ATLANTIC ZONE PROGRAMME

Report No. 47
Field Report No. 95

A STUDY ON GEOMORPHOLOGY, MINERALOGY AND GEOCHEMISTRY OF THE TORO AMARILLO-TORTUGUERO AND THE CHIRRIPO-MATINA RIVER SYSTEM IN THE ATLANTIC ZONE OF COSTA RICA

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February 1993

CENTRO AGRONOMICO TROPICAL DE
INVESTIGACION Y ENSEÑANZA - CATIE

UNIVERSIDAD AGRICOLA
DE WAGENINGEN - UAW

MINISTERIO DE AGRICULTURA Y
GANADERIA DE COSTA RICA - MAG

Figure 1. Location of the study area.

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 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

This report is the result of a five months thesis on geology. A number of persons have helped me during the period in which the fieldwork and the writing of the report took place.
First of all I would like to thank my supervisors Professor Salle Kroonenberg and André Nieuwenhuyse for their encouraging support and helpful comments.
Toine Jongmans, thank you for an enthusiastic introduction into micromorphology and optical mineralogy.
Jan van Doesburg and Bram Kuyper, thank you for helping me with the XRD and XRFS analyses.
I would like to thank the IGN, especially Olga Segura, for allowing me to work at their office and helping me with the airphotos.
Finally I would like to thank all persons that I have met during my stay in Costa Rica (May-October 1991) for making this period a very pleasant one.

Robert van Seeters,
August 1992

TABLE OF CONTENTS **PAGE**

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

In this report often abbreviations are used, indicating rivers or complete river systems. These abbreviations and their meaning are:

TTS	=>	Toro Amarillo-Tortuguero system (Río Toro Amarillo & Río Tortuguero, and their tributaries);
RT	=>	Río Tortuguero;
RTA	=>	Río Toro Amarillo;
RS	=>	Río Sucio;
ChMS	=>	Chirripó-Matina system (Río Chirripó Atlántico & Río Matina, and their tributaries);
RChA	=>	Río Chirripó Atlántico;
RM	=>	Río Matina;
RZ	=>	Río Zent;
RB	=>	Río Barbilla;
RR	=>	Río Reventazón.

1 INTRODUCTION

The purpose of this study was to characterize and compare geomorphology, mineralogy and geochemistry of the Toro Amarillo-Tortuguero and the Chirripó-Matina river system in the Atlantic Zone of Costa Rica.

River systems in this region are very dynamic. An example is the cut off of Río Tortuguero from Río Toro Amarillo. Extreme floods during the end of the sixties, caused by excessive rainfall, together with a highly increased sediment discharge due to a series of ash eruptions of Irazú volcano between 1963 and 1965 (Kesel & Lowe, 1987), resulted in shifting of stream channels and major inundations. Another example is the changing of flow direction of Río Chirripó, nowadays discharging in Río Sucio, but before 1970 in Río San Juan (Anonymous, 19??; Vahrson et al., in press); or the separation of Río Reventazón and Río Pacuare in the 19^{th} century (Vahrson et al. according to Gonzalez V. (1910)). Floods also regularly occur between such events, but mostly will not have highly increased sediment discharges (Kesel and Lowe, 1987).

To understand better what produces the considerable dynamics of the rivers in this part of the country, it is necessary to know more about the landforming processes that were active in the past and still are active today. Fortunately (that is for the true earth scientist) three of the most important landforming processes occurred shortly before and during my stay (may-october 1991) in Costa Rica: earthquakes, volcanism and floods. This made it a lot easier to study these processes and their effects.

The Toro Amarillo-Tortuguero system drains part of the eastern side of the active volcanic Cordillera Central with mainly andesitic rocks. The Chirripó-Matina system drains part of the eastern side of Cordillera de Talamanca with highly variable rock types, varying from calcareous sedimentary to plutonic rocks, in which active volcanism is absent. Consequently it was expected that soils formed in Toro Amarillo-Tortuguero deposits differ in chemical and physical properties from those formed in Chirripó-Matina deposits. In this survey sediments of both rivers and soils along RT and RM were described and sampled to study the differences.

The survey is concentrated on the lower reaches, and part of the middle reaches of the rivers, i.e., where net deposition by rivers takes place.

In this report first a short outline is given of the physical setting of the study area (Ch.2). Its geomorphology is discussed in chapter 3, and mineralogy and geochemistry in chapter 4. In the last chapter (Ch.5) all results are summarized and discussed.

In the text a distinction is made between flood and inundation. With flood is meant a very high water discharge of a river. Such a flood may produce inundations at the alluvial fan and in the alluvial plain, but will not necessarily do so.

