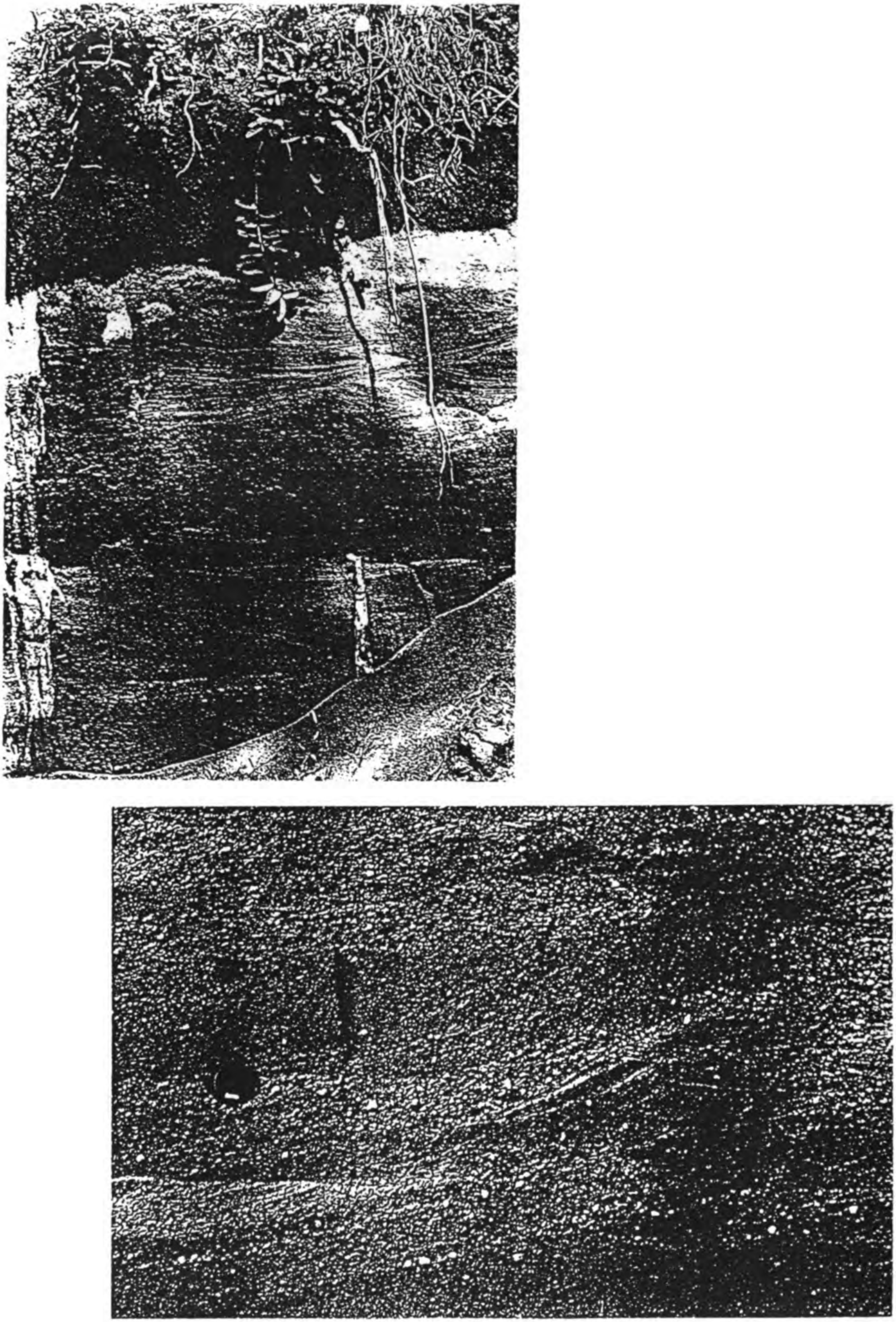


Fig 4.3 Examples of trough cross bedding at Los Angeles

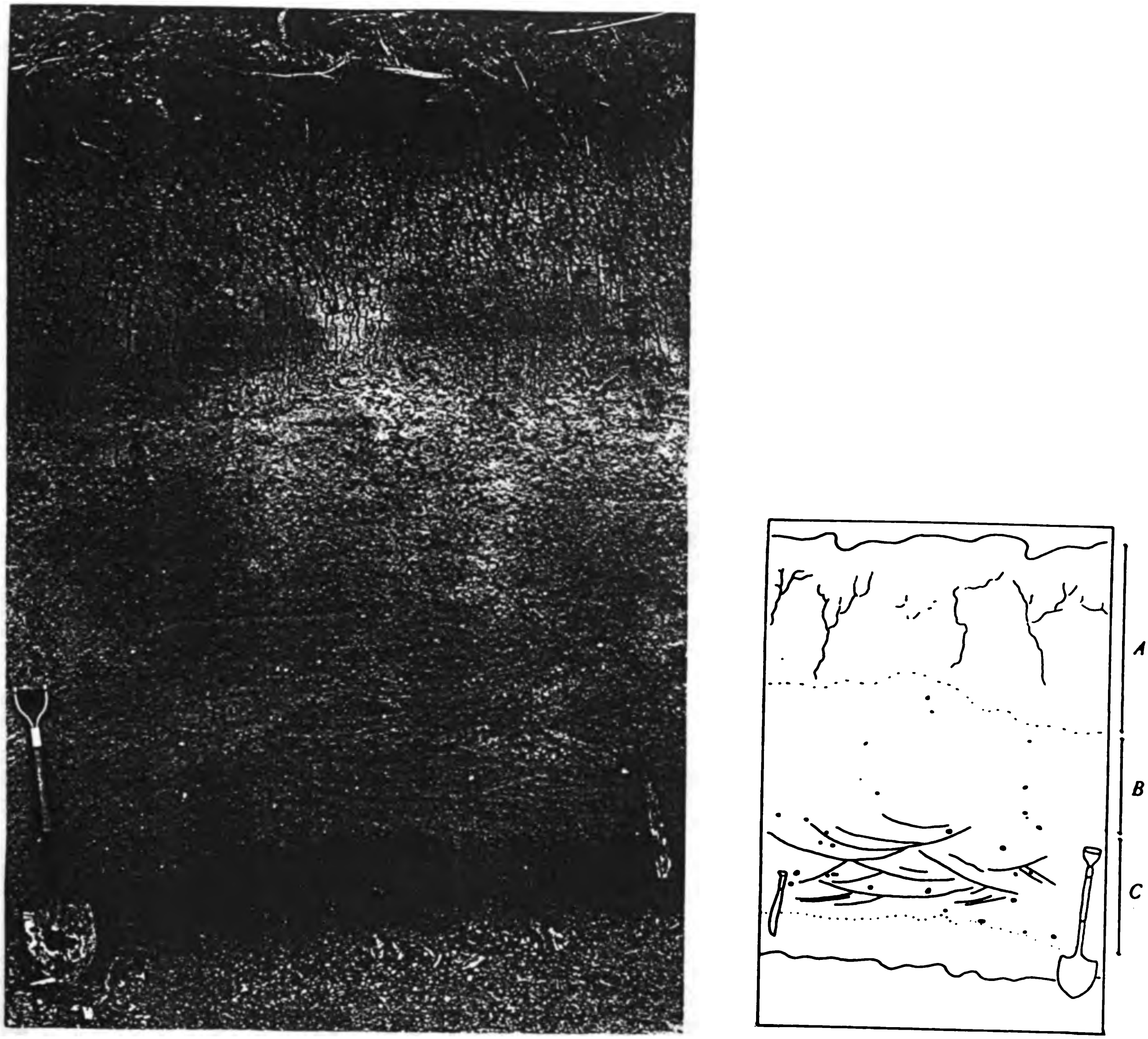


Fig 4.4 The lack of cross bedding in the upper profile is found in most profiles. Probably this is caused by pedogenesis.

*** Levee or disturbed levee deposits (g. in fig 4.2):**
Marked by a high loam content and a lack of sedimentary structures. No clear boundaries were found, because all levees seem to have been disturbed by soil formation. The recent levees of the Río Tortuguero show the same high loam content, which may be characteristic for levees in this densely vegetated area. An exception is formed by the point bar deposit at Lomas Finca II (see description in appendix 1), which can be distinguished by clay drapes (up to 5 cm thick) on lateral accretion planes.

*** Floodplain deposits [sheet or channel wing] (h + e in fig 4.2):**
The floodplain deposits cover the area surrounding the channel fill as a sheet. They vary in thickness. In the downstream parts of each channel fill they disappear (fig 4.2, section 2). Laterally, perpendicular to the channel they can be followed for up to 200 m at the proximally situated locations (La Guadalupe and Mola II), but mainly up to 100 m on the distal locations (the downstream channel fills). The base of these sheets laterally decreases in depth away from the channel fill. It reaches a thickness of 1.0 - 1.5 m near the channel fill, to ± 0.5-0.2 in the backswamp area.
In all studied cases a gradual transition from a sandy soil into a clayey and loamy soil, marks the most remoted parts of the floodplain deposit.
Sedimentary structures like small trough beds (max. 20 cm in wavelength/8 cm thick) are sometimes found at the base of the floodplain deposit, e.g. in the Lomas I and II sand deposits. In the youngest deposit (i.e. the Río Chirripó) current ripples and small dunes (fig 4.5) could be distinguished. However in most cases only pedogenetic features, lacking sedimentary structures were found.

At the bottom parts of these sheets load casts were found regularly. They have a length up to 25 cm and a height up to 8 cm.

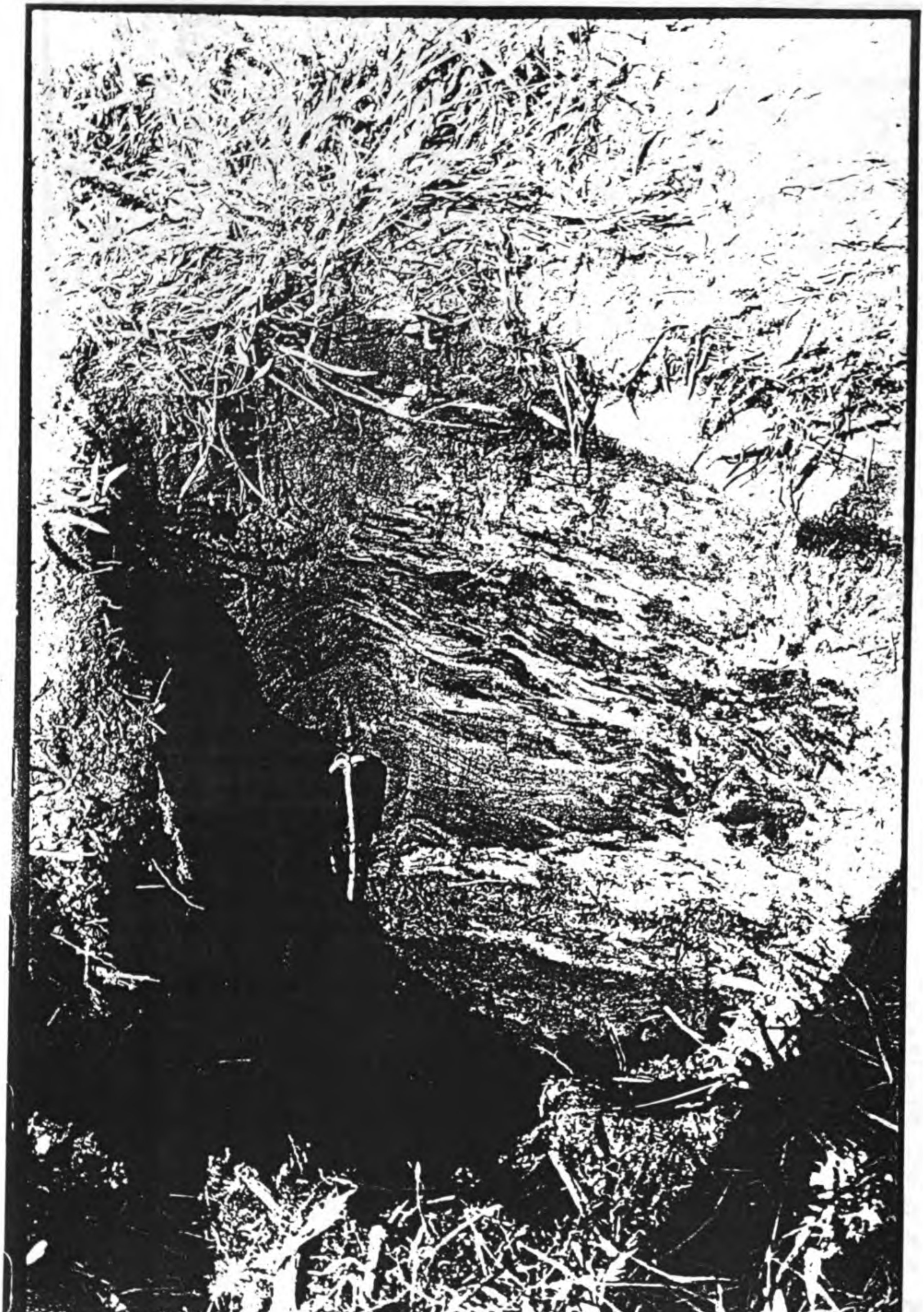
The sedimentary infill of the channels is often asymmetric, reflecting the asymmetry in the river bends. In most cases a coarser filled (cutbank) side could be distinguished, where throughbeds are larger and more pebbles occur than at the pointbar side.

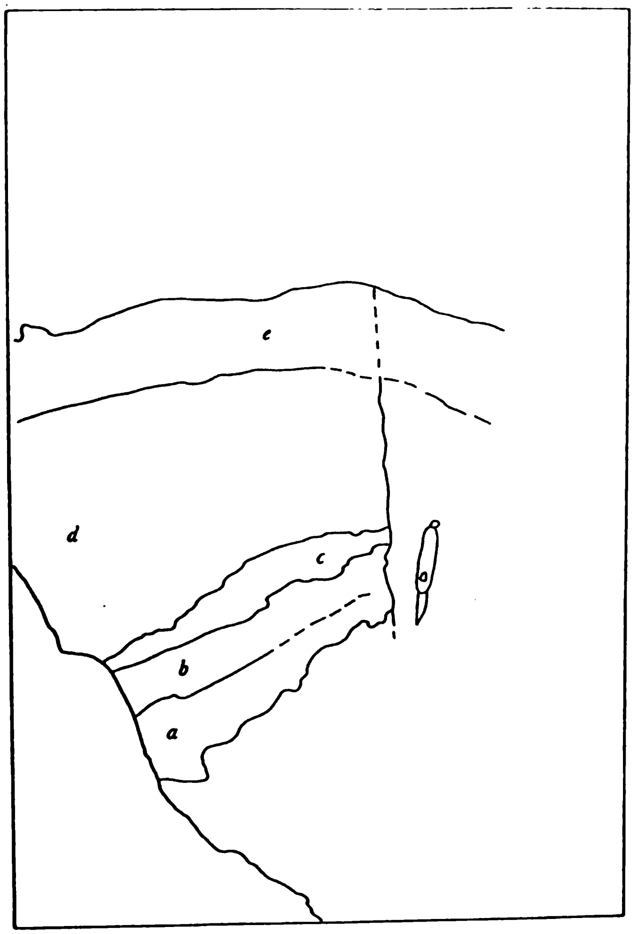
In the floodplain deposits of Lomas Finca II the base is every 3 to 5 m disturbed. These irregular structures are very and loamy and may reach a depth of 0.5-1.4 m (see fig 4.6). They seem to be caused by tree roots and the vegetation cover at the time of deposition.

IV.d Texture

Results of the textural analysis are given in Appendix B.

The cumulative grainsize distributions (App B) show similar trends with long tails in the finer fractions, and short coarse tails, indicating a skewness towards the coarse fractions. Sorting is moderately good, as indicated by the steepness of the slopes in the diagrams. There are differences between curves of the samples taken within the channels, and the samples of the levees and overbank deposits. These samples were influenced by soil forming and had a loamy character, as shown by the high weight percentage of the finer fractions (< 100 μm),





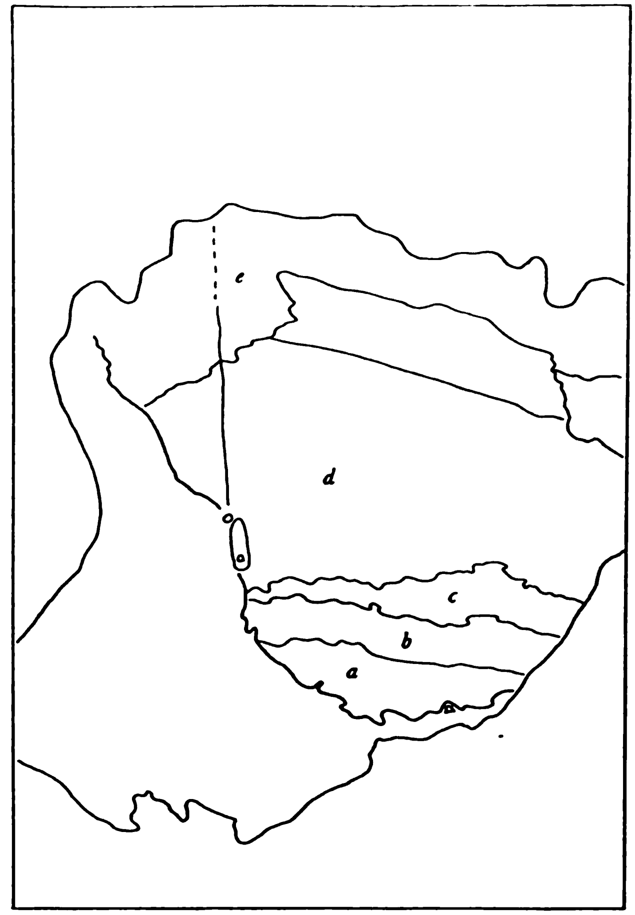


Fig 4.5 Ripples in the Chirripó floodplain sheets. *Flaser beds.*

a. Dark grey clay
b. Soil
c. Fine, silt and clay layer, deposited during an inundation before 1970.
d. Floodplain deposit of 1970.
e. Soil developed between 1971 and 1993.

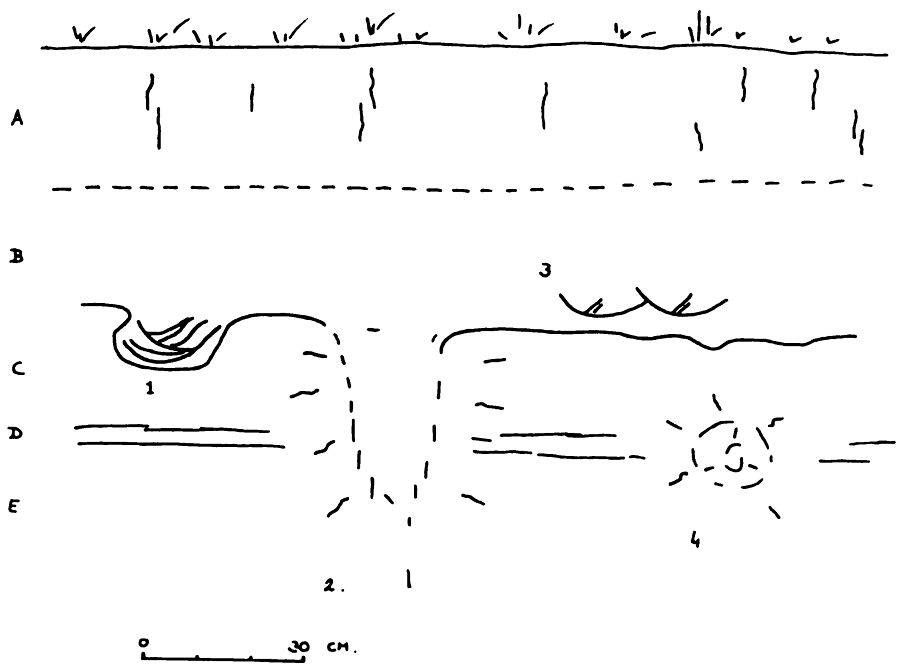


Fig 4.6 Disturbances found in the floodplain deposits of the channel fill.
1. Small runoff channel with convolute bedding.
2. Structure disturbing not only the floodplain deposits of the channel fill. Caused by a tree root.
3. Small trough cross beds.
4. (Tree) root.