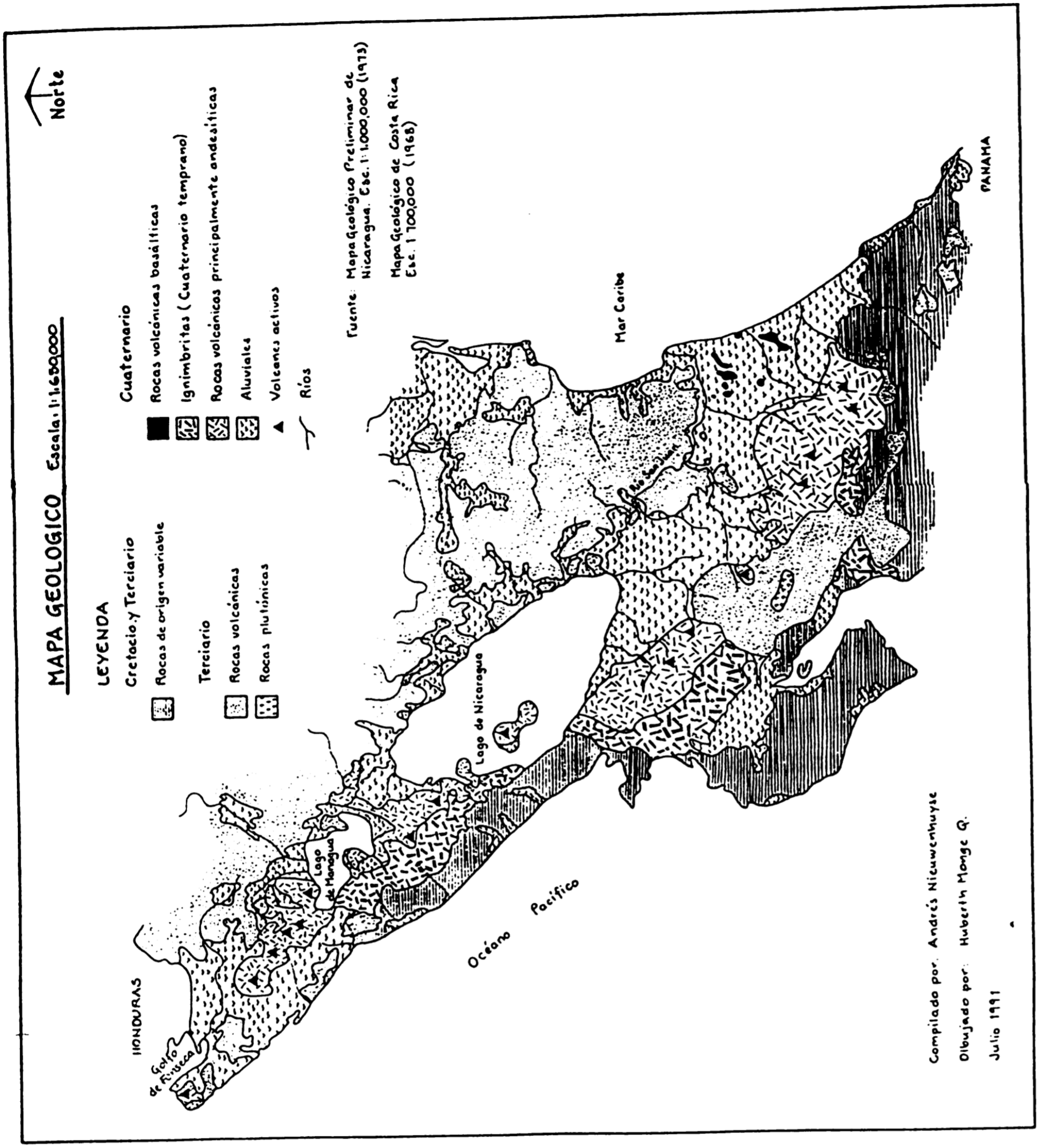


Fig 2.1 Geologic map of the northern part of Costa Rica and the southern part of Nicaragua.

2 THE PHYSICAL SETTING

2.1 Geology

The study area is situated in the Atlantic-Caribbean lowland of Costa Rica. This lowland is part of a large tectonic unit formed by the subduction of the Cocos plate under the Caribbean plate. Two morphologic features of a subduction zone are present in the study area: an island arc and a back-arc basin.
An island arc is a chain of stratovolcanoes, formed by (usually) andesitic magma that originates from partial melting of the subducting plate under the overriding plate (Skinner & Porter, 1987). The Cordillera Central, bounding the Atlantic-Caribbean lowland in the west and southwest, represents part of a large island arc, running parallel to the Pacific coast extending from the Mexican border to Costa Rica and continuing in a more dispersed pattern into Panamá (fig 2.1).
A back-arc basin is formed behind the island arc by crustal thinning, initiated by tensional stress in the overriding plate due to a faster rate of sinking of the subducting plate than the forward motion of the overriding plate. The crustal thinning may eventually lead to the rise of basaltic magma and formation of small regions of new oceanic crust (Skinner & Porter, 1987). The Atlantic-Caribbean lowland is the southeastern continuation of the Nicaragua Depression, a back-arc basin running from the Caribbean coast of Costa Rica through southwest Nicaragua to the gulf of Fonseca and continuing into El Salvador in the form of faults (Weyl, 1980). The Cerro del Tortuguero and Lomas de Sierpe are examples of basaltic volcanoes in the centre of the basin (fig 2.2).
On the southside the Atlantic-Caribbean lowland is bounded by the offshoots of the Cordillera de Talamanca, a Tertiary mountain chain (fig 2.1). Before the beginning of the Tertiary this region was a marine sedimentation area. From the early Tertiary onwards this region is being uplifted, during which periods of plutonic and volcanic activity took place (Weyl, 1980).

The Atlantic-Caribbean lowland has been a sedimentation area since the early Tertiary. The still subsiding region is intersected in a radial pattern by many rivers draining the Cordillera de Talamanca, like the ChMS, and the Cordillera Central, like TTS. The Reventazón system is draining both of these mountain ranges. The coast line is made up by a narrow strip of succeeding beach ridges, over long distances separated by lagoons, situated parallel to the coast. Like most of the rivers, Río Tortuguero discharges into lagoons. Only few rivers, for example Río Matina, discharge directly into the Caribbean Sea. Behind the beach ridges and canals, coastal swamps occur, gradually passing into a vast alluvial plain. At the foot of the Cordilleras the alluvium takes the form of alluvial fan deposits. This flat landscape is at a few places interrupted by remnants of the already mentioned basaltic volcanoes.

In the Cordillera Central two volcanoes of major importance for the study area are located: Irazú and Turrialba. They are composite large stratovolcanoes. The main rock types of Irazú are quartz-latiandesite, quartz-latite and dacite, according to the Rittmann/Streckeisen definition. The main rock types of Turrialba are andesite and rhyodacite (Rittmann/Streckeisen). Irazú was last active between 1963 and 1965, producing series of violent ash eruptions. These ash eruptions caused accelerated erosion and several mudflows. The average SiO_2 content of the pyroclastics during these eruptions was 53.86% (Nieuwenhuyse & Kroonenberg, submitted). The last reported outburst of Turrialba was between 1864-1866. The pyroclastics of this eruption had an average SiO_2 content of 52.83% (Nieuwenhuyse & Kroonenberg, submitted). Periods of activity are often accompanied or preceded by weak earthquakes, which may cause landslides on the slopes of the volcanoes. This actually occurred during the months of June till July 1991, when Irazú activated temporarily, showing only fumarolic activity. Landslides may also be triggered by excessive amounts of rainfall.