A. Soil
B. Floodplain deposits of the channel fill.
C. Clay and silt deposit underlying channel floodplain.
D. Ripened clay layer with organic matter.
E. Swamp clay.

RESERVOIR SEDIMENTATION MANUAL

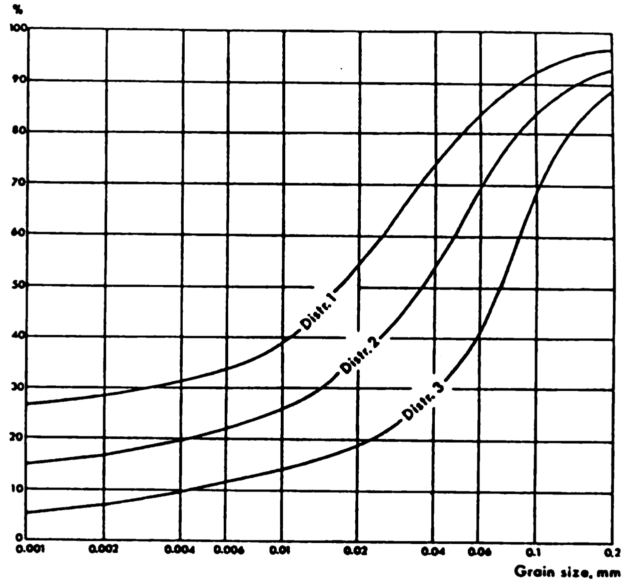


Fig. 4. Three different model grain size distributions for suspended sediments in the tributary rivers of the Cachí reservoir.

Water discharge: 500 m^3/s.
Grain size distribution: distribution no. 2 according to Fig. 4.
Flow conditions: normal flow.
Trap efficiency: at a reservoir level of 990 m the trap efficiency values for different grain sizes are taken from Table 5, discharge 500 m^3/sec.
Calculation: the grain size distribution in Fig. 5 is converted to a frequency curve, the percentages from Table 5 are applied (shown as the trap efficiency curve), and the total remaining suspended load is calculated. In this case, the result is 24% remaining sediments in suspension.

Fig 4.7 Three different model grainsize distributions of suspended sediments in the tributary rivers of the Cachí reservoir.

and a lesser degree of sorting. The sediments of Lomas III, which were interpreted as crevasse splay sediments, show the same curve as the sediments of the other sampled locations (app B).

Results of a study in the same area near Turrialba (Cachí reservoir, Jansson 1993), show the same long tails in the finer fractions and degree of sorting, under normal flow circumstances (fig 4.7). The samples of the present Río Tortuguero also show this similar character in sediment distribution under normal flow conditions as the sampled channel fills, which may indicate that hyperconcentrated flows may be excluded for the process of channel infill. However, in the environments of the proximal channel fills of La Guadalupe and Mola II deposits of hypercocentrated flood flows are found.

Grainsize of the channel fill deposits slightly decreases with distance from the source (Irazú and Turrialba volcanoes) (fig 4.8). Guadalupe (GD) and Lomas I (L1) form exceptions in this pattern, because they are much coarser than the channel fill deposits on the adjacent fincas. The Guadalupe channel fill deposits, which are interbedded with sheetflow deposits, are much coarser than the Santa Maria and Los Angeles deposits. These latter deposits however, are situated in a distinct environment (eastward of the other indicated channel fills, fig 3.2), with abundant Pleistocene deposits and no recorded fan influences, like sheet flooding. Another explanation is the amount of sample that was taken: a few extra pebbles in a sample of $\pm$ 100 gram may give a high percentage in the >2000 μm fraction.

Also the recent Río Tortuguero shows slightly coarser material than the deposits of Lomas II and III. This may be explained by the sampling place. The Río Tortuguero sample was taken in the main channel in the recent river. When this river would fill in, this sampling place would be 5 m below the surface and so would reflect another order of stream flow during the channel infill process than that of the described channel fills, which were sampled at a depth of $\pm$ 2m below the surface.

The pebbles and cobbles which were found in the channels, are commonly sub-rounded to rounded. Sphericity mainly ranges from 0.5 to 0.7. Sphericity and roundness do not change significantly in downstream direction, which is also found for the downstream grain variations between 40 and 60 km from the source of the volcan Fuego in Guatemala, which shows similar fluvial systems on its slopes (Davies and Vessel, 1978).

The pebbles show a volcanic (andesitic) composition. The minerals (plagioclase and feldspar), are mostly weathered. In some cases the minerals still can be recognized, sometimes only small holes remained. Andesitic rock fragments, that are completely weathered into clay pebbles are common in all studied channel fills.

Also vesicular rock fragments and buff (light yellow) pumice particles, of which the latter could be correlated by radiocarbon datings to an eruptional phase of the Turrialba volcano 2000 yrs B.P., occur among the pebbles and cobbles. In the parts of the study area where the Tierras Rojas are exposed at the surface, eroded fragments of these Pleistocene deposits could be found in the channel fills. These fragments are always coarser and less well rounded (mostly sub-angular to angular) than the other pebbles and cobbles in the channel fills. The specific weight of the Pleistocene fragments is less than that of the andesitic particles. This is accounts also for the pumice particles and vesicular rock fragments.

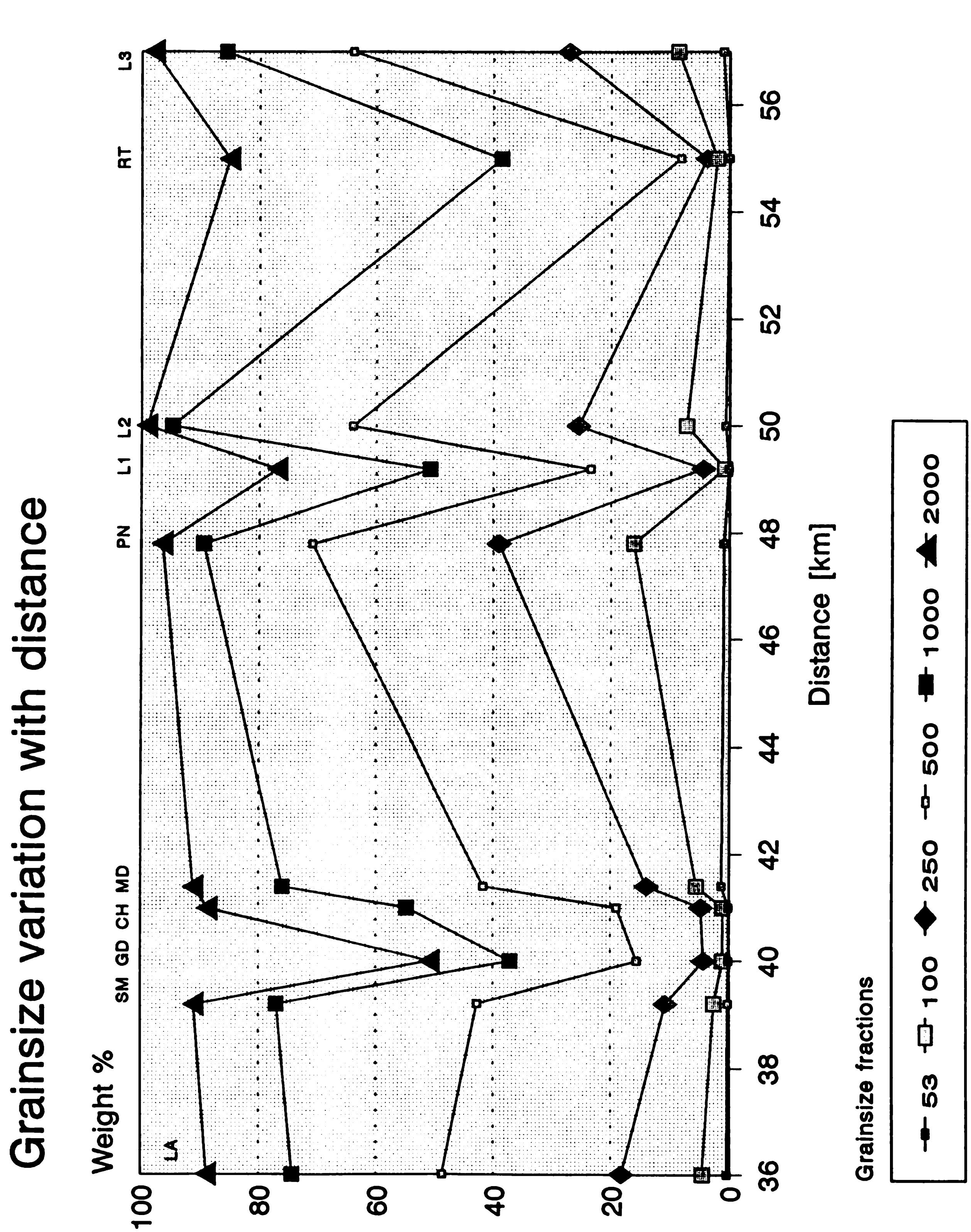


Fig 4.8 Grainsize variation with distance. The weight percentage of the analysed fractions is given in µm. For example: the 53 line shows the weight percentage of all particles of the sample that were between 0 and 53 µm, the 100 line shows the (cumulative) weight % of the sample that was between 53 and 100 µm.

Pebbles consisting of hardened swamp clays occur in the whole area. They were found as cobbles on the braided bedding plain near the mountains in recent rivers, and even as small particles in the Holocene beach ridge sands (Nieuwenhuyse, pers. comm.). Soft unripened clay clasts, which were mainly found at the bases of the channel fills are also common.

IV.e ^{14}C- Results

The results of the radiocarbon datings are given in table IV.1
The ages of the dated sand bodies in the Atlantic Zone agree well with the eruptional phases of the volcanoes of the cordillera Central during the past 2000 years.

* *Implications of the ^{14}C- method*

The samples were collected just below the channel fills, which means that the channels are younger than the given ^{14}C-datings, estimated this might be up to 100 years (or more).

Secondly partial river infill may have started several years before the catastrophic infill which lead to choking of the channel. Therefore the leaves might have been covered already by bed load sediment several years before final infill and choking.

Where organic matter consisted of a mixture of branches instead of leaves, a larger dating age can have been obtained, because branches grow during several (tens) of years, while leaves may be only one year old.

Therefore the ^{14}C-datings will give, in almost all cases, an larger age than the deposition age of the channel fill deposit. The ^{14}C-datings themselves give errors in accuracy. These errors are estimated by the laboratory.

Table IV.1 *Maximum ages of the studied sand bodies, correlated with the major eruptions of volcanoes of the Cordillera Central.*
T = Eruption of Turrialba
I = Eruption of Irazú
S = Several different eruptions

LOCATION	AGE (yrs)	ERUPTION (yrs B.P)
1. La Guadalupe	-	S ?
2. Mola II	2200 ± 75	T 2058 ± 52[1]
3. Calinda	2200 ± 75	T 2058 ± 52
4. Lomas Finca I	2480 ± 60	T 2058 ± 52
5. Lomas Finca II	**[2]	T 2058 ± 52
6. Lomas Finca III	230 ± 30	T 129[3]
7. Los Angeles	-	T? ?
8. Santa Maria	2975 ± 110	?
9. Río Chirripó[4]	23.5	I 28-30[5]
10. Finca Cobal	-	I/T ?
11. Yucatica[6]	2340 ± 60	T 2058 ± 52

1. Reagan 1987.
2. The sedimentary structures resemble the deposits of Yucatica and seem to be deposited in the same period.
3. Eruption of Turrialba in 1880.
4. Deposited in December 1970.
5. Eruption of Irazú between 1963 and '65.
6. van *Ruitenbeek, 1995.*

V. DISCUSSION

The influence of volcanic ash eruptions on sedimentation is of major importance for the Atlantic Zone. Without volcanic ashes on the mountain slopes the rivers will not block their courses easily, as demonstrated by the Río Chirripó, which was not filled up until 1970 five years after a major eruption of the Irazú, whilst inundations regularly occur in the area. Catastrophic rainfall like that of December 1970 (1436 mm/month) does not occur every year, but not immediately following a volcanic eruption it will not lead to avulsions by blocking of the old channel, because only shortly after a volcanic eruption sufficient sediments are available.

The results of the radio carbon datings gave evidence to relate periods of volcanic activity to the occurrence of channel fills in the alluvial plain. However, the datings give ages which are a few hundreds of years older than the periods of eruption in the Cordillera Central, because the ^{14}C samples were taken below the channel fills. This error is considered, but by this low accuracy a relation still existed. As an estimation is taken that channel infill occurs within about ten years after a volcanic eruption. Smith (1987 b) gives an increase in sediment discharge of the rivers for the Neogene Deschutes Formation (Oregon) of about 20-30 years after a period of volcanic eruption. Because complete channel infill asks large amounts of available sediment, and vegetation covers the sediments rapidly in the Atlantic Zone, a little shorter time interval is taken.

The studied channel fills all show an asymmetrical infill. This is caused by the bends in the rivers. However, seldom lateral accretion planes or point bar deposits were found. Only few observations of lateral accretion planes were made (Lomas Finca II).

It is assumed that the meandering river systems in the alluvial plain are so dynamic that lateral migration does not get a chance to develop, because in early stages of point bar migration the channel is choked by sand deposited after a period of high rainfall shortly after a volcanic eruption. The dense vegetation in the area may also play a role in stabilising river banks and that way, preventing rapid lateral migration.

This can be confirmed with studies of Smith and Smith (1980) and Pool and Baas (pers. comm.) who show that the lateral migration rates decrease and vertical aggradation increases as a result of stable, densely vegetated river banks.

The lack of lateral accretion plains may also have been a result of the fact that a) the infill might have been so catastrophic that these deposits were resuspended and destroyed by the flood, or b) that the channel fills were parts of anastomosing channel systems and that the channels did not migrate laterally (Smith and Smith, 1980), or c) that these planes were disturbed by pedogenesis and bioturbation, giving the planes a massive and unrecognizable appearance. The grain size of the sandy infill and the fact that the discovered lateral accretion planes were covered with thin, rooted clay layers (up to 8 cm in thickness) makes option a) not preferable because the river banks were apparently stabilized by vegetation and clay layers. Also option b) does not seem probable in all cases, because in the recent Atlantic Zone, anastomosing systems only occur in the most distal parts of the alluvial plain, and the sand bodies also occur in the meandering area of the river belts, where the channels are not interconnected.

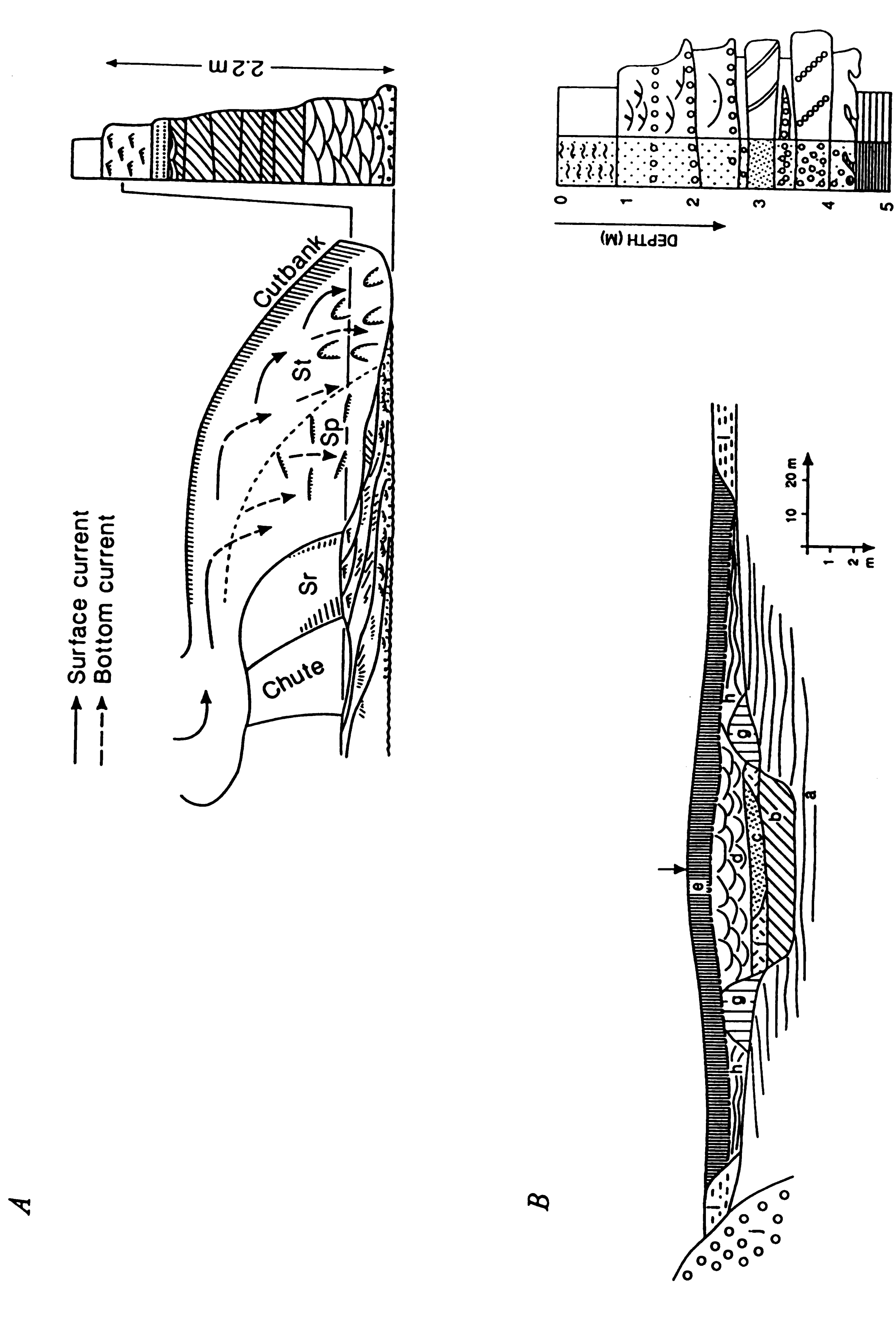


Fig 5.1 An idealised point bar sequence of Walker (1991) compared with a channel fill sequence of the Atlantic Zone. Both sections show a fining up in grainsize and structures. Comparing channel geometries, most striking difference is that at B lateral accretion planes are absent. See text for discussion.

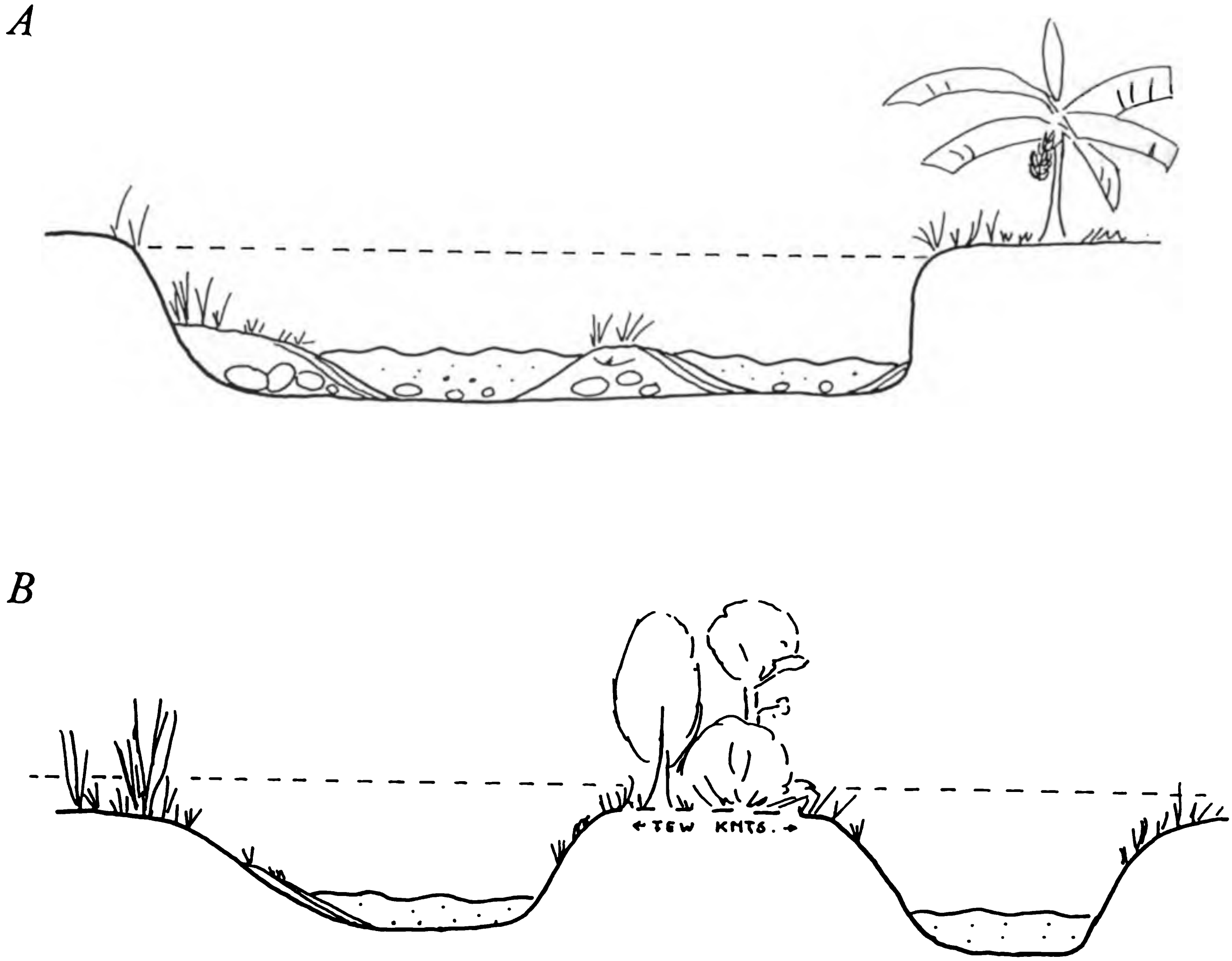


Fig 5.2 Stream bed of a braided river (A) and stream bed of a meandering river of the Atlantic Zone (B). The striped line shows the water level at flood stage. As can be seen the stream bed of the braided river is broad enough to transport the high amounts of water and not to inundate the banks. The stream bed of the meandering river is not broad enough during flooding and inundations occur. Although during normal discharges two or more channels can carry of the same amount of water as is transported by the braided river, during high discharge stages differences this is not the case. During high discharges the braided river region shifts towards the meandering river area, and the equilibrium developed during normal discharges is crossed.

The vertical profiles of the meandering river deposits fit with idealised sequences presented in handbooks (Walker, 1992) as can be seen in fig 5.1. Lateral accretion however, is largely lacking. This largely reduced amount of lateral migration may, as assumed above, be an effect of the highly dynamic deposition system. This dynamic deposition implies large quiet periods, in which an equilibrium in channels is formed for relative small amounts of sediment discharges in the meandering and anastomosing river parts, and short periods in which very high amounts of sediments are available. These amounts of sediments are too high for the, under lower sediment discharges, developed meandering river systems, and the meandering river parts become choked during large inundations. The infill sequences look like a downstream extension of the braided channel processes during flood periods in the area, where during normal periods meandering channels have developed. These channel shifts occur in braided river stream beds too. Smith (1987 b) describes for the Neogene sediments of the Deschutes Fm. in Central Oregon changes of these meandering channels into rapidly aggrading braided streams by the increased sediment load of the rivers due to volcanic eruptions.

Channel choking and changing of the river course is only found near the transition from braided to meandering rivers and downstream from this point. This is because the capacity to transport sediment during flood stages is much larger for braided rivers than for meandering rivers, due to the wider stream bed of braided rivers (fig 5.2). This is illustrated by the most recent case of channel choking in 1970, where infill occurred from a very sharp meander bend, which must have caused a direct decrease in stream velocity and (thus) a start of sediment settling (fig 3.1).

The Lomas III deposit is a crevasse splay deposit, reflected by its fanning form and lack of a main channel fill. Besides channel infill crevasse splays also occur during high discharges of the rivers. Deposition in two minor phases as indicate the two small f.u. cycles within one overall fining up, can be caused by two pulses in sediment supply. As mentioned by Smith and Smith (1980), crevasse splays > 40 cm often occur in anastomosing regions (Lomas III is >120 cm, because of the excess sediment supply by the last Turrialba eruption. Lomas II lies near the transition from meandering to anastomosing rivers in the coastal plain). Large scale inundations and a relative high sediment load may be the main reason for this thick crevasse splay sediment in an probably anastomosing river deposit.

V.a Texture

The fact that no erosional surfaces were found in any of the profiles and just one overall fining up sequence was present in the channel fills, indicates that infill corresponds with one period of high rainfall ("temporal").

A fining upwards sequence indicates that stream velocity decreased during filling of a channel. An event may have taken place in several days or up to 2 months, considering the newspaper reports of the Chirripó blocking in 1970.

Grain and pebble sizes show a slight decrease in the downstream direction, indicating a decrease in stream velocity in this direction. The cumulative grainsize curves indicate normal flow conditions during deposition.

Roundness and weathering of the pebbles in the sediment indicates that these pebbles were already transported and exposed to weathering on the alluvial fan, and were reworked and transported during the flood period. The sand grains are angular to sub angular, indicating a more direct transport from the mountains.

1

2

3

4

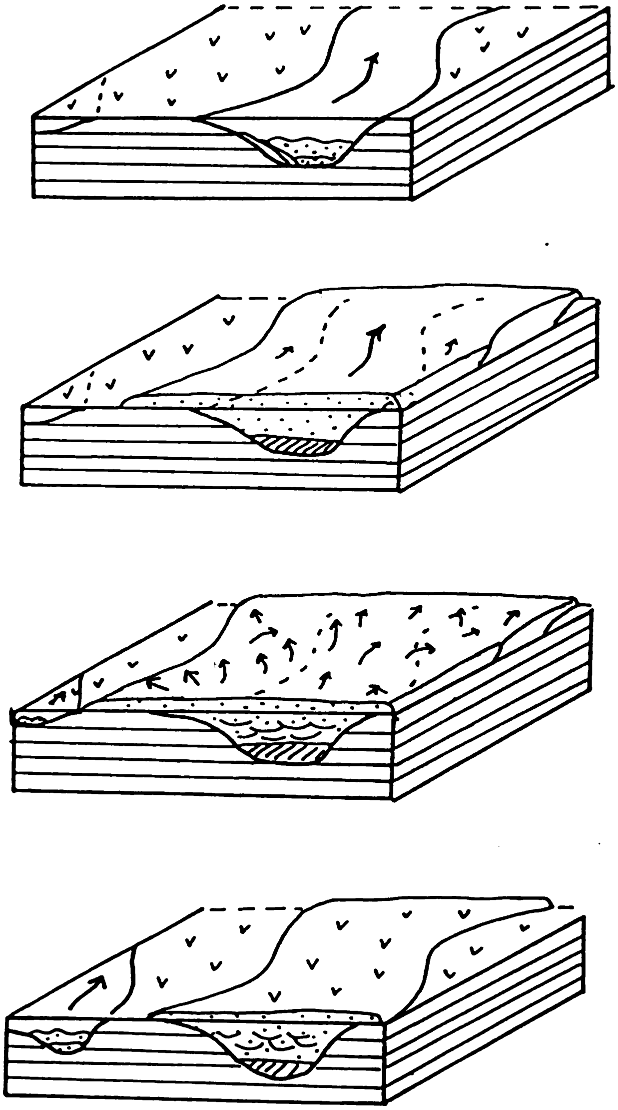


Fig 5.3 Chocking and (meandering) river course changing:

1. Normal river transport.

[Bed load transport in the area is estimated to comprise ±20 % of total sediment transport (Cachí reservoir; Jansson, 1993).]

2. High water discharge and high sediment load. Inundations start.

3. Main channel is half filled another channel is incised and occupied. Now two channels are active.

4. Waning flood stage: the old channel is now completely filled with finer grained sediments and smaller trough cross beds and ripples and only the new channel is used.

V.b Sedimentary Structures

The abundance of mainly trough cross bedding and other sedimentary structures within the channel fills also indicates deposition under normal flow conditions, and not hyperconcentrated sheet flow processes. Hyperconcentrated flood flow processes do not produce sedimentary structures (Ballance 1984, Blair 1986, Smith 1987a and b). They are characterised by a lack of sedimentary structures, and are an important phenomenon in the mountaineous areas near the volcanoes. Highly sediment loaded rivers are likely to be initiated as hyperconcentrated floods in the mountains, but downstream these flows are diluted and river transport will take place under more normal flow conditions.

The lag deposits at the base of the channel fills (fig 4.2 b) may have been transported and deposited during normal circumstances or during earlier floods, which are rather common in this study area. The flame structures indicate a large erosional force by bed load transport, dragging the soft swamp clay deposits below the channel in a downstream direction.

Figure 5.3 gives an overview of the sedimentation process:

The large trough cross beds (fig 4.2 c) are deposited during catastrophic flooding. The large troughs are often incised in climbing ripples (fig 4.2 f), which occur at the margins of the channel and which are formed due to deposition from overloaded flows (in sand fraction). By the rapid increasing water level soft and swampy parts of the river banks can be washed into the channel. Some of these bank parts are completely destroyed and what is left are clay balls (or pebbles), which can be found among the pebbles in the sediment. Other bank parts are not completely destroyed by soft sediment deformation and may remain as the soft clayey wedges at the margins of the channel.

When the main channel is half filled by sediments another, energetically more preferable river course is being formed in for example a local depression like an abandoned meander, which is widened and deepened by erosion, causing a decrease in stream velocity in the main channel and an increase of stream velocity in the newly formed channel. The decrease in stream velocity results in the former main channel results in a decrease in size of the sedimentary structures that are formed by vertical aggradation in the meandering channels. This way the size of the trough cross beds decreases upward in the channel fills (fig 4.2 d). The whole area has flooded in this stage because both channels cannot sufficiently transport the still large amounts of water. Now the floodplain deposits (fig 4.2 h) are formed under lower stream velocities as indicate the ripples. Load casts are formed by the sand load on the very soft clay deposits.

Afterwards a soil is formed in the sand deposit, disturbing the upper parts of the trough cross-bedded deposits, and the ripples formed in the floodplains. This is concluded by the lack of sedimentary structures in the upper 1.5 m of the ± 2000 yrs B.P. deposits, and the existence of ripples and structures in the upper profile of the channel and floodplain deposits of the most recent (23 yrs. old) channel fill (Río Chirripó, fig 4.5)

V.c Analogues

Surveys dealing with episodic fluvial sedimentation and dynamic channel patterns are rather scarce and mainly concern recent processes (Davies and Vessel, 1979; Pool and Baas, pers. comm.; Smith and Smith, 1980; Blair, 1986). Studies on the effects of episodic fluvial sedimentation [not necessarily related with volcanism], mainly deal with changes in the braided channel regions, where hyperconcentrated flow processes like sheet flooding and debris flows play a major role in sedimentation (Kesel and Lowe, 1987; Ballance, 1984; van der Wiel, 1991; Miall, 1978).

Smith (1987a) studied Neogene and Quaternary examples of the Pacific NW (USA) and noted that aggradation in volcanic areas occurs during short periods, when eruption-produced sediment loads choke braided streams with debris and such periods are separated by longer periods of non deposition. The choked streams are incised again during periods of normal discharge, and cannot be compared to the permanent blocking of the rivers in the Atlantic Zone.

Remarkable agreements exist with the process of complete channel fill and blocking of the recent Río Pilcomayo in Paraguay, which was studied by Pool and Baas et al. (pers. comm. 1993). However, this river is blocking its own course over several 100 of meters every year, after the spring floods derived from the Andes. Like the rivers studied in the Atlantic Zone, this river also disappears in a swampy, low gradient region.

Several widespread sand deposits seen on satellite pictures indicate that changes of the course of the Río Pilcomayo occurred more than once.

Smith and Smith (1990) describe processes of recent anastomosing rivers in a volcanic region near Banff, Alberta (USA). A downstream control, like a rapid sea level rise may be necessary to develop anastomosing channels, when combined with high sediment supplies and stable banks. These three conditions are also present in the Atlantic Zone. In Alberta string-like (elongated) coarse grained channel deposits, surrounded by overbank fines occur. These string deposits may be comparable with the channel fills of Costa Rica, even though they are less thick, and developed in anastomosing channels instead of in meandering channels as in the Atlantic Zone. The rapidly elevated base-level creates a back water effect (a downstream stagnation of the water that is transported by the rivers) that results in deposition in the anastomosing rivers of Banff, Alberta. This back water effect (by a rising Holocene sea level), may have favoured channel chocking in the Atlantic Zone: in the low gradient swamp area of the coastal plain water stagnation and large-scale inundations occur during high rainfall periods. Although the transition from alluvial fan to alluvial plain and the rapid decrease in fan gradient and channel width/depth ratio (from $\pm$ 6 to $<$5) are apparently most important for the start of channel chocking during extremely high sediment discharged river periods, this downstream control may be of influence too: the water stagnation in the coastal swamps and the induced decrease in flow velocity has caused sediment settling in the distal areas, while from the transition from alluvial fan to alluvial plain the channel choking is initiated by the decrease in fan gradient.

Peak flood-flow sedimentation patterns were compared with a recent dam collapse in Rocky Mountain National Park (Blair, 1986). Blair describes that deposition took place in three phases. During the peak-flow most of the sediments were deposited during the first five hours after the dam failure, and they consisted of mainly sheet-flow sediments, with high-flow regime sedimentary structures in the lobes (horizontal bedding and low angle cross stratification). In the downstream sediments lower flow structures were found, like trough-, ripple-, and planar cross bedded sand and climbing ripples. These lower flow structures agree with the structures found in the alluvial plain of the Atlantic Zone. Channel incision, as found at small scales in the channel fills in the Atlantic Zone (large trough cross beds, fig 4.2) occurred on a larger scale during the latest phases of the dam collapse. In Costa Rica they may reflect a decrease in rainfall intensity and by this deposition of most of the sediment.

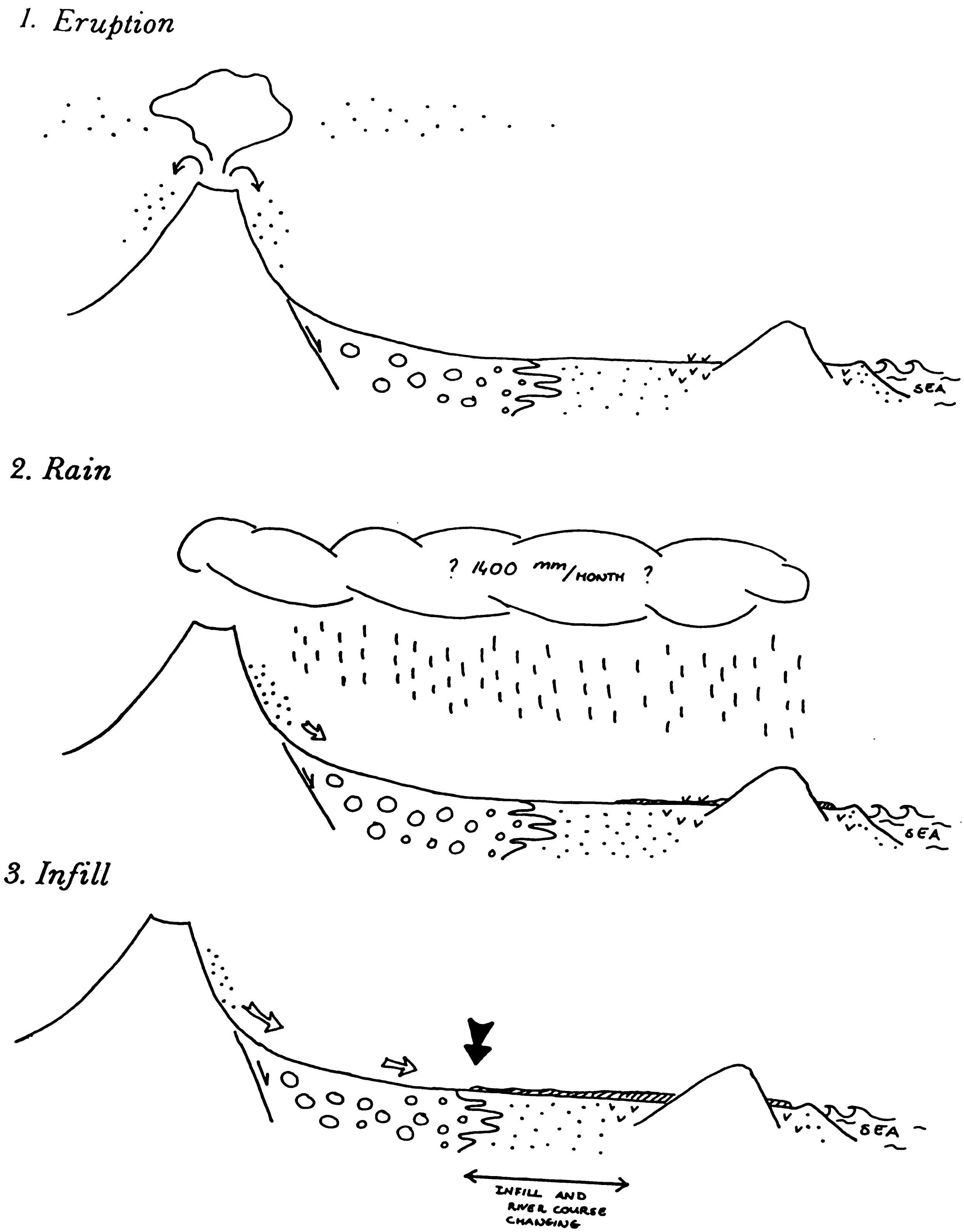


Fig 6.1 Schematic cross sections through the Atlantic Zone showing the main factors and different stages of channel infill for the whole zone (compare with fig 2.5 for a legend and with 5.3 for a description of channel infill):

1. Eruption brings abundant ashes and sediments on the mountain slopes.

2. Heavy rainfall within a ten years period after eruption will cause inundations on the alluvial and coastal plains. Sediments on the mountain slopes are transported downward. Stagnation of water, and large scale inundations probably start in the swamp area, but soon inundations will occur in the whole area.

3. Infill and course changing of rivers occurs from transition of braided to meandering rivers, on the alluvial fan (fig 2.6).

VI. A DEPOSITION MODEL

*** *Phase 1***
VOLCANIC ERUPTION [fig 6.1 1]

In periods of volcanic eruptions large amounts of ashes are deposited in the area (fig 6.1 1). Part of the ashes is immediately (and already during an eruption) washed down by the rivers draining the slopes of the volcano. This part is transported into the sea and with this material new beach ridges are formed along the Atlantic coast (Nieuwenhuyse and Kroonenberg, 1993). Another part of the ashes is deposited on the slopes of the volcano. It becomes vegetated and weathered after several years. In periods of high rainfall (for example during "temporales"), within about ten years after an eruption, the still loose and not completely vegetated ashes are washed down into the rivers by surface streams. This way the Turrialba and Irazú volcanoes are drained by the Río Toro Amarillo and Río Sucío.

When water discharge of the rivers increases rapidly, high amounts of the relative fresh ashes will be taken into suspension. Bed load and suspended load of the rivers increase. On the slopes the fresh sediment is mixed with older material from landslides and transported downward.

*** *Phase 2***
RAINFALL [fig 6.1 2]

During periods of extremely high amounts of rainfall large- scale inundations occur in the alluvial plain. In the river channel trough cross beds and climbing ripples are deposited, which hinders downstream transport by partly blocking the meandering channel. In the braided stream area only high discharges and a lot surface run off will be recorded, but no large scale inundations occur outside the braided channel plain, because of the relatively steep relief.