The Cordillera de Talamanca is the largest and highest mountain range in Costa Rica. According to fig 2.2, derived from 1:200,000 geology maps (Dirección de Geología, Minas y Petróleo, 1982), sedimentary volcanic rocks, mainly of andesitic and basaltic origin, including breccias and conglomerates, make up 71% of the Chirripó-Matina catchment area. Other sedimentary rocks, mainly limestone, calcareous sand-, silt-, and claystones, make up 22%. The remaining part of the catchment area is made up by intrusive rock (6%), mainly granites and granodiorites, and by Tertiary-Quaternary volcanic rock (1%), mainly of andesitic origin.

The Cordillera de Talamanca has many faults (fig 2.2), pointing out seismic activity. Most of these faults originate from internal deformation in the Caribbean Plate. Severe earthquakes occurred in 1798, 1822, 1916, and more recent at 22-04-1991. These earthquakes all produced liquefaction, a phenomenon which only occurs during heavy earthquakes (OVSICORI & UNA, 1991). The 22-04-1991 earthquake had a magnitude of 7.4 (Richter). Besides much infrastructural damage, it caused many landslides in the Chirripó-Matina catchment area, which, triggered by excessive amounts of rainfall, gave rise to disastrous floods in the months after the quake (see also section 3.3). Moreover, the earthquake caused a rise of the coastline from Puerto Limón to Panamá of about 0.3-1.8 m, and subduction in the area northwest of Puerto Limón.

2.2 Climate

The Atlantic Zone has a maritime humid tropical climate with small temperature changes throughout the year. Annual variation of temperature is dominated by the monsoon with the highest temperatures before the onset of the summerrains (Portig, 1976). Average annual temperature in the Atlantic Zone is 26°C. The most important factor in seasonal (summer-winter) as well as diurnal temperature variation is cloud cover. Diurnal temperature differences are about 5°C or less at cloudy and rainy days, and about 12°C at clear days (Nieuwenhuyse & Jong van Lier, 1988).

In the northern summer the prevailing winds are the trade winds coming from the Caribbean Sea. From measurements by the Instituto Meteorológico Nacional in Puerto Limón in 1972, it appeared that northern, northwestern and southwestern winds prevailed. Most of the time these winds are not strong. Less frequent but generally stronger, were the eastern and southeastern winds. Hurricanes are not known to have reached the Atlantic coast of Costa Rica. According to Battistini & Bergoeing (1984) is Costa Rica outside the main route of these hurricanes.

Potential evapotranspiration in the Atlantic Zone varies between 30 mm/10 days in june and july, and 42 mm/10 days in march and april (Rojas, 1985). Nieuwenhuyse et al. (submitted) calculated for the Tortuguero weather station Penman mean monthly potential evapotranspiration values, using also data from nearby weather stations. They found the highest values from March till May and from August till October, with a maximum of 113 mm in March. The lowest values occurred from November till February, with a minimum of 81 mm in December.

From a geomorphological point of view, the most important meteorological element in the Atlantic Zone is precipitation. The most important contributors to the precipitation are the temporals (Spanish: Temporales) and the heavy downpours (Spanish: Ondas Tropicales/Aguaceros). Temporals occur during invasions of cold air from the northern temperate regions, mainly during the months of November till February. They may last for days, have no or only little electrical activity, and have light to moderate winds. Due to the excessive amounts of rain over relatively large areas, temporals may cause flooding, land slides, and other water damage (Portig, 1976). The heavy downpours occur more locally than temporals. They last relatively short, but may bring excessive amounts of rain. They occur more often than the temporales, and mainly during the months of May till October. Heavy downpours may have large electrical activity. Because they generally occur locally, so are their consequences: an enormous increase of water discharge in a very short time, resulting in floods, and damages to especially roads and bridges, in small areas. Rain intensity during downpours may exceed 2 mm/min (Nieuwenhuyse & Jong van Lier, 1988).