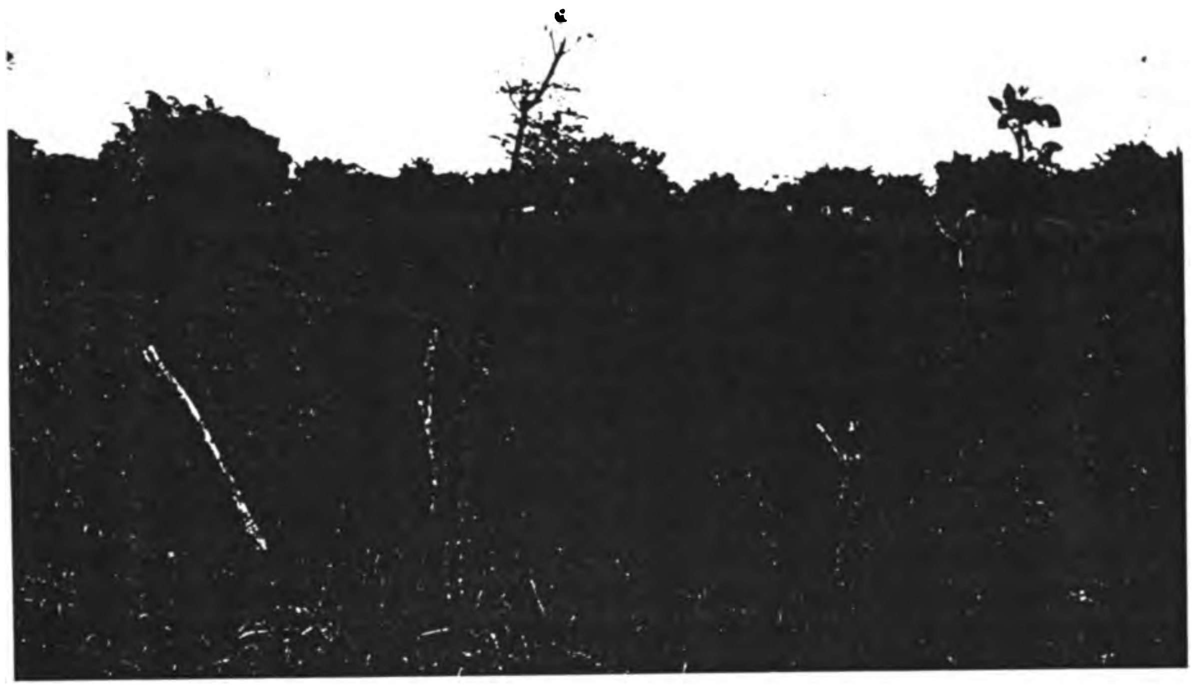


Fig 6.2 After complete abandoning of the old river course, small relict channels remain on the surface of the main channel fill. This photo shows a small relict channel at San Gerardo (A at fig 3.1), but relict channels were also found on the surface of the Los Angeles channel fill (fig A.8).

*** Phase 3**
CHANNEL CHOCKING [fig 6.1 3]

The climbing ripples are incised by small channels and large troughs, because the cross sectional area of the channel decreases by deposition of the climbing ripples and trough cross beds. Stream velocity increases causing the incision of a small, rapidly transporting channel.

However, such small channels cannot transport all the water running down from the mountains also because the floodplains are flooded, and the river changes its direction into an energetically more preferable regime, like a former abandoned meander bend [as happened in the Río Chirripó, 1970]. In the braided stream region the relief is still sufficient to handle with the large amounts of water, but in the zone with meandering channels water flows over the banks onto the floodplains. A new channel develops in a depression like a former meander bend, which is widened and deepened by the increasing amount of water that flows into the direction of the lowest area. The water may occupy both the old and the new channel, until the water level decreases. For the Río Chirripó this took two months according the newspapers. Thus small channels on the surface of the old bed as found at the Río Chirripó (fig 6.2) and at Los Angeles (fig A.8) were still active for some time. They are reactivated during new floods.

When the water level falls the most deeply incised channel is occupied and forms the new river course.

*** Phase 4**
AFTER DEPOSITION

After changing of the channel course, the deposited sand is rapidly covered by vegetation due to the humid tropical climate. Small relict channels which are not filled in the latest stages may remain visible at the surface, and during new flood stages they will be temporarily occupied again (fig 6.2).

After some years, the surrounding sand and especially the clay deposits compact and the former channel shows a slight elevation in the landscape, due to its lower compaction properties. The amount of compaction of the surrounding deposits strongly depends on their composition, but generally the elevation of the order of 1 m.

VII. CONCLUSIONS

* Volcanic eruptions in the Cordillera Central can be correlated with elongated channel fill sand bodies in the Atlantic Zone.

* Large amounts of irregularly supplied volcanic sediment washed downhill during periods of high rainfall cause chocking of river channels and changes of river courses in the alluvial plain. The meandering rivers in the alluvial plain do not show wide laterally extensive lateral accretion planes as is normal for meandering rivers. Episodic channel choking does not allow enough time for the point bars to migrate laterally.

* Channel choking and avulsion mainly occurs within about ten years after a volcanic eruption, which deposited sufficient ashes on the mountain slopes.

* Channel infill of meandering rivers occurs in the alluvial plain, where channel gradient decreases leaving the alluvial fan. At this point braided streams change into a meandering river pattern. However, during periods of high sediment discharge the braided rivers seem to build out of towards the alluvial plain where then (braided) processes as channel choking by rapid vertical aggradation and channel avulsion start to occur.

* The sedimentary infill of all channel fills in the Atlantic Zone is similar. This indicates that the process causing the channel infill did not change too much the last 3000 years.

* Complete channel fill can occur in just one flooding considering the lack of erosional boundaries and the absence of soil horizons within the sand deposits. Stream velocity decreases during one inundation event.

* Tropical forests and dense under-vegetation may have stabilised river banks and have limited fast lateral migration of the meandering parts of the rivers.

* The abundance of sedimentary structures in the channels fills excludes hyperconcentrated flood flows reaching the alluvial and coastal plains.

VIII. FUTURE RISKS OF VOLCANIC ACTIVITY FOR THE ATLANTIC ZONE

Besides the risks of a volcanic eruption, the years after an eruptional phase can be dangerous for the Atlantic Zone as well.

In the years after an eruption, the risk of large scale inundations and destructions of farm land and -houses due to channel switching exists. This will cause major changes in land properties for the farmers in this dynamic region. During extreme floodings, rivers like the Río Tortuguero might be reconnected with the Río Toro-Amarillo or the Río Sucío and channel chokings may occur in this part of the region. Channel chokings near the former course of the Río Chirripó may also occur when reconnections are made with the rivers of the Toro-Amarillo alluvial fan.

Human activity on the mountain slopes like the construction of roads and farming, will increase the number of landslides up in the mountains and so increase the amount of loose sediments on the mountain slopes. This will increase the risk of channel choking in the alluvial plain area (fig 1.2 and fig 2.6).

IX. RECOMMENDATIONS

In this study some questions remained unanswered, because of the limited time that was available. These questions still remain interesting and the most striking ones are summarised below:

* What are the processes up in the mountains: how are the sediments transported downstream? How large is the influence of landslides? Does there a lot of mixing take place between the freshly deposited ashes after an eruption and the eroded debris on the slopes of the volcanoes?....

* How much sediment and rainfall are critical for infill of a channel? What are the sedimentation rates?

* Is there a similar relation between the chemical composition of the sands of the channel fills and volcanic eruptions as was found for the beach ridges (Nieuwenhuyse and Kroonenberg, 1993).

....

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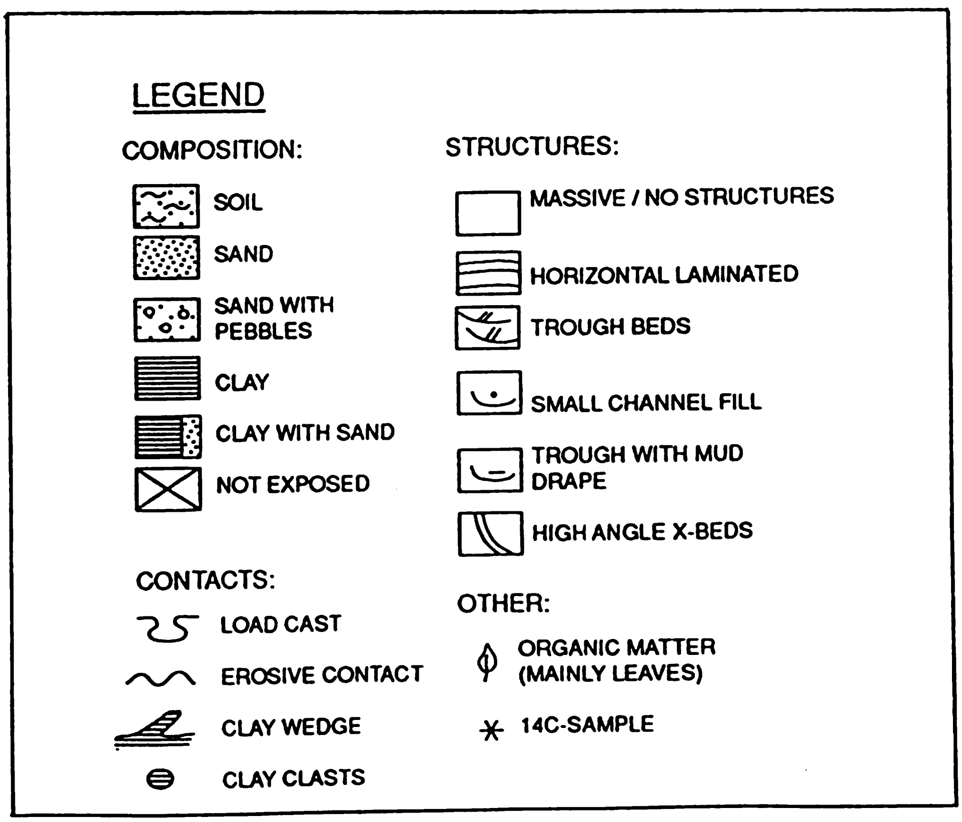
Appendix A

Descriptions of the studied Deposits



Tabel A.I *Overview of the described outcrops (fig 3.2 for location).*

LOCATION	GRADIENT [m/km]	CHANNEL WIDTH [m]	CHANNEL DEPTH [m]	STREAM DIRECTION	REMARKS
1. La Guadelupe	± 2.0	30	-	E-ENE	Fan influences: poorly sorted sheet floods and channel fills.
2.a Mola II	± 2.0	60-70	-	N-NE	Clasts up to 20 cm floating in the channel sands occur.
.b Mola II (pumice)	±(2.0)	30	-	E	Buff pumice particles found. Age ± 2000 yrs (table IV.1).
3.a Calinda	1.6	100-200	> 3		Continuation of the buff pumice particles of Mola II.
.b Calinda (2 km dstrm)	1.6	200	0.50		idem.
4.a Lomas I	0.78	40	4.5	NE	
.b Lomas I (4 km dstrm)	(0.78)	15, 20	3	NNE	Channel is now splitted up in branches.
5. Lomas II	(0.78)	40	8	E - NE	Resemble the Yucatica deposits (Van Ruitenbeek, 1993).
6. Lomas III	(0.78)	-	3.2	SE ?	crevasse splay; maximum thickness 3.2 m. No sedimentary structures.
7. Los Angeles	1.16	30	8-10 ?	E	Trough cross beds were not disturbed in upper profile.
8. Santa Maria	(1.16)	25	5.5	E	Badly exposed.
9. Río Chirripó	<0.8-0.3	50	6-10 ?	N	Most recent deposit (1970 A.D).
10. Cobal	0.5	45	-	N	

Table A.I

(Structures are listed in order of decreasing importance at each outcrop.)

Structures: R = Climbing ripples
C = Cross bedding
HX = High angle cross beds
LX = Low angle cross beds
T = Trough cross beds
S = Trough (wavelength > 2m)

	STRUCTURES LOWER PROFILE (<2m)	**MEAN SIZES [cm] ↔ / ↕**	**STRUCTURES UPPER PROFILE (>2m)**	**MEAN SIZES [cm] ↔ / ↕**	**MAX. PEBBLE SIZE [cm]**
1.	(H)X, S, R	100 / 40	T	20 / 10	25
2.a	-	-	S, HX		20
.b	-	-	HX	100 / 50	4.5 [1]
3.a	T, HX	100 / 20	T, S, HX, R	40 / 10	2-3
.b	- [2]	-	T	50 / 20	1 [3]
4.a	T, R, HX, S	120 / 20	T	25 / 15	5
.b	T	-	T	80 / 20	2.5
5.	T, R, S	120 / 30	T	60 / 25	20
6.	-	-	-	-	0.1
7.	T, R, S, HX	120 / 40	T, S, HX	50 / 15	8
8.	-	-	(HX)[4]	/ 40	2
9.	-	-	Beds, HX	/ 40-50	25
10.	-	-	T, S, R, HX	100 / 40	5

[1] Pebbles also consisted of pumice, but largest clasts were not the pumice pebbles.

[2] Maximum thickness of the floodplain deposit was 50 cm.

[3] Pumice particles (Light material).

[4] As far as could be determined (bad outcrop).

	LOCATION	*DISTANCE FROM SOURCE* (KM.)
SM	Santa Maria	35.8
LA	Los Angeles	39.2
GD	La Guadelupe	40.0
CH	Chirripó	41.0
MD	Mola II	41.4
PN	Calinda	47.8
L1	Lomas I	49.2
L2	Lomas 2	50.0
L3	Lomas 3	57.0
RT	Río Tortuguero	55.0

APPENDIX A

Deposits of the Río Toro Amarillo and Río Tortuguero system

1. La Guadalupe

a. Location

Several sand deposits were found at this location (fig 3.2). They cause drainage problems at the bananera. Outcrops were studied in the canals of the banana plantation "La Guadalupe". The outcrops consisted of two recently cleaned north-south orientated canals, each with a length of 500 m (see fig A.1). At least two elongated channel fills were encountered in these canals. Stream directions were E to ENE.

This finca is the most upfan situated location were the elongated channel fill sand bodies were studied. This is expressed by the relative high amount of (very) coarse sand deposits between the channels compared to the other studied locations. Remnants of fan related processes as sheet flooding are also found at this location.

b. Sand bodies

Two elongated sand bodies were found, each varying in width between 30 and 50 m, with gradual transitions into finer and more loam containing floodplain deposits. A remarkable white clay layer often separates the different floodplain deposits, but is sometimes interrupted by other deposits. The clay layer ranges in thickness from 5-12 cm, and contains branch fragments. The layer is interrupted by the channel fills. At one place (between B and C) a small swamp has been formed in a depression in this layer. This swamp was covered by a sheet flow.

On top of the southernmost deposits (E at fig A.1) an at least 300 m wide sheet flow deposit was found, covering all other, older deposits. The sheet flow is poorly sorted with small pebbles up to 3 cm in diameter, and contained mostly angular to subangular fragments. The matrix was cemented. The reason for that seem to be weathering of originally volcanic material and pedogenetic processes.

At the base of the canal (1.5-2 m below the surface, and 250 m wide at the south side of the canal) another sheetlike poorly sorted sand body was found, consisting of a matrix of medium to coarse sand and containing outsized clasts up to 25 cm along the longest axis. Clasts were matrix supported, and showed weathering of minerals. A mixture of roundnesses was found, mainly 0.7-0.9 but in some cases also exposing 0.3. Sphericity was mainly 0.7-0.9. This sheet seems to have been exposed at the fan surface for some time, before reworking and deposition by sheet flood processes.

Also at the northern part of the canals poorly sorted sheet deposits were found. Pebbles showed sizes of max. 12-15 cm. This indicates that sheet flooding still has had a large influence in this transition area from alluvial fan to alluvial plain.

c. Structures

In the northern part a channel fill with a width of 30 m was found, consisting of poorly sorted medium to coarse sand, with pebbles up to 4 cm in diameter. These were concentrated at the base of horizontal laminations and trough beds. This channel fill deposit resembles the deposits of those found at Los Angeles (see this Appendix [nr.7] for description).

At a depth of three meters ripples with a height of 20 cm were found. At a depth of 2.5 m they are covered by cross beds with a height of 40 cm, and a wavelength of 100 cm.

At a depth of 1.25 m under the surface pebbles disappear in upward direction. In the upper 1 m of the profile soil processes have disturbed the sedimentary structures and the mainly medium sand shows a high loam content (see fig A.1 A)

The second channel fill also has a width of 30 m. At the canal floor (2.5 m under the surface) very coarse sand and gravel are found with boulders of 20 cm along a-axis. These boulders lie horizontally with their longest axis, but they do not show any imbrication. At a depth of ± 2 m a small channel with a width of 5 m was found within the sequence, containing pebbles up to 6 cm in diameter. The channel is covered by dunes, with a height of 60 cm and the structures fine up into small trough cross beds with a height of 10 cm.

The soil at the surface only shows a thickness of 25 cm.

Both sequences show a slight upward fining.

Between these two elongated channel fills, floodplain deposits of medium to coarse sand slowly shift into silt and fine sand, in which small trough may have developed (wavelength 50 cm, height 20 cm).

At some places also thin clay and silty clay banks with thicknesses of 2-3 cm are found among the floodplain deposits. Also many swamp and unripened clay deposits are found in small layers up to 10 cm and in sequences up to 1.5 m. The swamp deposits contain tree fragments, branches and leaves. Sometimes these deposits cover the sheet deposits, sometimes they lie under the sheet and other sandy deposits.

The floodplain deposits are alternated by coarse sheet flow deposits (see fig A.1 C). In this case the "white clay layer" separates silty and clayey floodplain deposits in the lower part of the canal, and medium to coarse sand in the upper part, deposited under sheet-flow circumstances.

In the south coarse boulder containing deposits remain visible in the undermost 50 cm of the canal and can be followed over 75 m towards the north.

2. *Mola II*

a. Location

Mola II is situated 8 km downfan (north) of La Guadalupe (see fig 3.2). On this finca also many elongated channel sand deposits appear, which show an overall stream direction towards the N-NE.

The channel fills were studied in canals. More than four channels were found, but only two were described in detail.

b. Sand bodies

Like at La Guadalupe, large amounts of sand deposits could be found at this finca. The channel fills are 60-70 m wide. The depth could not be determined. The widespread floodplain deposits are interbedded with unripened clayey swamp sediments, which contain organic material in the form of branches and leaves, and show an alternation of silty- medium sand, and ripened clay sediments. These alternating deposits are found in beds varying from 10-60 cm in thickness.

c. Structures

The channels show the same sedimentary structures as found at all locations where this kind of channel sands were described, like troughbeds, and small channels/large trough fills (see fig A.2 for a detailed overview).

The texture shows a poorly sorted pebbly sandstone, with pebbles showing a great variation in diameter. Cobbles up to 20 cm occur at the bases of the coarsest banks. Pebbles are angular to subrounded.

In one of the channels with a width of $\pm$ 30 m, buff pumice particles were found at the bases of high angle cross beds (height 50 cm, wavelength 100 cm). The buff pumice particles are up to 2.5 cm in diameter, and are coarser than the other grains, because of their low weight. Texture of the upper 1.5 m ranges from medium to course sand. Maximum pebble size does not exceed 5 cm. The buff pumice particles are all well-rounded, with a low sphericity. The pumice can be related to the buff pumice layer at the Turrialba volcano as described by Reagan, 1987 (Table VI.1).

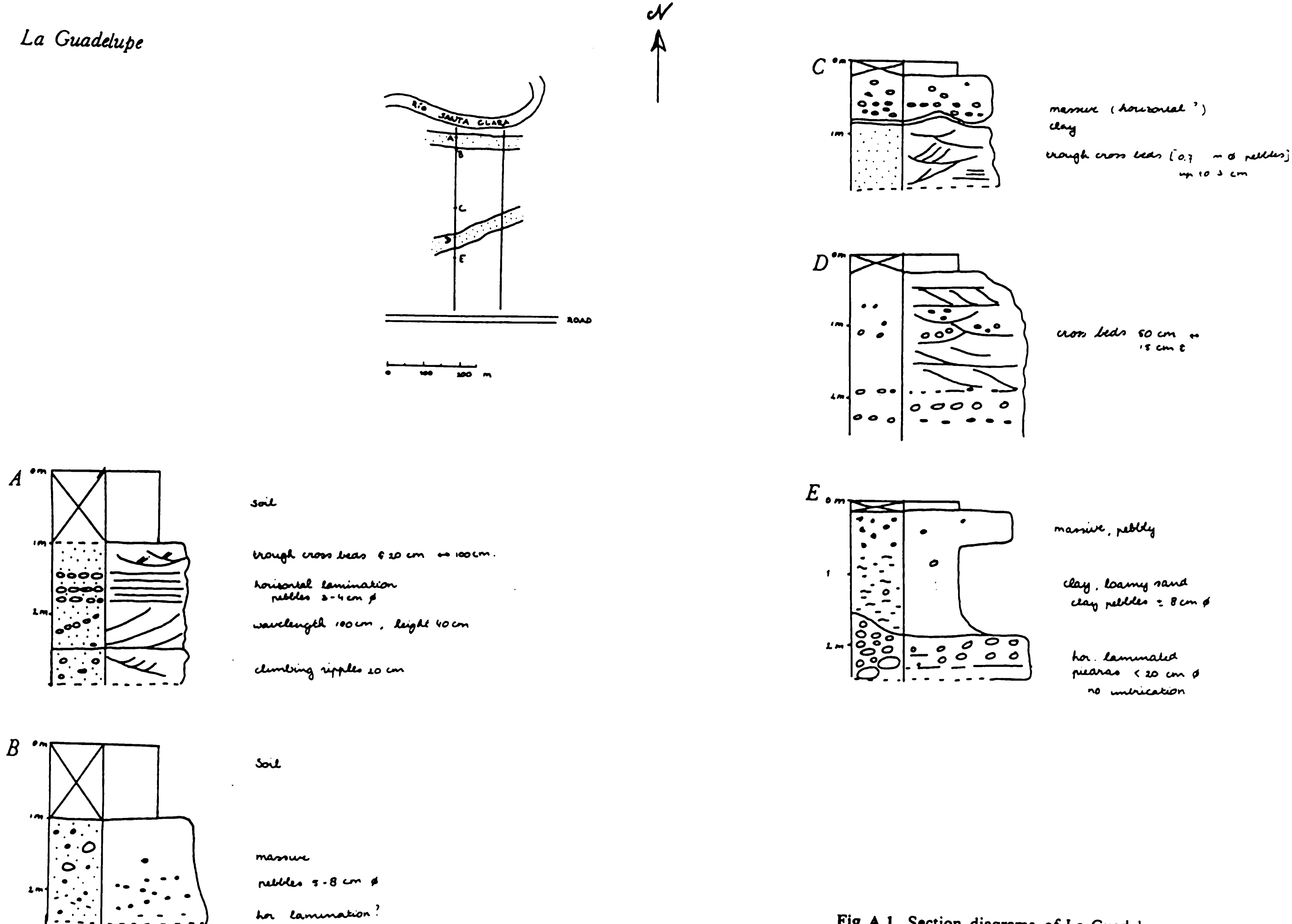
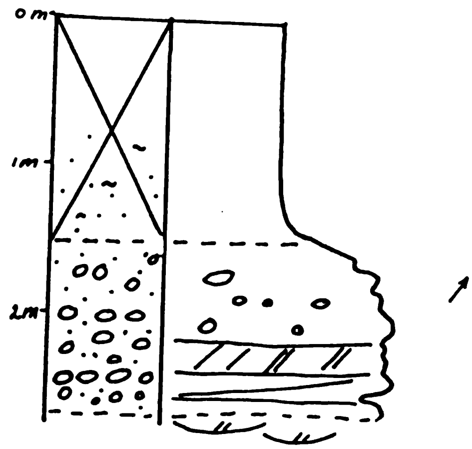


Fig A.1 Section diagrams of La Guadelupe.

B CENTRE OF THE CHANNEL

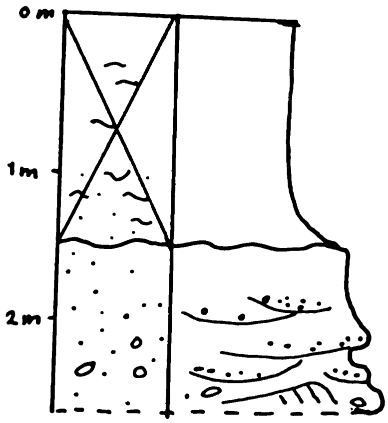


Soil : developed in other material as channel.

Horizontal lamination

high and low angle x-beds

A TOWARDS CHANNEL MARGINS.



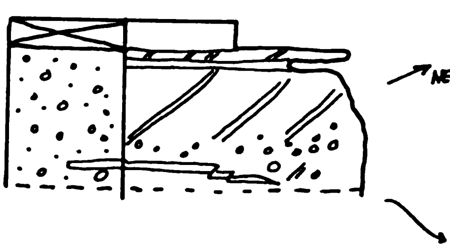
Soil : other material then channel

Trough cross bedding : 120 cm ↔ 30 cm ↕

Ripples

Pebbles : mean size 3,8 cm ϕ

pumice containing channel



PUMICE ! cross bedding ↕ 8 cm

↕ Pumice : ϕ 0,5-1,0 cm , well rounded

cross beds : 50 cm ↕ / 100 cm ↔

pebbles : max 5 cm ϕ

mean : 0,3-0,5 cm ϕ

med sand layer : faulted

3. *Calinda*

a. Location

Finca Calinda is situated 14 km downstream of Mola II (fig 3.2). The continuation of the channel with the buff pumice particles can be followed well over this finca (fig A.3).

b. Sand bodies

The pumice containing sand deposit enters the finca in the SW with a depth of over three meters. In the northern part of the finca, the channel fill turns towards the west and its sandy floodplain deposits cover an area of about 800 x 200 m. These sheet deposits shallow and finally disappear towards the NE (fig A.3). Along the western side of the finca and along the northern side, the sand deposit covers swamp deposits of dark grey, unripened clays, which sometimes contain tree trunks. The sand/clay ratio of the whole area is half that of Mola II and will not exceed 40% compared the 80% at Mola II.

An other channel sand deposit, without pumice was found at the western border of the finca. Its stream direction was N-NW, around the basaltic volcano "Lomas de Sierpe" (fig A.3).

At the east side of the studied channel with pumice, two channel fills were found too. They have flowed into the same direction as the channel fill, which contained pumice and are probably younger, but this could not be determined exactly.

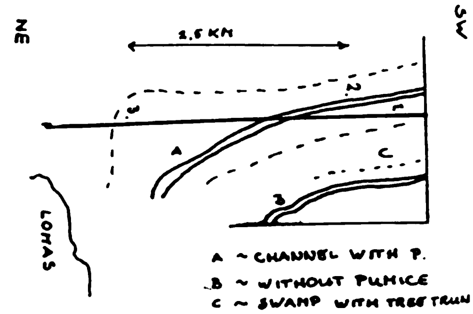
c. Structures

The channel fills show a fining upward sequence. The sands are moderately to poorly sorted (because of the larger pumice particles) and vary from coarse to medium sand.

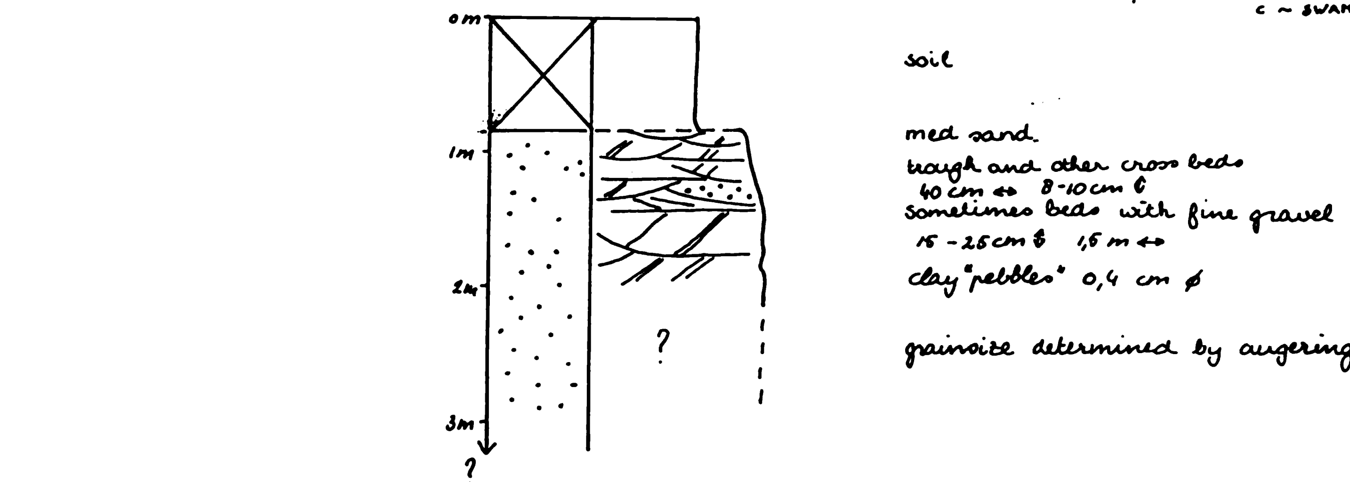
Sedimentary structures are similar to the other described channel fill deposits, and consist of ripples and trough cross beds, decreasing in thickness downstream.

Structures of the sheet deposits could be studied well, because of the easy recognizable pumice particles. (fig A.4)

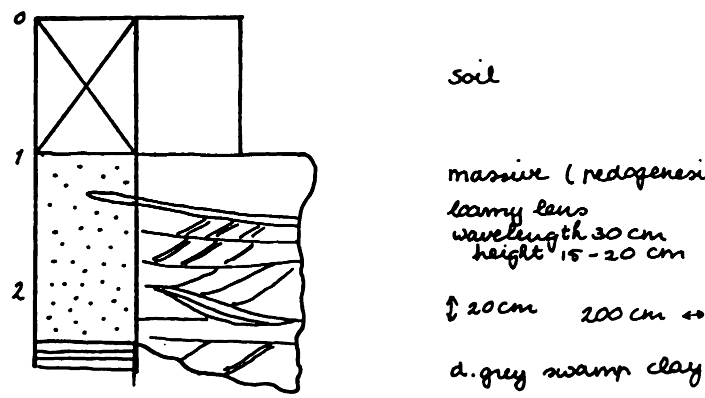
CALINDA



1. MAIN CHANNEL



2. 25 M TOWARD NE: (DOWNSTREAM)



3. FLOODPLAIN WITH PUMICE (2,5 KM DOWNSTREAM OF 1)

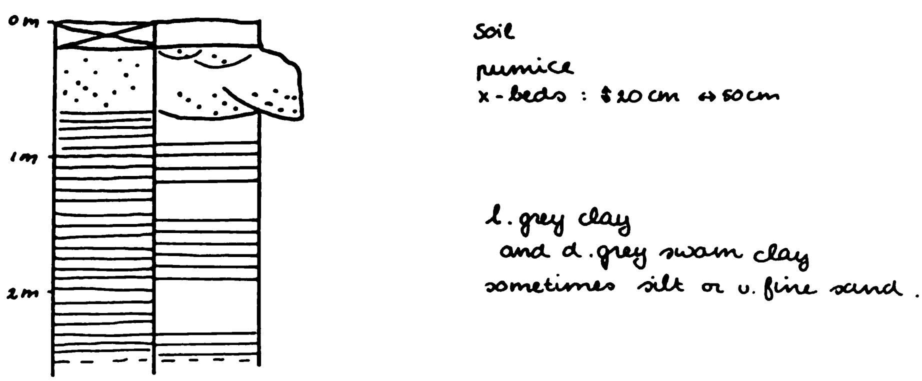


Fig A.3 Section diagrams of Calinda.

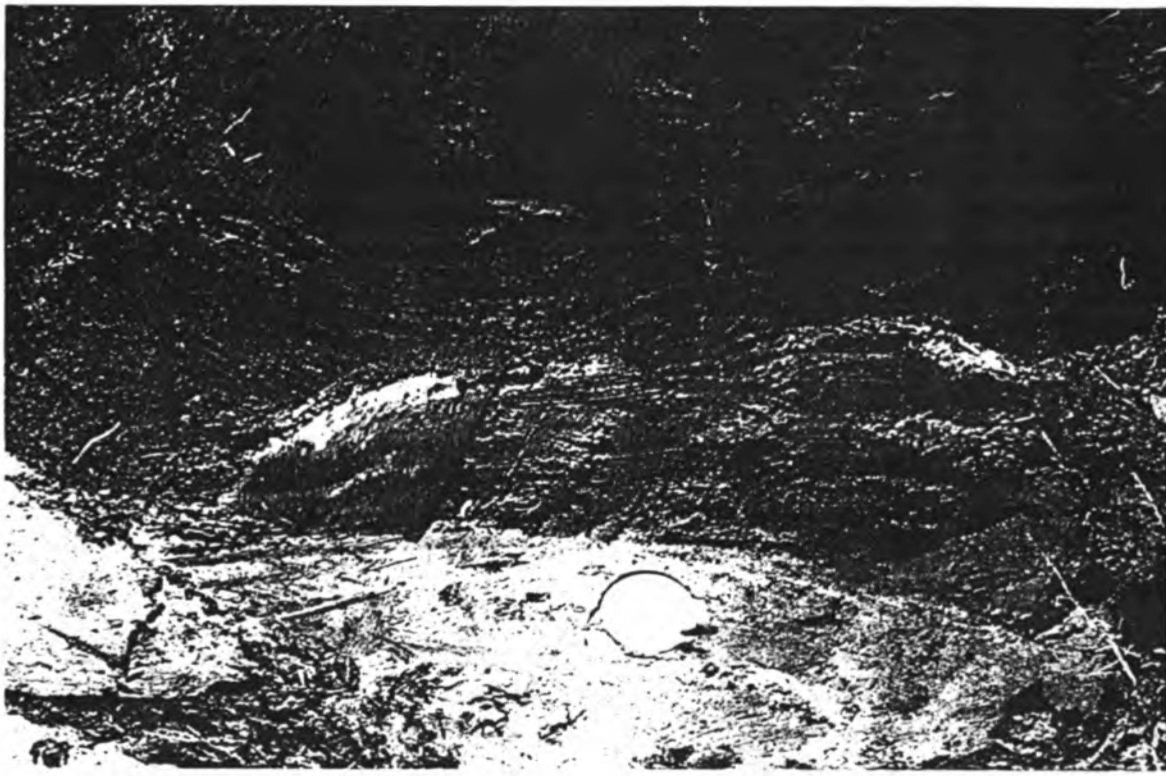


Fig A.4 Ripples/small dunes which still contained pumice in floodplain deposits. Covered by clay and silt. Coin for scale.

At the banana plantation "Lomas the Sierpe" three locations of detailed study were situated.

4. Lomas Finca I

a. Location

At Lomas I one channel sand was described at two places. These places are located at a distance of 4 km apart (fig A.5). Outcrops were in the canals.

The infilled channel is situated between the Pleistocene "Red Hill" deposits and Holocene swamps.

b. Sand body

The cross section at 1 (fig A.5) includes a channel fill with a width of about 40 m and a depth of 4.5 m. The channel is surrounded by Holocene horizontally layered and clayey floodplain sediments (fig 4.2). The sheet, deposited during channel infill extends laterally up to 150 m from the overbanks.

At section 2 (fig A.5) the main channel has split up into two minor channels of 25 and 15 meters respectively, and a depth of 2.5 m below the surface. The sheet is not as widely extended as in the first section (fig 4.2). Unripened, organic matter containing clays, and sandy and (ripened) clayey floodplain deposits surround the channel fills (bed thicknesses ranging from 0.05 to 0.8 m). Due to compaction of the soft clays, the channels are elevated in the landscape by a height of 1 m.

c. Structures

[FIG 4.2]

1-Section:

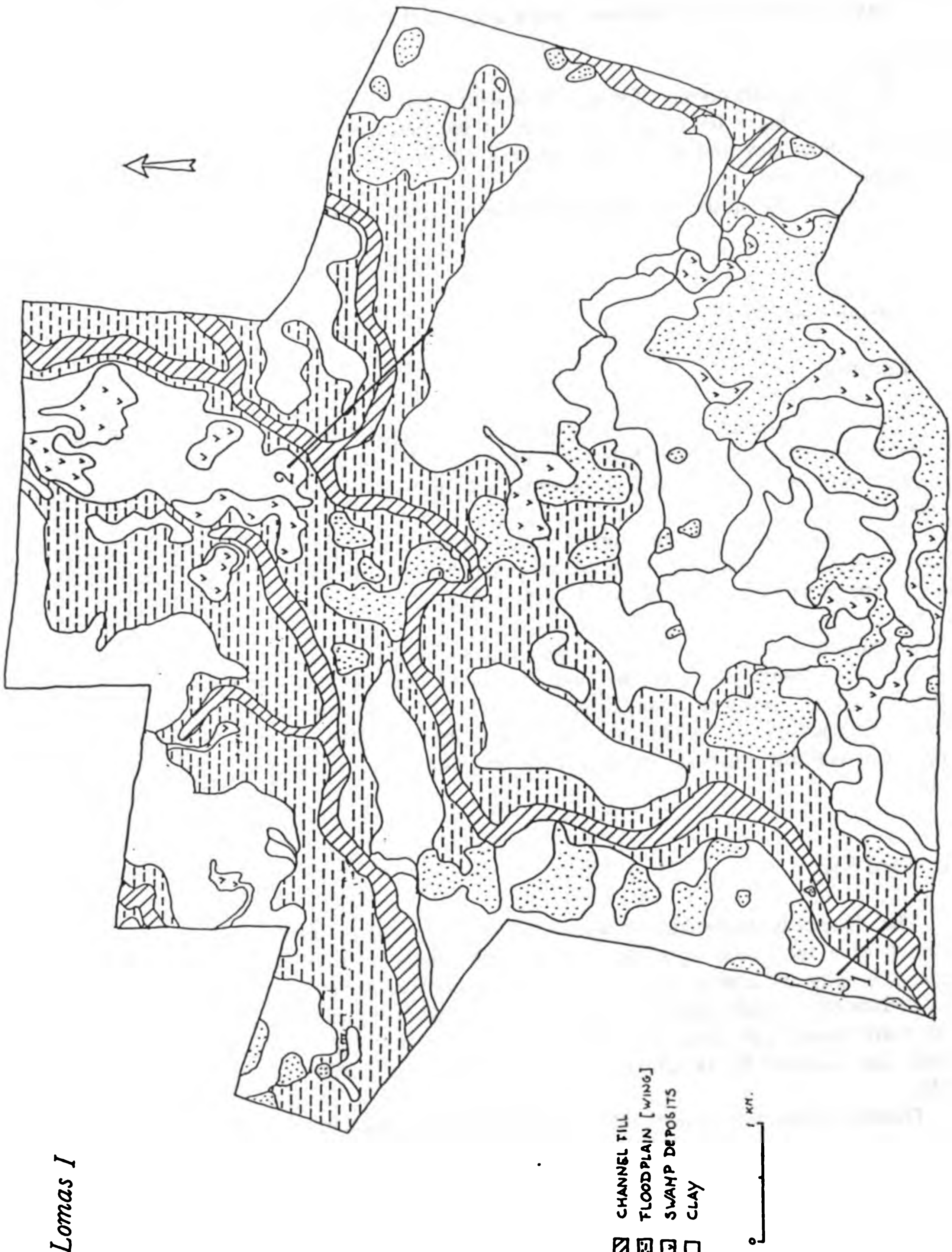
The channel fill consists of very coarse to fine sand in an overall fining upward sequence.

The base is irregular and contains clay wedges at the margins (3-5 cm thickness and a length of 25-30 cm). These wedges seem to be a result of high stream velocities and soft sediment deformation at times of infill. The base layer (lag deposit) consists of fine gravel and very coarse sand, with rounded to subrounded pebbles up to 5 cm. The sedimentary structures are not very clear.

Small beds of 0.4-0.6 m in height and small, coarse grained channels (or large troughs) of the same height and up to 3 m in length are situated on the base. The beds show high angle cross bedding structures, with pebbles up to 2 cm at the base of these structures.

The upper 2.2 m of the profile shows troughbeds decreasing from 20 cm in height and 120 cm wavelength to a height of 15 cm and a wavelength of 25 cm at 1.0 m under the surface. At 0.8 m no structures can be discovered due to soil formation. There the deposit tends to have a higher percentage of loam.

Fig A.5 Map of the Lomas I area. Towards the north the channels split up in smaller and shallower channels, sometimes they may interconnect. The numbers 1 and 2 indicate the location of the cross section in fig 4.1.



At the sides of the channel fill the sandy sequence is sometimes interrupted by small clay layers of about 5 cm thickness, and a length and width of sometimes several meters.

2-Section:

The channel fills consist of trough beds with a wavelength of about 80 cm and a height of 20 cm. Pebbles up to 2.5 cm occur at the bases of the troughbeds. The channel margins show clay and silt wedges up to 2 cm in thickness. An overall fining upward sequence is found.

The sandy floodplain deposits sometimes show trough cross beds and small ripples.