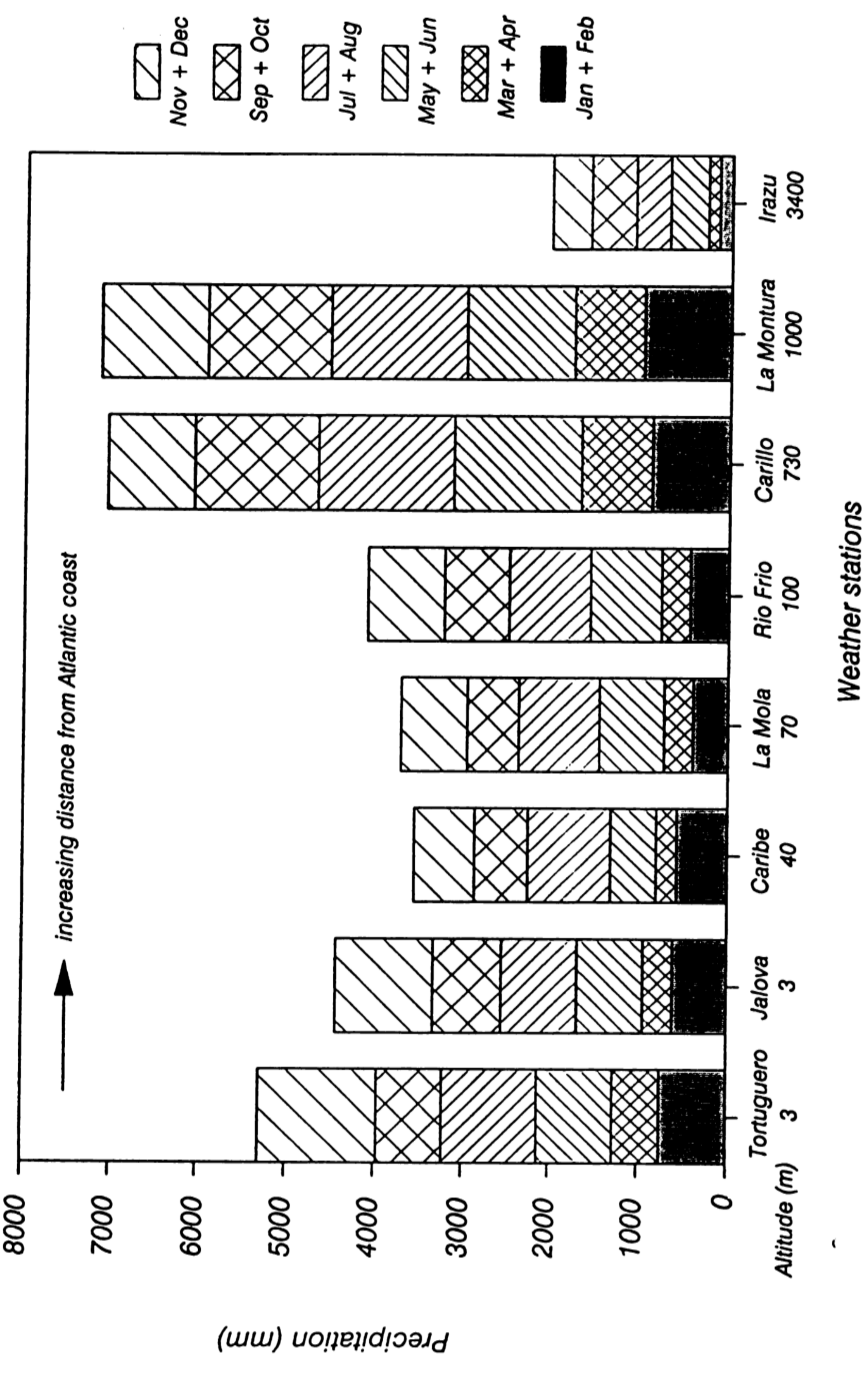


Fig 2.3 Precipitation distribution of a number of weather stations in the Atlantic Zone.

Fig 2.3 shows the precipitation distribution of a number of weather stations at different altitudes in the Atlantic Zone; the weather stations are depicted on fig 2.2. Exact monthly and annual precipitation amounts are summarized in appendix A.
Fig 2.3 gives a good impression of the annual amounts of precipitation in the Atlantic Zone, of the monthly distribution, and of the distribution with altitude. It is clear that the overall average annual precipitation is very high. February, March and April are relatively dry. Looking at the average annual precipitation, it becomes obvious that precipitation decreases from the coast to La Mola, at the distal part of the Chirripó-Sucio fan, and increases from La Mola onwards until the higher reaches of the Cordillera Central, where precipitation decreases again. Highest annual values occur in the lower and middle reaches of the Cordillera Central (Carillo and La Montura). According to Vahrson et al. (in press) zones of probably highest amounts and intensities of rainfall are the windward parts of the mountains at altitudes between 1500 and 2000 m. Also Portig (1976) stated that large rainfall totals are concentrated on the tops of lesser mountains and on the slopes of higher mountains, while the crests above approximately 2500 m receive less than half of what falls on the slopes. The maps of mean annual precipitation in Costa Rica in Hall (1985) and Nuhn (1978) are in contrast with these statements and incorrect.
Besides long-term precipitation data of La Lola (1949-1985), derived from a JICA (1988) report, no other data of weather stations nearby or in the Chirripó-Matina watershed could be obtained in time. At La Lola mean annual precipitation is 3520 mm. Mean monthly precipitation is highest in July (420 mm) and December (460 mm), and lowest in March (140 mm). There are no distinct dry periods during the year. Considering the precipitation data of La Lola and common knowledge, precipitation amounts and distribution in the ChMS watershed are thought to be of the same order of magnitude as those of the TTS watershed.
Annual precipitation amounts may vary much over short distances. This becomes clear from the weather stations La Mola and Río Frío. La Mola is situated at 70 m above sea level, only 6 km away from Río Frío, situated at 100 m above sea level. The minimum annual precipitation in La Mola (2716 mm) was measured in 1985, while in the same year in Río Frío an annual precipitation of 4446 mm was measured. The opposite occurs too: the minimum precipitation in Río Frío (2863 mm) was measured in 1980, while in the same year in La Mola an annual precipitation of 3934 mm was measured.

3 GEOMORPHOLOGY

3.1 Introduction

This chapter deals with the geomorphology of the Toro Amarillo-Tortuguero and the Chirripó-Matina system. Except (old) topographic maps and airphotos, little information about the two river systems could be found. Useful were reports of Kesel and Lowe (1987), who studied geomorphology and sedimentology of the Toro Amarillo alluvial fan, of Battistini & Bergoeing (1984), who studied the geomorphology of the Caribbean coast of Costa Rica, of Nieuwenhuyse & Kroonenberg (submitted), who studied the volcanic origin of Holocene beach ridges along the Atlantic coast of Costa Rica, and of the Japan International Cooperation Agency (1988), who studied the feasibility of an integrated agricultural development project in part of the Río Matina-Madre de Díos alluvial plain.
In section 3.2 the materials and methods used for the survey are treated. In section 3.3.1 river characteristics such as water discharge and longitudinal profile, are discussed. The floods are discussed in section 3.3.2, with emphasises on the 11/12-08-91 floods of RTA-RT and RChA-RM. In sections 3.4.1-6 and 3.5.1-4 the results of the geomorphological (field) survey on the two river systems are presented and discussed.

3.2 Material and methods

The geomorphological study included collecting river characteristics, studying airphotos (app E), topographic (IGN) and geologic maps (Dirección de Geología, Minas y Petróleo, 1982), and field work. River characteristics like river length and longitudinal profile were derived from 1:50,000 topographic maps, size of watershed and catchment area from 1:200,000 topographic maps. Water discharges are measured by the Instituto Costarricense de Electricidad (ICE). An indication about suspended load was obtained by taking some samples in plastic jerry-cans with volumes of 20 lt, at places with high stream velocities, preferably in the centre or in an outside bend of the river. After settling the water was poured off. The remaining sediment was oven dried (105 °C). Sediment discharges could be calculated by multiplying water discharges with suspended loads (app B).
Historical information about floods were obtained from Anonymous (19??), Bedoya B. (1984), Nuhn & Perez R. (1967), Vahrson et al. according to Gonzales V. (1910), the national newspaper La Nación and personal comments.

Table 3.1 Selected river characteristics of Río Toro Amarillo-Tortuguero and Río Chirripó-Matina; data distracted from topographic maps (IGN).

Characteristics	Toro Amarillo-Tortuguero	Chirripó-Matina
Watershed[a]	400 km^2	1350 km^2
Catchment area[a]	160 km^2	1200 km^2
River length		
Total	112 km	103 km
Erosion[b]	31 km	68 km
Deposition[c]	81 km	35 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.

Table 3.2 Mean monthly and maximum observed water discharge during the period of observation, at stations in the study area, including 11/12-08-91 maximum discharges.