5. *Lomas Finca II*

a. Location

Finca II is located about 2 km southward of Finca I. This is an area of 16 ha with recently dug canals were the differences over short distances within a sand sheet could be studied very well. The canals make cross sections almost perpendicular to the studied channel fill.

The channel enters the study area in the west and splits up in a bend towards the south and a part that continues towards the northeast. The channel fill can be recognised in the landscape as an elevation of about 1 m (fig A.6).

According to S.B. Kroonenberg and A. Nieuwenhuyse (pers.comm, 1993) this area shows many similarities with the Yucatica area as studied by F. van Ruitenbeek (1993). Sedimentology, structures, morphology and soils of Lomas Finca II could be compared to those of Yucatica. A "white clay layer" was also found and by that the same (short) period of volcanic eruptions and deposition may have been responsible for the infill of this area.

b. Sand body

The channel is interbedded in mainly older overbank deposits of the floodplain, which consist of a succession of sandy (coarse to fine sand, LZover in Appendix B: texture analysis), silty and clayey deposits. The bed thickness varies between 0.05 and 1.0 m.

Pleistocene Tierras Rojas are covered by Holocene sediments of varying thicknesses. In the north-eastern part dark-grey, leave containing swamp deposits are very common and have been covered by floodplain sediments and by the "sheet" deposits of the channel fills.

Directly below the channel fill, at a depth of 8 m, dark grey unripened clay without organic matter was found. The boundary between Holocene and Pleistocene is at a greater depth and was not discovered.

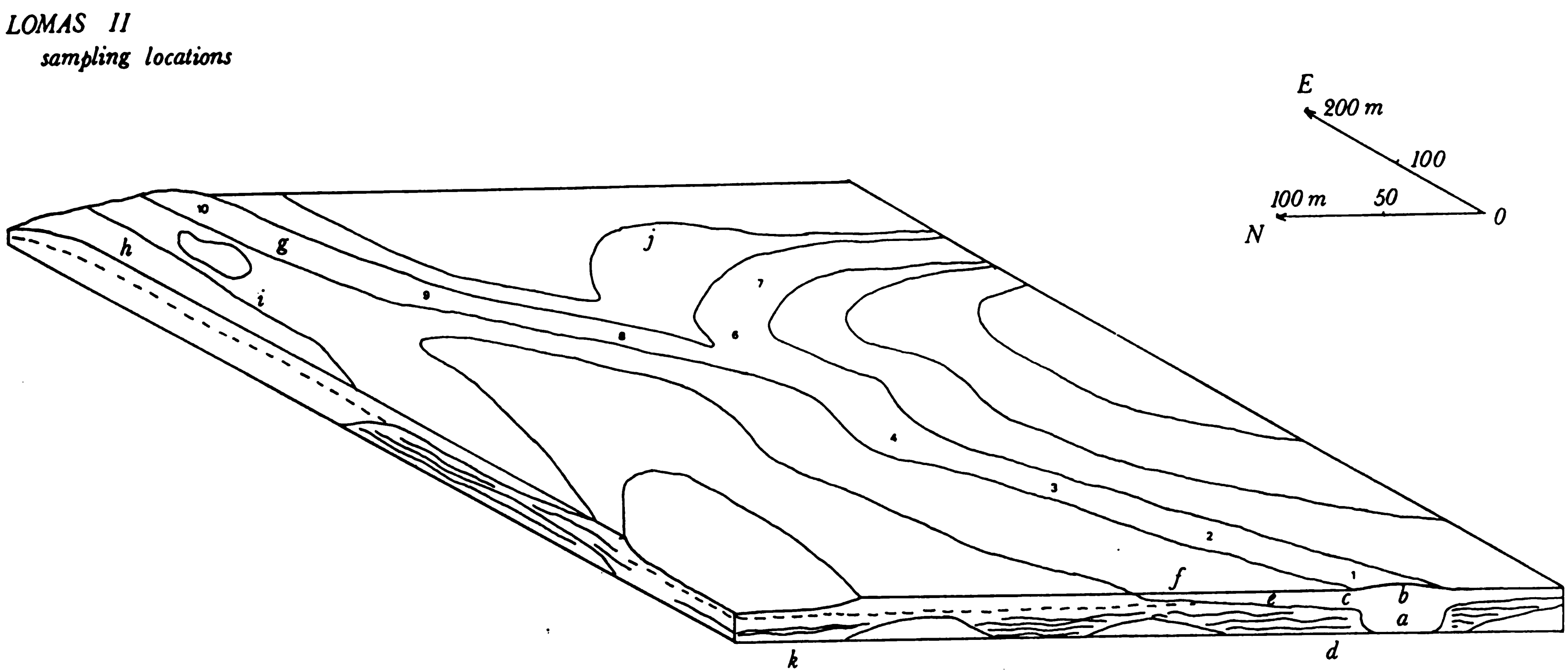


Fig A.6 Block diagram of Lomas II.
Sampling locations:

a. LZ 8.7a
b. LZ 8.7b
c. LZ 8.7d
d. LZ 8.7e
e. LZ 8.7f
f. LZ over
g. LZ 7.4
h. LZ 7.6
i. LZ 7.8
j. LZ 10.6
k. LZ 8.1

c. **Structures**

In canal 1 (fig A.6) the channel fill has a width of 40 m and a depth of 8 m. The channel fill is asymmetrically filled and shows a steep north side (cut bank) and a flatter southern side (point-bar). The cut bank side shows a coarser grained infill. In this part pebble containing trough beds with a height of 0.3 m and a wavelength of 1.2 m are found. Between the two channel sides these pebbles at the bases of the trough beds disappear and trough beds slightly shift into smaller structures (fig 3.2).

The bulk channel fill consists of poorly sorted very coarse to coarse sand. A slight fining upward can be found and the base which consists of fine gravel, with a higher content of pebbles than found up in the channel profile. Pebbles are subrounded to rounded and they all show weathering of minerals. Sometimes the pebbles are completely weathered and the content has changed into clay with different colours of the different minerals of the former pebble. Parts of the Tierras Rojas and well rounded clay pebbles are also found.

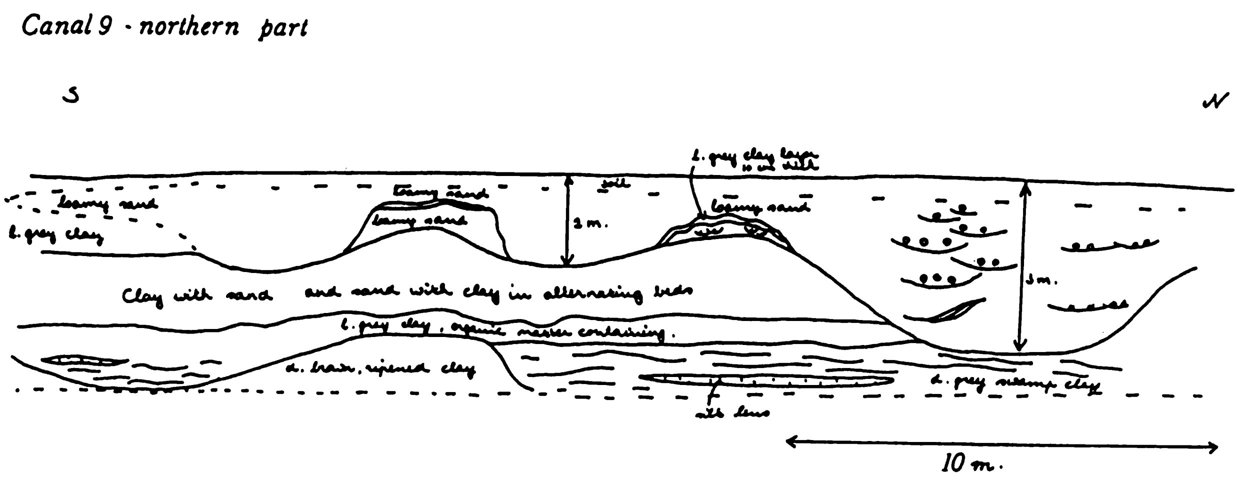
Both sides of the channel fill (1.5 m under the surface) show an increase in loam content probably due to pedogenesis. These sides may have been the overbanks, as found for the recent banks of the Río Tortuguero which are loamy and massive up to a depth of 3.2 m.

The sheet deposits belonging to the channel fill have a thickness of about 1.2 m. They laterally extend over about 100 m. There they change within 10 m from sandy and loamy deposits into a clayey soil.
The base of the sheet is irregular and load casts occur. Also almost every 5 m a disturbance by tree roots is found at the base of the sheet and the underlying clayey and silty deposits (up to a depth of 50-60 cm into the clayey deposits) (fig 4.5). This can be caused by the tropical forests in the area during Holocene times.

In the upper 0.8 m of the profile soil processes disturbed the sedimentary structures. Two different soils seem to have developed. A dark brown soil (0.4 m thick) may have developed in the years after channel fill and is covered by a light brown soil of 0.4 m thick, which may have formed in floodplain deposits of a later event.

100 m Downstream (fig A.6 canal 2), the channel has the same width, but shows a coarser infill than in canal 1. At a depth of 2.5 m below the surface, the channel is very pebbly, poorly sorted, with variable pebble thicknesses (mainly 8 cm, but sometimes larger). Up to a depth of 1 m under the surface, cobbles are found with maximal sizes of 20 cm in lenght by 7 cm in diameter. No imbrication could be distinguished.
Horizontal bedding (beds $\pm$ 20 cm in thickness) and sometimes small channels with a height of about 0.3 m and a length of 2,5 m are found. Troughbeds could also be found in the upper profile.
The soil in the upper 0.8 m of the profile contains pebbles and pebble remnants up to 3 cm. The soil also appears to consist of two different parts.

At point 6 (fig A.6), the channel diverges. One part follows its coarse to the northeast. This part is coarsest. Troughbeds with pebbles up to 5 cm are found. At this place the channel has a width of 30 m and a depth > 6 m at this place (point 8).



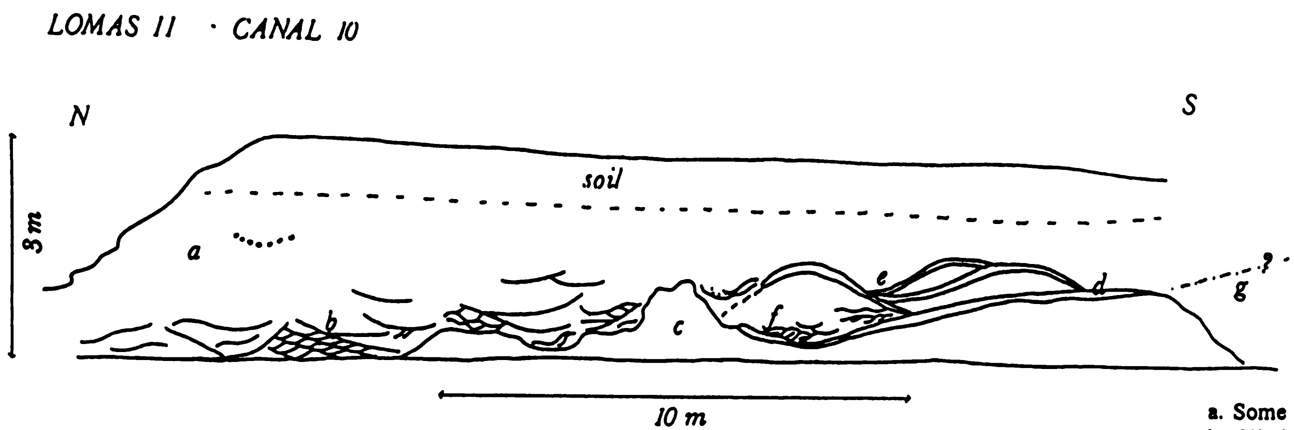


Fig A.7 Two canal cross sections:
Canal 9 shows the main channel with trough cross beds and dunes. The smaller depressions in the floodplain are separated by very loamy intervals with a thin white clay layer of 10 cm thickness interbedded.
Canal 10 probably shows lateral accretion planes, but lacks a main channel fill.

a. Some trough cross beds with pebbles at the base.
b. Climbing ripples.
c. Dark brown paleosol.
d. Light grey clay layer.
e. Lateral accretion planes ?
f. Current ripples.

Typical for this part of this study area is a white clay layer. This clay layer appears within a few meters from the sides of the channel fill and separates the sheet deposit of the channel from an underlying older floodplain deposit.

The white clay is ripened and contains little branches. Layer thickness varies between 5 and 20 cm.

The other branch bends to the south. Pointbar deposits with lateral accretion planes were found at point 7 and may be present in canal 10 too (fig A.7). The sheet deposits of this part can be followed 100 m towards the east were they have a thickness of 1.25 m. They are very loamy and shift slightly into clayey deposits.

6. Lomas Finca III

a. Location

Lomas III is situated about 7 km northward of finca I and II. It is an area in which no canals were dug yet. At the northern side the area is bordered by the Río Tortuguero, which in former times had a direct connection with the Río Toro Amarillo, draining the slopes of the Irazú and Turrialba volcanoes (See chapter II, geological setting and van Seeters, 1993)

The recent area is covered by a swamp vegetation in the northern part, and pasture in the south. Because of the dense vegetation the area is badly accessible, and only borings were made.

A map was tried to make of the sand deposits in the area, but due to the bad accessability of the terrain the map was not finished.

b. Sand body

The deposits of Lomas finca III differ from the deposits found in the other parts of the study area. At this place a specific channel like in the other deposits was not found; however, in the area widespread sand deposits were discovered. They all seem to be deposited by the Río Tortuguero, of which this is a floodplain area.

The sands vary in thickness from 25 cm to over 220 cm in the southern and more distal part. In the landscape an elevation of 1.0-1.5 m indicates the presence of coarse sand deposits. The soft, swamp clay deposits have been compacted with time.

The area contains coarse sand deposits and a lot of mostly badly drained medium to fine sands, varying in bed thickness. They are interbedded between dark grey swamp clays and sometimes organic matter is found in these sands. These deposits seem to be small crevasse splays, widespread floodplain deposits or the most lateral extended parts of a coarse crevasse splay. The coarsest sand body may have been deposited by a large sediment supply from the mountains[1].

[1] Compare with volcanic eruptions (Table IV.1).

c. Structures

The sands found in the elevated ridge in the landscape are coarse and show two times a small fining upward cycle, visible in pits dug. The first fining upward cycle of 60 cm thickness, varies from very coarse to medium sand. The second f.u, with a bed thickness of 40-50 cm, varies from coarse to medium sand. This supposes that deposition took place in two periods (or pulses), following in short time, because the lack of a soil in the first f.u.

The banks of the Río Tortuguero consist for a thickness larger than 320 cm, of sand mixed with loam. By use of hand bore no sedimentary structures could be found, and the banks looked massive like the banks at Lomas I and II.

Similar deposits of the Río Jiménez and/or the Río Parismina

7. Los Angeles

a. Location

The deposits of Los Angeles were studied in one canal dug for drainage near the village with the same name (fig 3.2). The outcrop was up to 4 m deep. The canal was situated 100 m south of the Río Jiménez, and the channel fill is probably a deposit of this river. Stream direction is east, equal to that of the recent river.

b. Sand body

The sand deposit shows a main channel of 30 m width, a probable depth of 8-10 m, and a smaller side channel with a width of 10 m and a depth of 3.5 m. The floodplain deposits of this channel fill can be followed over 50 m in southward direction, where they thin out against the older Pleistocene Tierras Rojas (fig A.8).

The channel fill (texture and structures) of both channels is asymmetric and coarser in the northern (cutbank) sides.

After infill of the main channel the remaining surface of this channel contained two smaller channels (± 3.0 m wide and 0.80 - 1.0 m deep/fig A.8), which were completely filled with clay and silt during later depositional events of the Río Jiménez. It shows a different soil as formed in sand deposits.

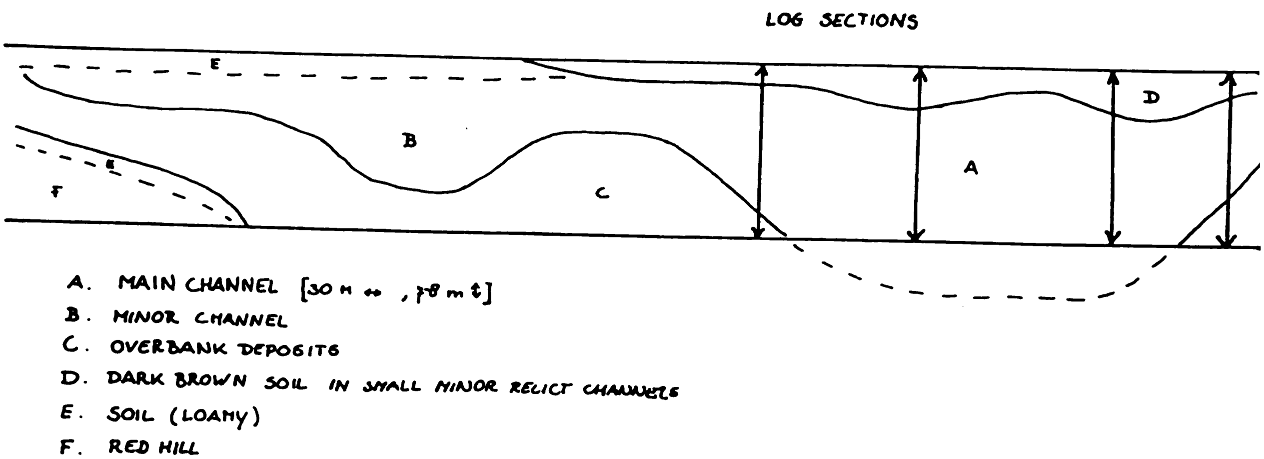
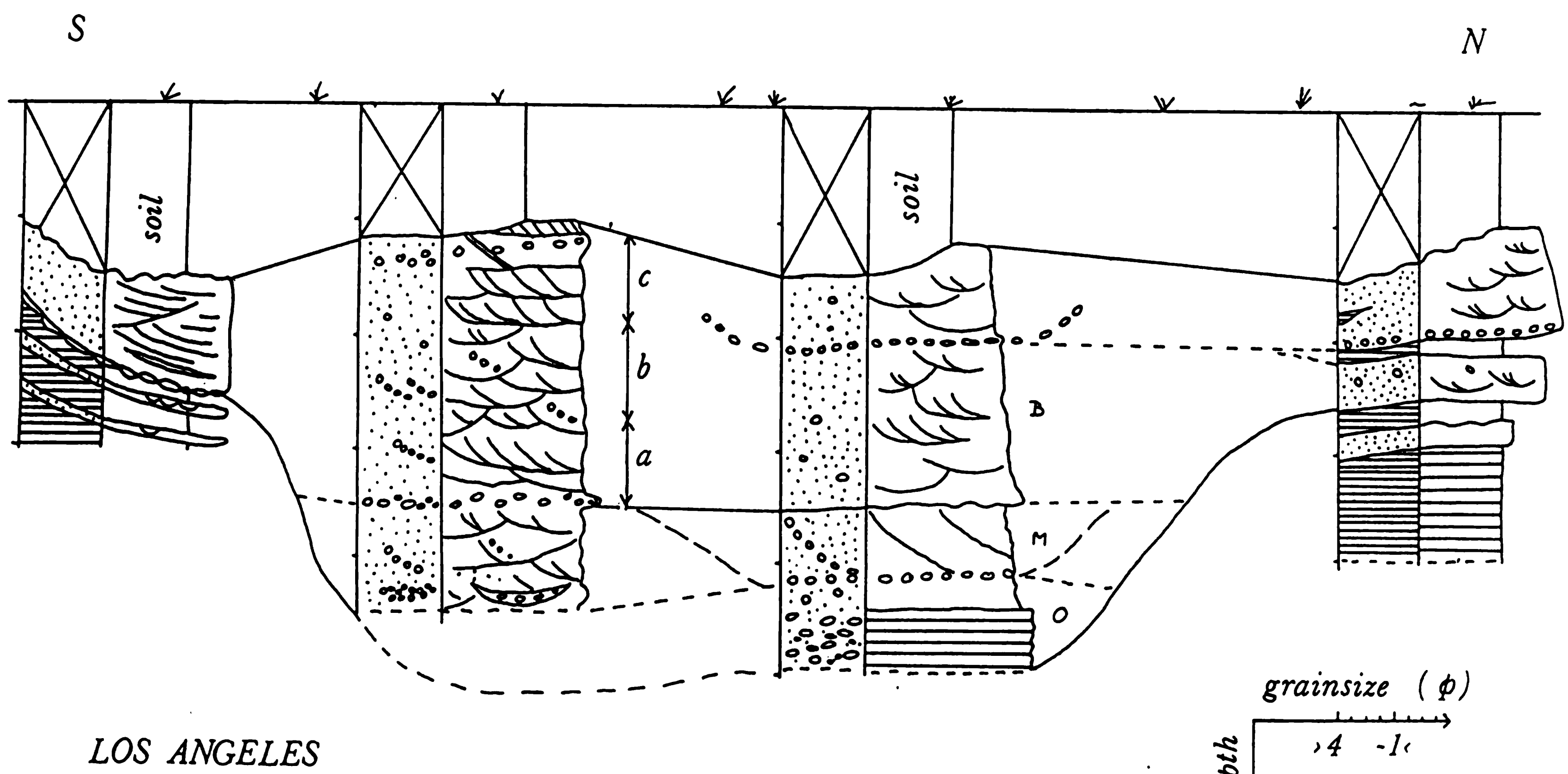


Fig A.8 Overview of the facies relations of the Los Angeles Channel fills.



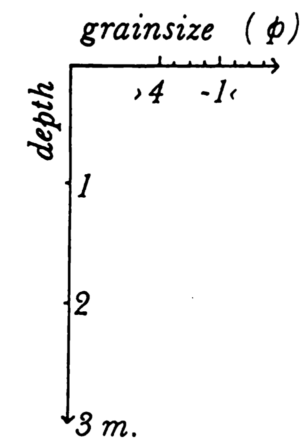


Fig A.9 Sequence diagrams of the Los Angeles channel fill. Compare with fig 4.2; a.b.c.= Dunes. Comparison with facies (after Smith 1987 b):

B. S_t/S_r - Sinuous crested dunes, ripples (bar top, secondary channel, floodplain). [Height 10-20 cm/ width 50 cm.]

M. $S_t/S_p/S_r$ - Sinuous crested dunes, straight crested bars, lingoid bars,ripples, small channels. [Height 20 cm/ width 120-150 cm.]

O. S_h - Horizontal lamination, deposition under high stream velocities. [Very coarse sand and fine gravel]

c. **Structures**

Sedimentary structures show mainly trough cross beds (fig 4.3). Wavelengths are ± 50 to 60 cm, and heights of 10-20 cm. Lower in the profile horizontal lamination and high angle cross-bedding were found (fig A.9). The cross beds had wavelengths up to 120 cm and heights up to 40 cm.

The sides of the main channel show an alternation of silt, clay and medium and coarse sand with small througbeds (fig A.9). Wavelengths of these troughbeds were ±15 cm, and heights ±10 cm.

The deposit contains andesitic and pumice pebbles, but also pebbles which consist of non weathered clay particles. These clay pebbles are mainly smaller than the other (volcanic, mainly andesitic) pebbles. Clay pebbles were found with a mean diameter of 4-5 cm, volcanic pebbles were found with diameters up to 3 cm.

8. Santa Maria

a. **Location**

Location of this sand body as shown in fig 3.2, is about 8 km upstream of Los Angeles. The sand body is only described in one small outcrop (1.4 m deep) in pasture.

b. **Sand body**

The deposit can be followed over 1 km as an elevation in the landscape of about 1 m high. Stream direction of the channel fill is towards the E.

The elevated ridge in the landscape, caused by the main channel, is 25 m wide. Channel depth is ± 5.5 m.

c. **Structures**

The texture consists of poorly sorted medium to coarse sand.
Sedimentary structures are hard to find. Structures, which could be discovered were high angle X-beds with a height of 40-50 cm.

The deposits of the Toro Amarillo - Chirripó system

9. Río Chirripó

This deposit is the youngest channel fill in the Atlantic Zone. It was deposited in 1970 after a period of heavy rainfall in the first days of December of that year. The amount of precipitation was 1436 mm, while the mean for December lays at 494 mm (Hartman, 1992). During this period the Río Chirripó has blocked its course with its own sediments and after two months, in which the river has occupied two channels according to the newspaper (La Nacion, 28-1-1971), a new course was occupied. Now the Río Chirripó flows 4 km to the west into the Río Sucío.
The abandoned course was studied.

a. Location

The channel fill, which is situated in the west side of the area (fig 3.2), can be recognized in the landscape over 30 km until the filled channel disappears between the swamps and Pleistocene deposits (up to 100-150 m high in this part of the area).
This sand deposit was studied over almost its whole length. In the field borings were made in two line profiles perpendicular to the stream direction (one at San Gerardo and one at Cerro Negro/fig A.12 and fig 3.2) and at several places in the stream direction, which was to the N. At some places pits were dug to a depth of 1-1.5 m below the surface. The northernmost 15 km of the channel fill could not be studied in the field, because of the bad accessability of the terrain. These river parts were studied by means of aerial photos (Chapter 4.a).

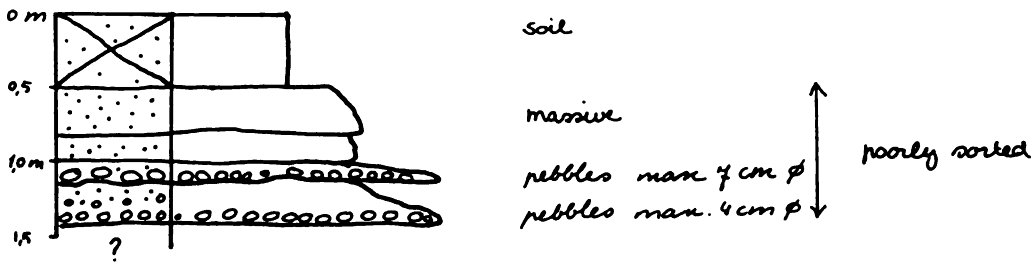
b. Sand body

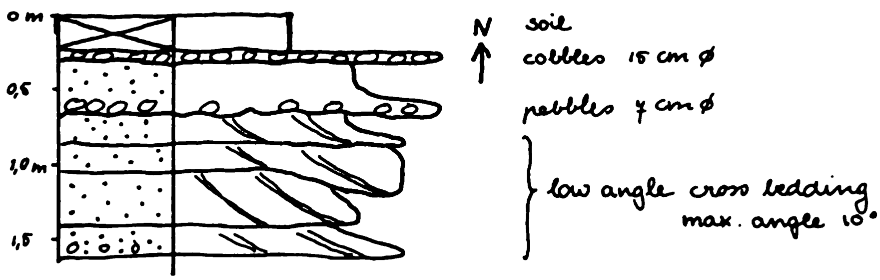
The Río Chirripó had a total length of 100 km before 1970 and covered an area of 1.271 km^2. Now its total length from the mountains is reduced to $\pm$ 55 km up to the point where this river confluences with the Río Sucío (fig 3.1 and 4.1).

The abandoned channel has a length of about 40 km. Point A at fig 4.1 marks the transition between braided and meandering channel patterns. At point B the channel changes its meandering pattern into anastomosing as a result of the low gradient in this coastal swamp area (0.1 m/m). Channel width decreases from $\pm$ 50 m to $\pm$ 20 m and smaller.
Table A.II shows the sinuosity and gradients over the length of the abandoned channel. At the blocking point the gradient decreases from 3.7 to 0.8 m/km. This might be of influence for river course changing.

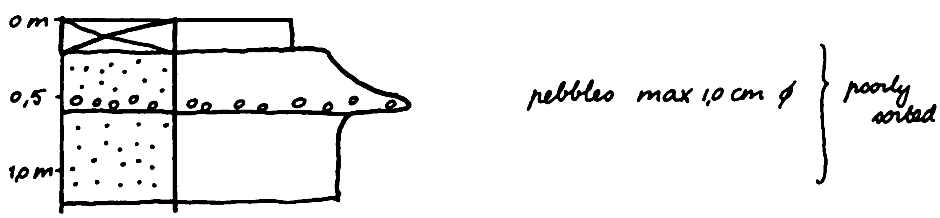
CHIRRIPO

main channel





floodplain



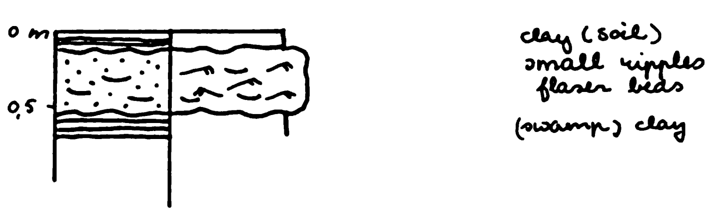
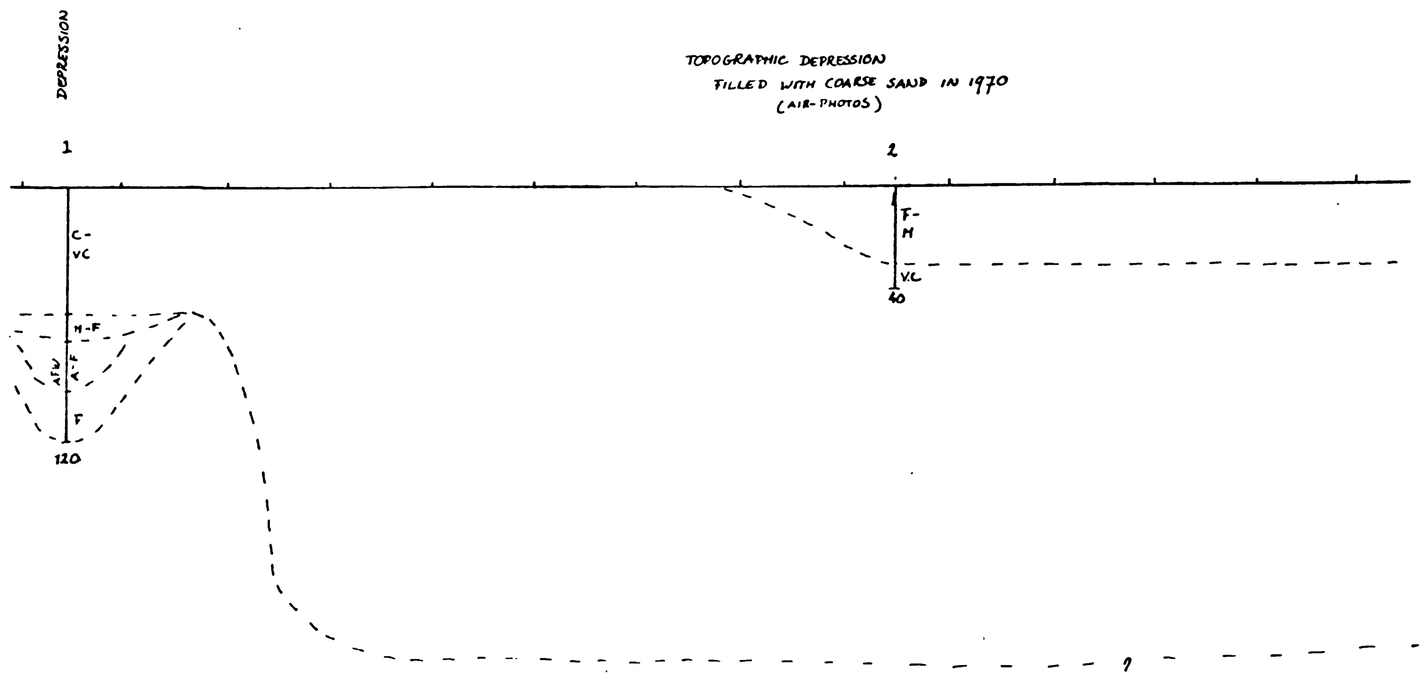


Fig A.10 Sequence diagrams of the Chirripó channel fill.

Fig A.11 Photograph of the upper 1.20 m of the Chirripó channel fill. Beds varying in thickness between 8 and 20 cm. Low angle cross beds are shown.



DEPRESSION
TOPOGRAPHIC DEPRESSION
FILLED WITH COARSE SAND IN 1970
(AIR-PHOTOS)
1
2
C-
VC
M-F
A-F
AFW
F
120
F-
M
V.C
40
?

Table A.II *Channel patterns and gradients over the length of the abandoned channel of the Río Chirripó.*

LOCATION (fig 3.1)	*RIVER PATTERN*	*GRADIENT (m/km)*	*SINUOSITY*
- A	braided	3.7	1.15
A - B	meandering	< 0.8	1.28
B - C	anastomosing	0.3 - 0.1	1.14/1.29

At the surface of the abandoned channel at San Gerardo incisions of smaller channels occur (with depths of ± 2 m and widths of 3 m). In these channels little swamps are formed (fig 6.2).

The flood plain deposits extend over 100 to 200 meters perpendicular to the old channel. At the final extensions of the floodplain, the fine sand floodplain deposits were covered by younger clay deposits, with thicknesses up to 30 cm.

c. Structures

Mainly texture analysis were pointed out for this area. Texture profiles, made by augerings and pits are shown in fig A.10, A.12 and A.13.

In the pits in the main channel, beds (thicknesses 40-50 cm) of coarse to very coarse sand with horizontal lamination and cobbles (max. 20 cm), altered with beds of low angle cross bedding and smaller pebbles (up to 8 cm) were exposed. Up in the profile bed thickness decreases into beds of 7-8 cm. Cross beds are the most common structures for these beds. No troughbeds were found in this deposit.
The floodplain deposits showed small ripples (fig 4.5).

10. Finca Cobal

a. Location

Banana Plantation Cobal is situated ± 10 km downstream to the NE of San Gerardo, the point were the Río Chirripó has changed its course. One recently cleaned canal was studied.

b. Sand body

The deposits on Finca Cobal but showed many similarities to the other elongated sand deposits found in the Atlantic Zone (mainly with Lomas Finca I). The channel fill was interbedded in (swamp) clay and floodplain deposits.

c. structures

A coarse base is found, with small channels, up to 2 m in length, fining up into cross- and trough beds of decreasing wavelength. Texture also fines up from poorly sorted pebbly coarse sand to moderately sorted medium and fine sand. The upper 1 m contains more loam due to pedogenesis.

Cerro Negro

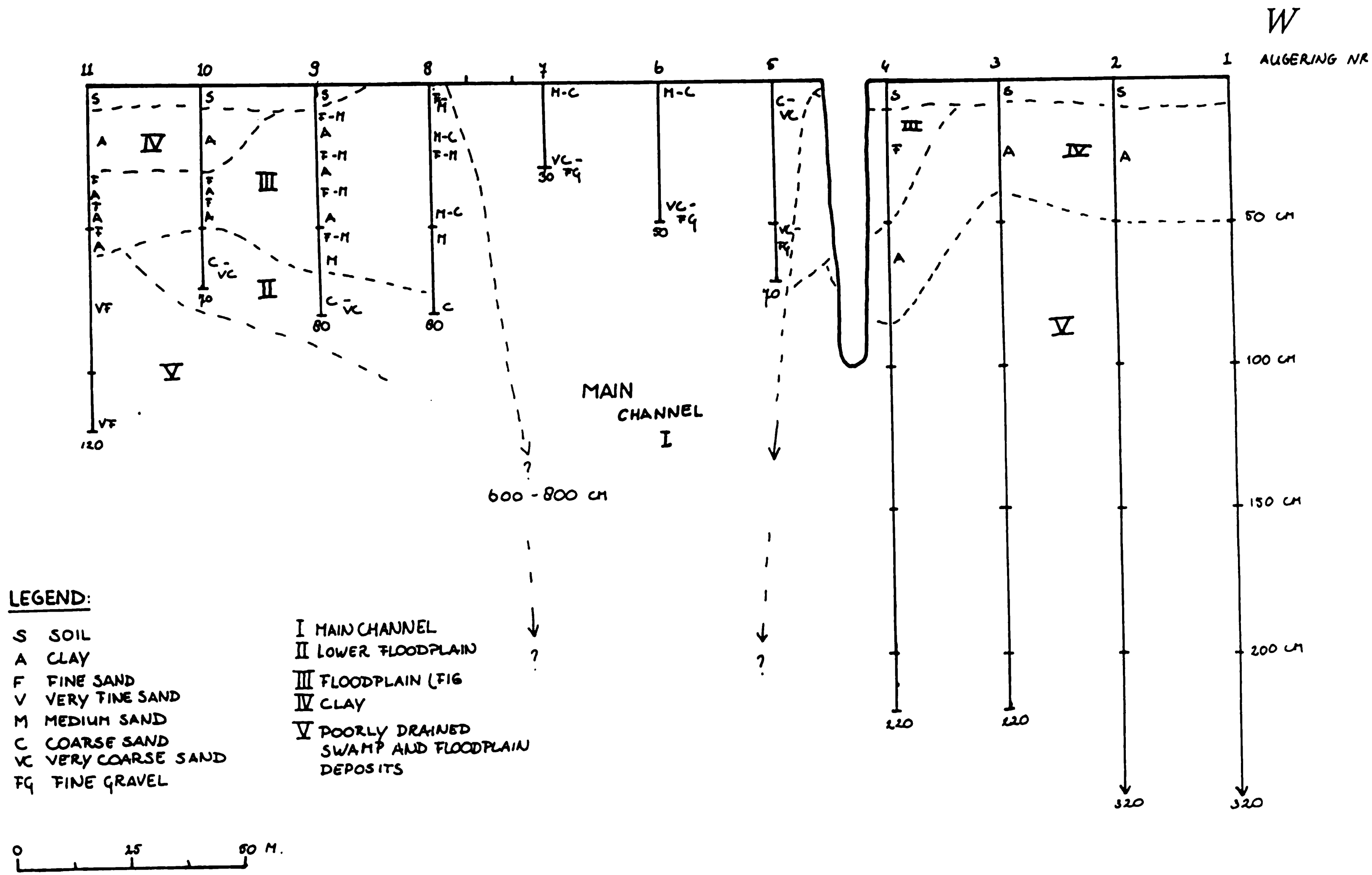
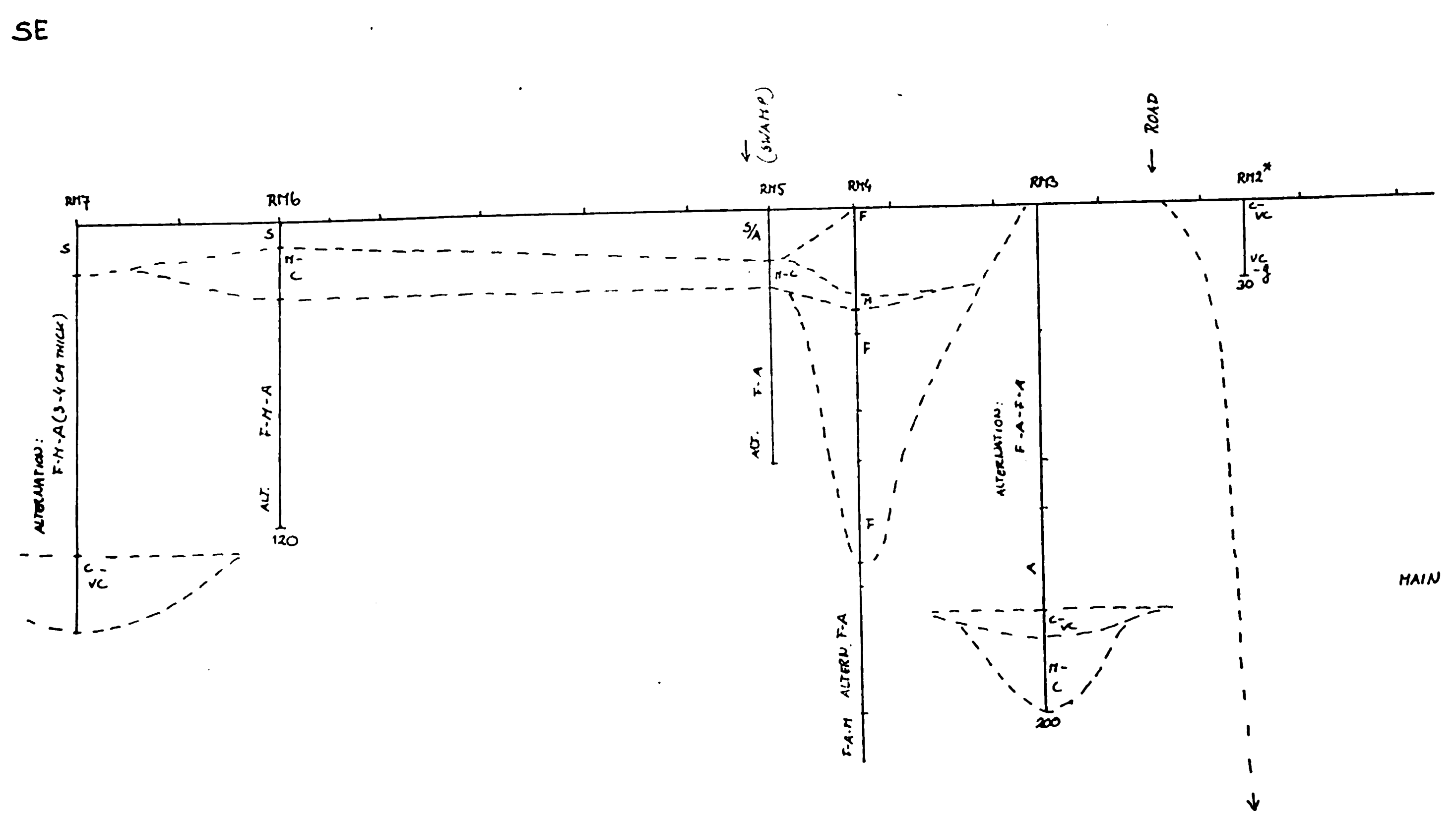


Fig A.12 Profile of the augerings made at Cerro Negro. Grainsizes and facies are indicated.