Discharge station[a]	Drain.area (km^2)	Period of observation	Water discharge (m^3/s) Mean	Max	Max (08-91)
Carillo[b]	299	1987-1990	136-219	901	1200 (11-08)
Playa Hermosa	821	1981-1988	38-122	1460	2500 (12-08)
Barbilla	212	1976-1988	16-33	1040	972 (12-08)

Source: Instituto Costarricense de Electricidad (ICE) and Vahrson et al. (in press).

[a] Depicted on fig 2.2.
[b] Note that Carillo discharge station is not Carillo weather station.

Table 3.3 Indication of suspended load of Río Toro Amarillo, Tortuguero, Chirripó Atlántico and a drainage channel in a banana plantation, at normal and high water discharges, and right after the August-91 flood.

River	Location Nr[a]	Suspended load (g/m3) Normal	High	Flood (Aug-91)
Toro Amarillo	1	35	400	7000
Tortuguero	3	30	70	-
	5	-	75	-
Chirripó Atl.	11	5000	14000	-
Drainage ch.	7	0	250	-

Source: measurements carried out during this study.

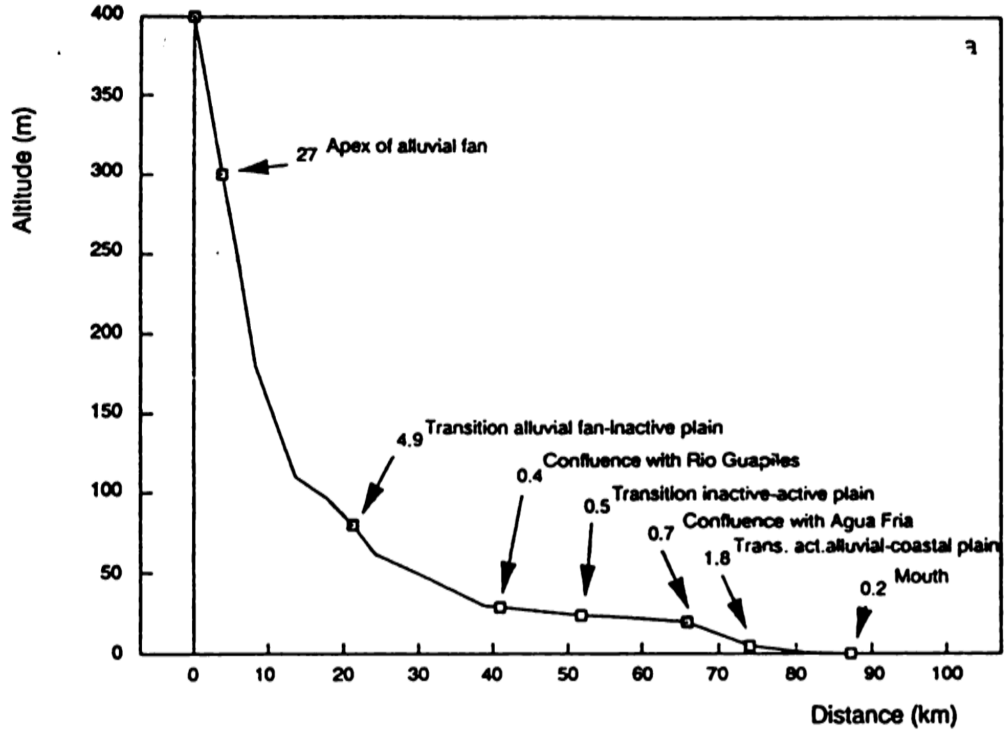
[a] Depicted on fig 2.2; additional data on samples in appendix C.

The airphotos and topographic maps, used to draw the geomorphologic maps (maps I and II), were of different ages in order to get more insight in river dynamics. Photo interpretation, checked in the field, made it possible to divide both the Toro Amarillo-Tortuguero, and the Chirripó-Matina system in sectors. The sectors were distinguished on geomorphologic unit and channel pattern. In each of these sectors a typical site was selected. These spots were studied in detail by making a number of augerings (with a maximum depth of 5 m) in a cross section perpendicular to the river. The augering descriptions needed to draw these cross sections have been compiled in appendix D. The types of channel patterns, mentioned in sections 3.4 and 3.5, are after a system developed by Brice (1975). The texture names are according to the USDA classification (Gee & Bauder, 1986). The particle size limits and names were derived from the USDA classification (Gee & Bauder, 1986) and Compton (1985): clay and silt (< 0.05 mm), very fine sand (0.05-0.125 mm), fine sand (0.125-0.25 mm), medium sand (0.25-0.5 mm), coarse sand (0.5-1 mm), very coarse sand (1-2 mm), pebbles (2-75 mm), cobbles (75-250 mm) and boulders (> 250 mm). The classification of the degree of sorting is after Compton (1985).
As the total survey area was too extended for one person to cover in a three-months-period, the procedure of selection would save a lot of time. Nevertheless, the sectors could not be studied equally well, partly due to inaccessibility of the area, and partly due to the sudden floods of 12-08-1991 which swallowed part of the time available for fieldwork.
All sample locations are depicted on fig 2.2. The site descriptions of the cross sections can be found in sections 3.4.3-4 and 3.5.3 (figs 3.2b, 3.3b and 3.5b). Additional data on the individual samples can be found in appendix C.