CHIRRIPÓ '70

~ SAN GERARDO ~

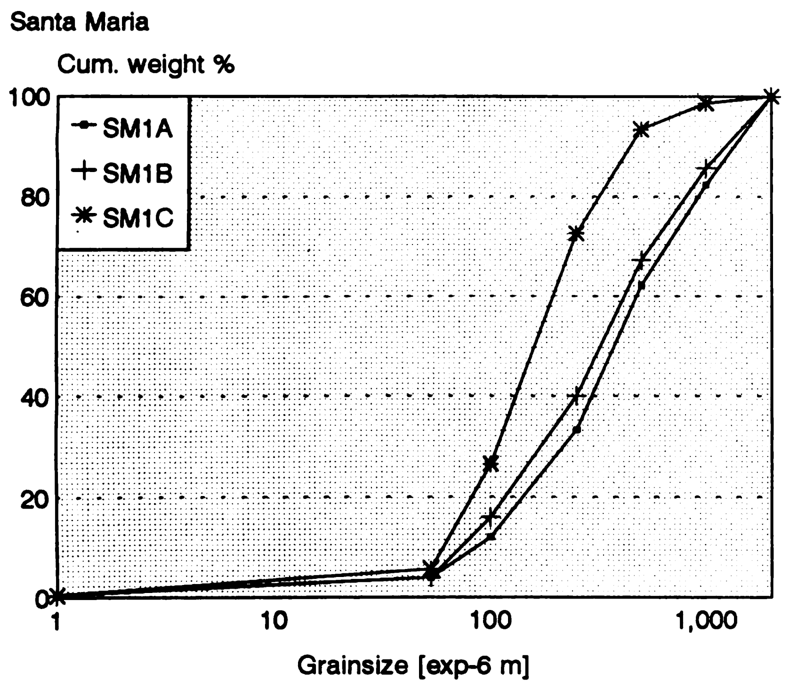
LEGEND AND SCALE CORRESPOND WITH THE CERRO NEGRO PROFILE (FIG A.12)

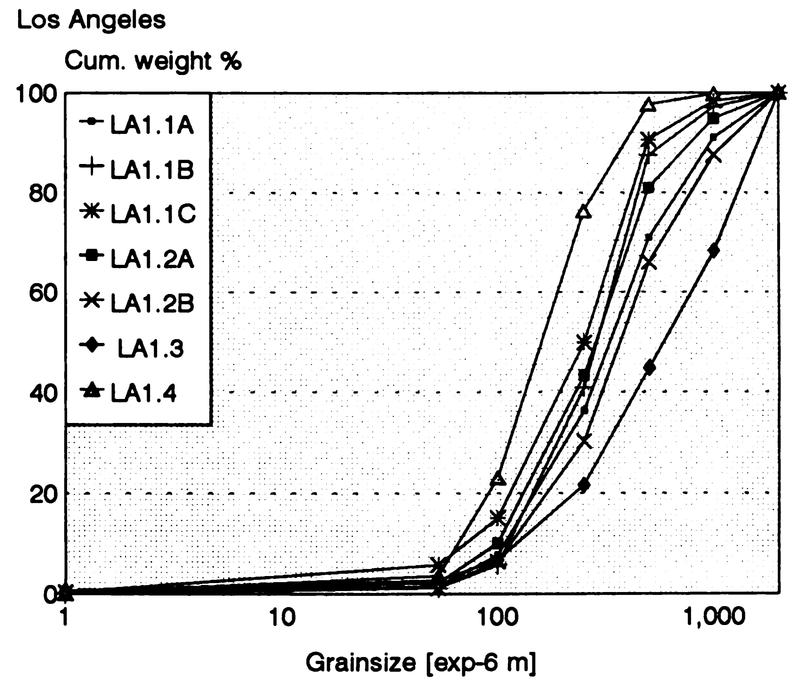


APPENDIX B

TEXTURE ANALYSIS

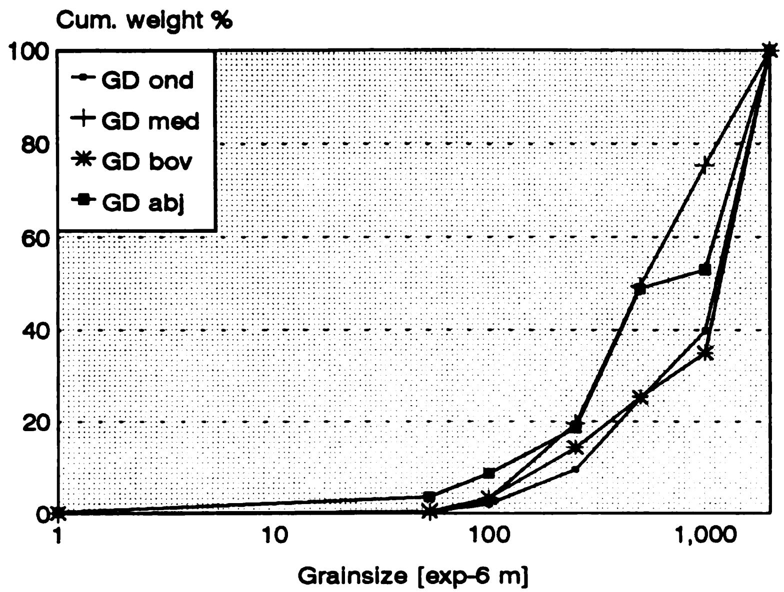
Cumulative Grainsize Diagrams



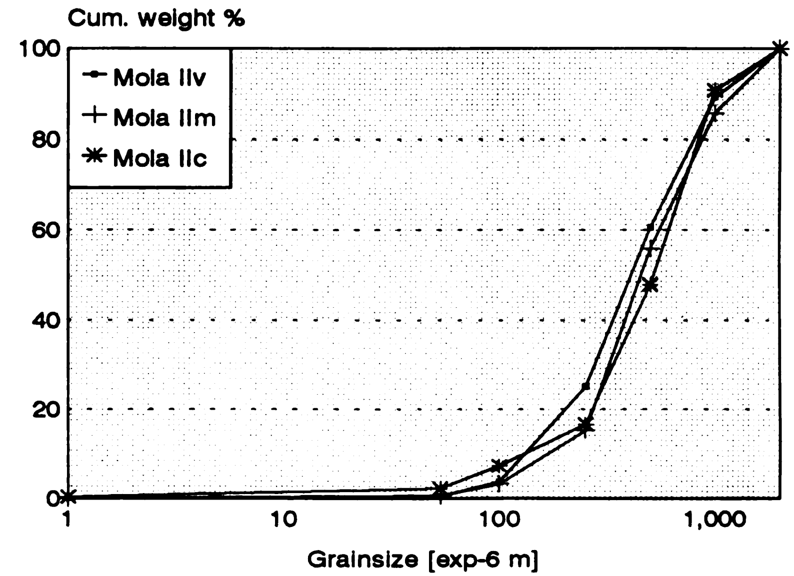


TEXTURE ANALYSIS

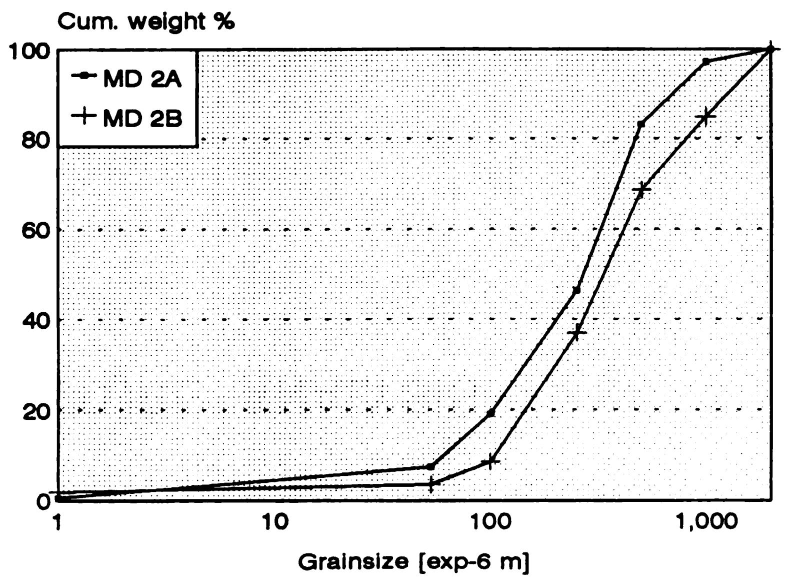
La Guadelupe



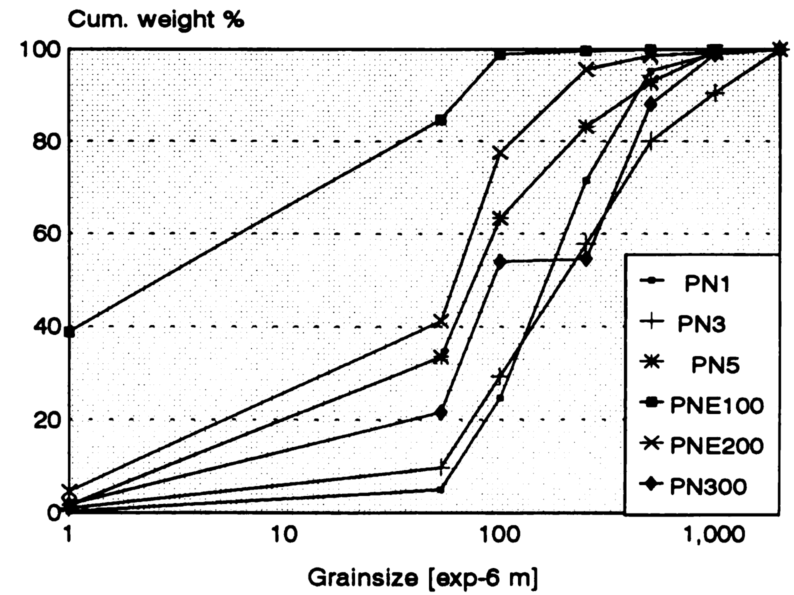
Mola II (without pumice)



Mola II (pumice containing)

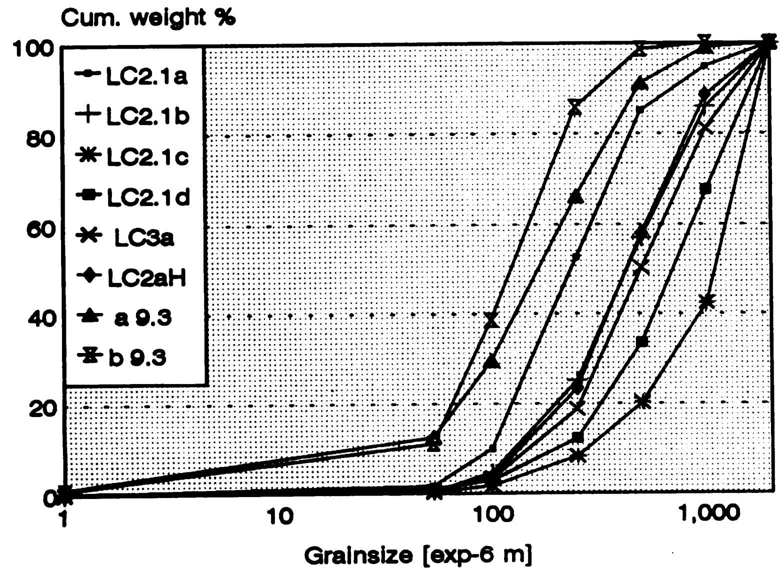


Calinda

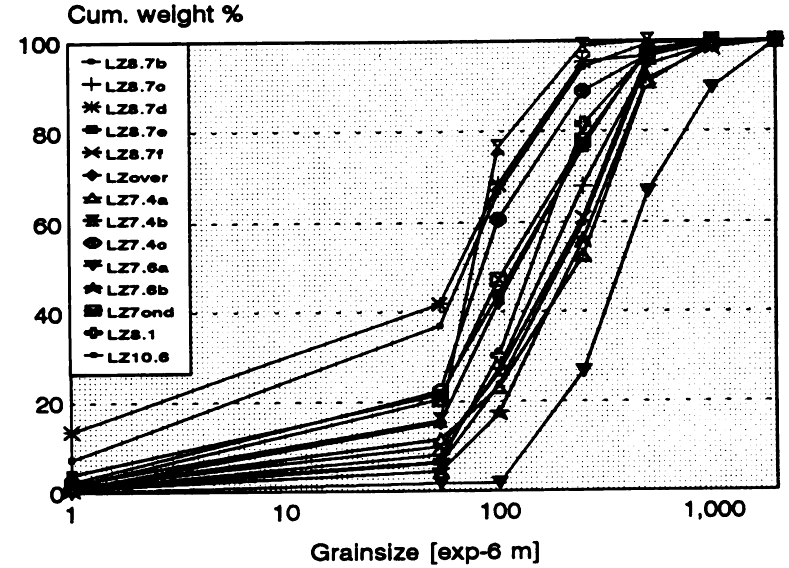


TEXTURE ANALYSIS

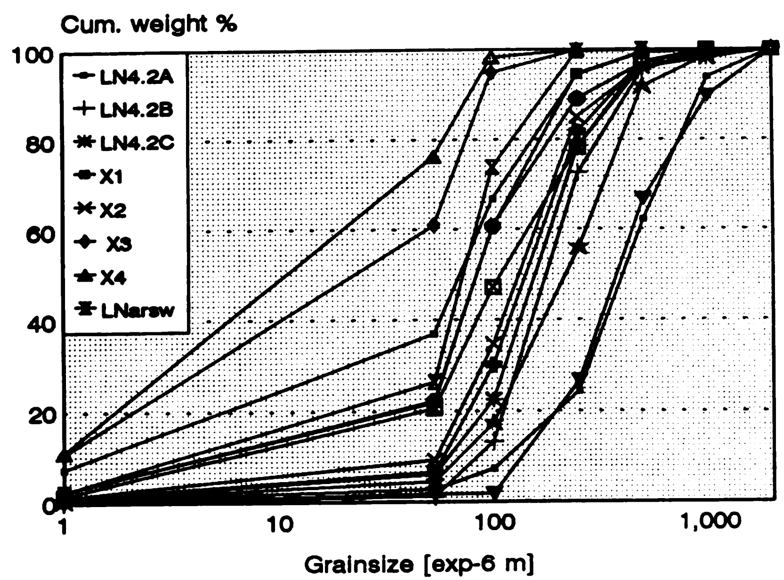
Lomas I



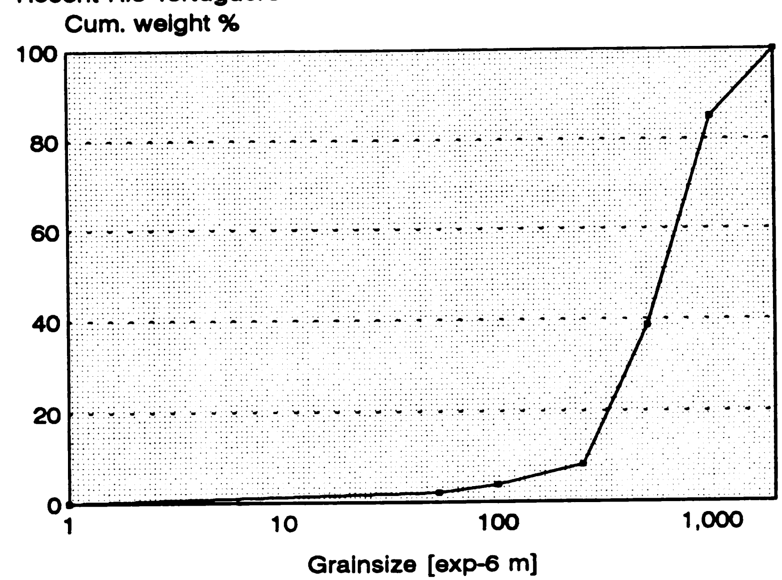
Lomas 2

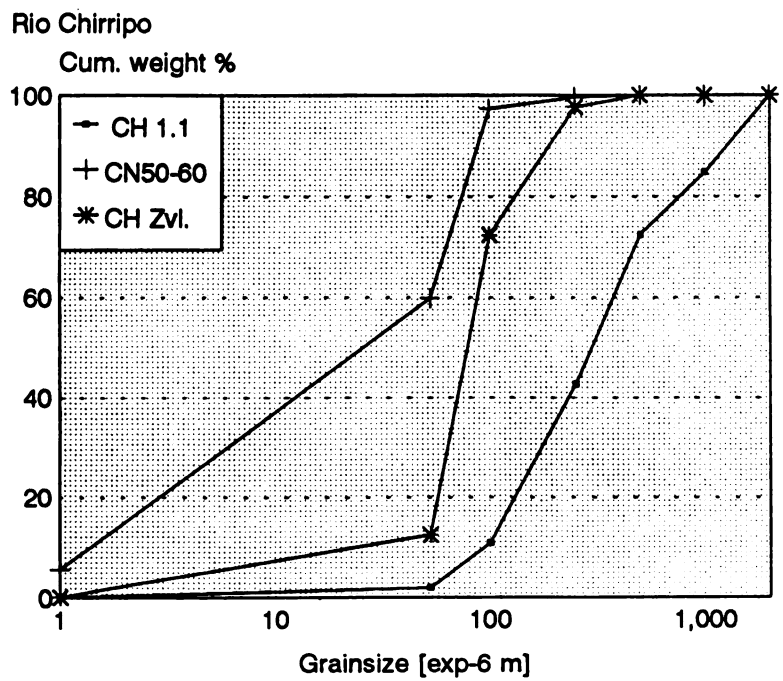


Lomas 3



Recent Rio Tortuguero




Rio Chirripo
Cum. weight %
100
80
60
40
20
0
1
10
100
1,000
Grainsize [exp-6 m]
CH 1.1
CN50-60
CH Zvl.

List of Channel deposits	List of Floodplain and Swamp deposits
GDond	
GDmed	
GDbov	
GDabj	
MolaIIv	
MolaIIm	
MolaIIc	
MD 2A	
MD 2B	
PN1	PNE100
PN3	PNE200
PN5	PNv
	PN300
LC 2.1a	
LC 2.1b	
LC 2.1c	
LC 3.a	
LC 2aH	
a 9.3	
b 9.3	
LZ 8.7b	LZ 8.7d
LZ 8.7c	LZ 8.7e
LZ 7.4a	LZ 8.7f
LZ 7.6a	LZover
LZ 7.6b	LZ 7.4b
LZ 8.1	LZ 7.4c
LZ 10.6	LZ 7 ond
LN 4.2a	X1
LN 4.2b	X2
LN 4.2c	X3
	X4
	LN arsw
Tort	
LA1.1A	
LA1.1B	
LA1.1C	
LA1.2A	
LA1.2B	
LA1.3	
LA1.4	
SM 1A	
SM 1B	
SM 1C	
CH 1.1	CN 50-60
	CH zvl.