3.3 River characteristics

3.3.1 *General*

Results
Table 3.1 shows that RTA-RT and RChA-RM are comparable concerning total river length of the main channel, but not concerning the part where net erosion/deposition takes place, nor concerning size of watershed and catchment area. The size of the RChA watershed, which in this study was derived from topographic maps, coincides rather well with the size given by JICA (1988), viz. 1365 km^2. So does the size of the RTA catchment area with the size given by Kesel and Lowe (1987), viz. 138 km^2.
Table 3.2 (discharge) shows the big difference between mean monthly water discharges and the (short-lasting) maximum discharges. It is remarkable that the 11/12-08-91 water discharges were the highest observed so far at Carillo and Playa Hermosa (probably due to the relatively short measuring



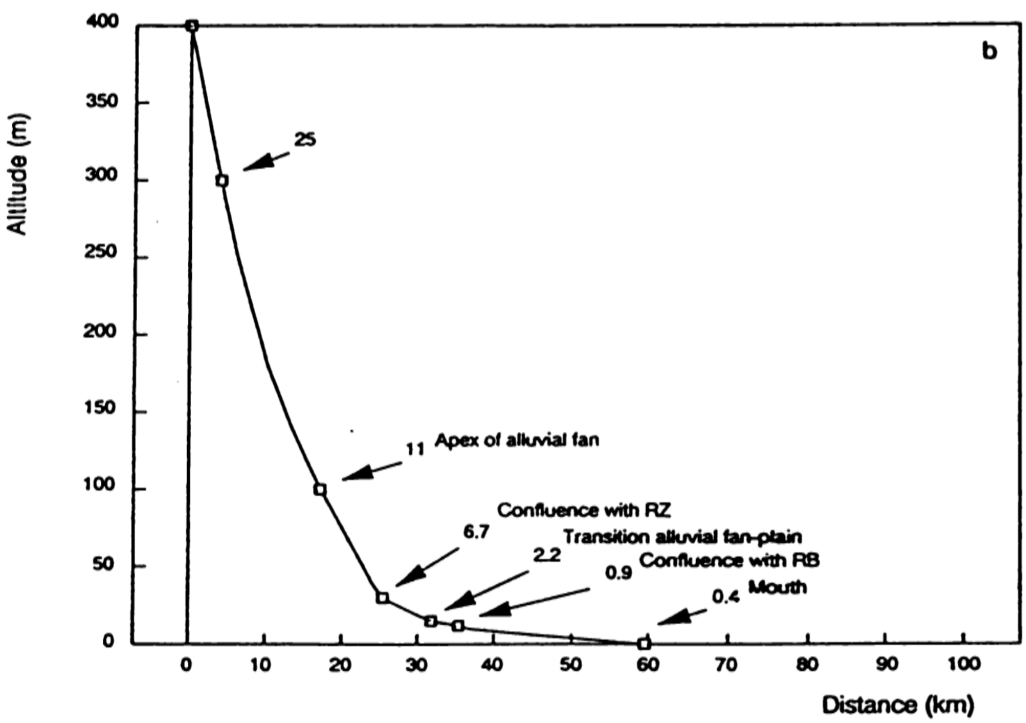


Fig 3.1 Longitudinal profile of RTA-RT (a) and RChA-RM (b).

period). Note that Carillo discharge station is not situated along Río Toro Amarillo, but along Río Chirripó-Sucio. This is important, because the mean monthly water discharge of RTA at the same altitude will be less. However, as an indication of the water discharge of RTA, and the difference between mean monthly and maximum discharges, Carillo discharge station will satisfy.

In table 3.3 suspended loads at normal and high water discharges were summarized. These results are merely indications, not official measurements (see section 3.2). Like the big difference in the water discharge of RTA, also its suspended load shows a big difference between normal (average) and maximum suspended load. At first sight RChA does not show such a big difference between normal and maximum suspended load. But after including suspended load data of RChA from Vahrson et al. (in press), it appears that RChA shows a big difference too, with mean monthly suspended loads at Playa Hermosa of 9-140 g/m^3, and a maximum of 170,000 g/m^3 (after the 22-04-1991 earthquake). RT does not show a large range in suspended load. The suspended loads of RChA, measured after 22-04-91 might be called sediment loads instead, because the river carried not only fine sediment in suspension, but also large quantities of sand. The same is true for the suspended load of RTA, measured after the 11/12-08-91 flood.

Figs 3.1a-b show that both RTA-RT, and RChA-RM have a high profile concavity. Both rivers show a clear transition alluvial fan-alluvial plain. Stream channel gradients at the alluvial fan of RTA-RT are markedly higher than those of RChA-RM.

Discussion

Considering the approximately equal amounts of annual precipitation in both catchment areas (see section 2.2), the difference in water discharge of RTA-RT and RChA-RM, especially maximum discharges, may largely be explained by the different size of both catchment areas. Although maximum water discharges of RTA-RT are remarkably lower than of RChA-RM, the difference between mean monthly and maximum discharge in both rivers is of the same magnitude, and so is the effect of floods.

The extreme increase of suspended load (and probably bed load) of RChA after 22-04-1991 is completely due to the earthquake at that date. This earthquake caused many landslides in the RChA catchment; some slopes were slided down completely, leaving only bare parent rock (photo 3.1). About a week after the earthquake, the first rains of the rainy season started. With the discharge of the rain the loose soil material and the fallen trees could easily be transported. Moreover, the rain may have caused new landslides, especially on slopes where cracks had formed because of the earthquake. During intense rainfall such cracks may serve as sliding paths for new landslides. In addition already stripped slopes have a smaller water storage capacity, which causes increasing run off of the rainwater and consequently increasing erosion of the slopes. Eventually most of the landslide and run off material will end up in the rivers, causing an increase of sediment load.

Photo 3.1 Landslides in the Cordillera de Talamanca due to earthquakes and heavy rainfall; deposits of mud and debris at the RChA alluvial fan.

In appendix B it was tried to estimate the time it would take for ChMS to discharge all landslide and run off material from the catchment area, i.e. the duration of the increased sediment discharge of rivers in the ChMS. With the assumptions made, a duration of the increased sediment discharge of 6-12 years was calculated. This period may even be a minimum estimation, considering the, expected, low rate of recovery of vegetation on the slopes. Vahrson et al. confirmed this suggestion by stating that the invasion of the damaged areas by pioneer plants was and is a very slow process. In relative dry periods RChA-RM and their tributaries will probably become almost clear of sediment (normal situation). This actually happened already in October'91 in Río Barbilla; at that time RChA-RM was still full of sediment. At times of continuous rainfall in the Cordillera de Talamanca, when vegetation has not recovered yet, sediment discharge will rapidly increase, and rivers will be full of sediment again. The influence on sediment discharge by clearing slopes from forest in a catchment area, and reforestating them again after a period, has also been demonstrated by Burt et al. (1984).
The increased suspended/sediment load of RTA is also due to landslides in the catchment area. These landslides were caused by series of weak earthquakes near the cone of the Irazú during June and July 1991, and intense rainfall during and after this period.
Although RT received water from RTA during the 11/12-08-1991 flood, an increased suspended/sediment load of RT could not be noticed. This was probably because of the very short period during which RT received water, and the composition of the suspended load of RTA during the flood, which appeared to be dominantly of sand size. With a rapidly decreasing stream channel gradient this sand will become part of the bed load or become deposited.
Generally an increase of sediment load of RT may largely be subscribed to erosion of/along the river channel and along drainage channels of banana plantations. The edges of channels in plantations are most of the time free of vegetation, which makes them, during intense rainfall, very susceptible to erosion. During intense rainfall also loss of top soil occurs in banana plantations, but probably to a lesser extent than channel erosion.
Jiongxin (1991) found clear relations of river profile concavity with the suspended sediment concentration (=suspended load), and the change rate of water discharge downstream. According to this author, profile concavity is relatively low in rivers with a high suspended load, and is high in rivers where water discharge increases more rapidly downstream. The high profile concavity of both RChA-RM and RTA-RT may well be explained with these relations. The very humid climate in this region causes the rapid downstream increase of water discharge. And although the suspended load of RChA-RM was very high after the 22-04-91 earthquake, usually both this river and RTA-RT have low suspended loads resulting in high profile concavity. Moreover, it may be stated that during the Holocene these rivers never had high suspended loads, except for the occasional extreme sediment discharges related to earthquakes and/or volcanism. Remnants of higher floodplain levels, occurring in the upstream depositional parts of both rivers (not meaning the red hills; see also sections 3.4.2-3 and 3.5.2), are probably the results of these extreme events. Jiongxin also mentioned a relation of

Table 3.4 Flood record of Río Toro Amarillo, Tortuguero, Chirripó-Matina, Barbilla, and Zent; data compiled from Anonymous (19??), Bedoya B. (1984), Nuhn & Perez R. (1967), Vahrson et al. according to Gonzales V. (1910), La Nación, personal comments.

River	Date	Effects and remarks
RTA	23/27-12-1966	Over-bank flow
	1969	Inundations and course changed, most likely induced by mobilization of ashes accumulated by Irazú during its 1963-65 eruptions (Kesel, 1985), death of several persons and animals, and destruction of houses
	12-1970	Inundations and course changed, also induced by the mobilization of accumulated ashes
	16-12-1980	Inundations, six houses damaged
	29/30-01-1988	Inundations, course moves about 1500 m to the east (probably temporarily), two houses destroyed
	23-03-1988	Small inundations
	11/12-08-1991	Inundations, temporarily activation of abandoned courses, including former Tortuguero course, roads and bridges slightly damaged
RT	14-11-1962	Over-bank flow
	13/15-12-1980	Inundations
	27-10-1985	Inundations, Cariari isolated
	21-06-1985	Inundations, road Guápiles-Cariari closed
	29/30-01-1988	Inundations, marginal damage in Campo Dos and many other villages and settlements
RChA-M	12-12-1800	Matina area inundated, considerable losses due to excessive rainfalls, preceded by a major earthquake at 21-02-1798
	05-1822	Heavy earthquake caused liquefaction, destruction and series of inundations, normally during the month of november (see also next inundation)
	11-1828	Inundations, inhabitants left affected zone
	1861	Frequent inundations mentioned, not certain whether RChA and RM were inundated
	11-1928	Matina (village) inundated, water-level six feet above railway at railway-bridge, severely damaged railway
	12-1938	Matina (village) heavily inundated
	11-1939	Inundations
	06-12-1949	Estrada inundated, bridge destroyed
	23/27-12-66	Inundations
	10-01-1970	Matina (village) inundated
	10/11-04-1970	Estrada, Baltimore, Penshurst inundated, houses and agriculture affected
	18-11-1970	Over-bank flow

profile concavity with river channel patterns. Rivers with high profile concavity generally have no or only short wandering braided reaches after entering the plain. This is also true for RChA-RM and RTA-RT. Although both rivers have a number of channels at the alluvial fan, under normal conditions both rivers occupy only one of them. After a relatively short distance this, relatively straight, channel starts meandering, indicating the transition to the alluvial plain. Both rivers only become braided during high discharges, mostly for a rather short period depending on the duration of the high discharge. The high stream channel gradient on, especially the proximal part of, the RTA fan is probably the reason for the dominant presence of cobbles and boulders (diameter range 7.5-200 cm) there, besides relative small amounts of finer sediments. After the 11/12-08-91 flood the composition of the deposits was changed in favour of sands and pebbles. This confirms the suggestion of Kesel & Lowe (1987), that at the RTA alluvial fan most sediment is supplied during episodic, short-lived disastrous events separated by longer inactive periods in which weathering, reworking, and removal of finer sediments farther downfan are the dominating processes. At the proximal part of the RChA fan the recent deposits are dominantly sands and pebbles. Cobbles and boulders (diameter range 7.5-50 cm) do occur, but not in large quantities. Probably these cobbles and boulders are relicts of older deposits, because after the 11/12-08-1991 flood no (large) cobble/boulder deposits could be found. The different size of the deposits at the proximal part of the RChA and RTA fan may also be explained by the different source rock of the sediments of both rivers, and by the different distances over which these sediments are transported before they reach the alluvial fan (RChA longer than RTA), what obviously enlarges breakdown of sediment (see also sections 3.4.2 and 3.5.2).

3.3.2 *Floods*

Results

Table 3.4 shows the flood record of RTA, RT, RChA-RM, RB and RZ. This record is far from complete, because only since recent times floods and other disasters are continuously being registered. Before, registration happened only incidentally. In the discussion is emphasized on the 11/12-08-1991 floods of RTA and RChA-RM.

Discussion

From table 3.4 it may be stressed that flood hazard is biggest in November and December. This is not strange, because the highest precipitation values occur during these months (fig 2.3 and app A). However, because floods may occur in every month of the year, and the impact of a flood is not only related to high water discharges, but also to high sediment discharges, the flood hazard is not only

Table 3.4 continued:

	04-12-1970	Over-bank flow
	11/13-12-1970	Matina (village) inundated, RChA shifted more into RZ
	10-01-1971	Over-bank flow
	04-12-1980	Inundations, houses affected
	13/15-12-1980	Inundations, RChA caused death of two persons, and damages in agriculture and on motorway
	27-07-1982	Inundations, motor- and railway affected
	28-07-1982	Inundations in RChA sector, fincas 5, 3 and 8 affected
	04-11-1984	Inundations
	04-12-1987	Matina (village) inundated, severe damages
	23-12-1987	Inundations
	29/30-01-1988	Matina, Zent Viejo, Estrada, Corina inundated
	23-03-1988	Inundations
	10/11-05-1991	Inundations near Matina, transportation and deposition of many mud and debris (trees), increase of sediment discharge caused and/or triggered by 22-04-1991 earthquake
	12/13-08-1991	Matina, Estrada, Corina, Bristol, 23 Millas, 24 Millas, Quatro Millas inundated, deposition of vast amounts of mud and debris (due to the 22-04-1991 earthquake), agriculture (mainly bananas) affected
RB	10/11-04-1970	Sta.Marta, La Luisa, B Line inundated, bridge destroyed, houses affected
	14-12-1980	Inundations
	28-07-1982	Inundation, fincas 5, 3 and 8 affected
	29/30-01-1988	Inundations, during the 80-s banana companies have started dredging, to decrease the risk of flooding
	12/13-08-1991	23 Millas, 24 Millas, Placeres inundated, deposition of mud and debris
RZ	11-1928	Zent (village) inundated
	10-1952	Zent (village) inundated
	06-11-1962	Over-bank flow, Estrada and Matina affected
	23/27-12-1966	Inundations
	25-11-1969	Inundations, railway affected
	11-12-1970	Over-bank flow
	19-12-1970	Zent Viejo inundated
	12/13-08-1991	Inundations before confluence with RChA, inundated, deposition of mud and debris

correlated to seasonal high precipitation values, but also to incidental earthquakes and/or volcanic eruptions. This means that flood hazard and impact of floods, are quite unpredictable.
From table 3.4 it may be stated that two types of floods exist: the ones reflected by over-bank flows and inundations with relatively few sediment, and the ones reflected by shifting and/or changing of stream channel, producing major inundations with much sediment. The first type is probably completely caused by exceptional amounts of precipitation, whereas the second type by high precipitation and (enormously) increased discharges of mud and debris, resulting from previously occurred earthquakes, landslides and/or volcanic eruptions. The first type occurs more often and causes generally less damage than the second type, although this may be questioned because the flood record is far from complete and more rivers, such as Estrella, Sixaola and Reventazón should be included. Vahrson et al. (in press) mentioned also two types of floods in their report about hydrological changes and floods after the 22-04-1991 earthquake in Limón. They mentioned floodings related to extreme peak flows with long return periods (>50 years), and floodings related to peak flows with relative short return periods (<10 years) in combination with highly damaged catchment areas caused by earthquakes. So the first type of flooding is the result of extreme precipitation without (highly) increased sediment discharges, the second type is the result of high precipitation together with enormous increased discharges of sediment and debris. According to the definition of Vahrson et al. the RTA flood belongs to the first type and the RChA-RM flood to the second type.
To use the expression long/short return periods may be tricky, because no long-term flood records of most observation stations exist, nor do long-term precipitation records. This can be explained with the 11/12-08-1991 flood of RTA, which should have a long return period. However, a similar kind of flood occurred in 1988, and probably also in 1980. And although no data are available, it may be assumed that floods like the August'91 flood, also regularly occurred before the 1963-1965 outburst of Irazú, which caused the second type floods of 1966, 1969 and 1970. From this it may be assumed that floods with peak flows with long return periods more often occur than is expected by Vahrson et al..

In the following part more information is given about the august'91 floods of RTA and RChA-RM. An estimation of the duration of the increased sediment discharge of RChA-RM (see also section 3.3.1), and newspaper articles about the August'91 floods, can be found in appendix B.

August'91 RTA flood

In the night of 11/12-08 this river reached a maximum width of 100-150 m, downstream of the bridge of the Carretera Braulio Carillo (normally 15-20 m at that point), and a rise of water level of 1-4 m. The highest flood stage probably lasted for about two hours (personal comment). During this short period the active part (see section 3.4.2) of the alluvial fan was reworked completely (photos 3.2a-b).

Photo 3.2 RTA alluvial fan before (a) and after (b) 12-08-91 flood.

Boulders with diameters up to 2 m were transported and sometimes piled up, together with trees. A number of presently inactive branches became occupied during that period: Brazo Río Toro Amarillo, Quebrada Gavilán, Quebrada Las Flores, Río La Suerte, Río Tortuguero (photo 3.3), and possibly also Río San Rafael. This caused inundations in areas downstream, especially in the Ticabán area, where roads and bridges were slightly damaged. No persons were drowned, or killed in other ways. Several farmers lost cattle. Sediment discharge also increased during the flood (see section 3.3.1), and large amounts of especially coarse sands were deposited. The increase of sediment discharge lasted for a few days, a period in which the water discharge had already reached normal values again (in little more than a day). Total precipitation on the 11-12th of August measured in Carillo was 316 mm (244+72), whereas in the lower situated Guápiles precipitation was "only" 95 mm, although it is unknown (by the undersigned) whether this is the total for the 11-12th or just the 11th (see fig 2.2 for weather station locations).

August'91 RChA-RM flood

This flood affected a vast part of the alluvial fan and the alluvial plain (app B). At the point where RChA enters the floodplain (near the old rail-way bridge), the highest flood stage lasted for about 2-4 hours (personal comment), with a maximum rise of water level of 2-3 m. During the flood a great number of presently inactive channels were temporarily activated. Damage was probably severest at the west side of the proximal part of the alluvial fan, where the flood entered the floodplain and had its largest power. Especially the activation of Quebrada Agua Fría, an old stream channel of RChA, caused much damage near Corina (photo 3.4). At the, somewhat more elevated, east side of the fan no inundations occurred. In the alluvial plain virtually all area along RM was inundated, and this lasted for about two days. The inundations nearly always started at the point where the bending of meanders begins. At such a point the river flowed straight through, over the concave bank, causing there the largest sediment deposits and damage. Because of the very high suspended load, the river could deposit much sediment, with thicknesses varying from 30-100 cm at sites near the river, to 10-20 cm in a broad area 100-200 m away from the river. Particle sizes varied from medium/fine sand near the river to loamy very fine sand further away. Besides some pebble and coarse sand deposits at the proximal part, also at the alluvial fan the deposits mainly consisted of medium/fine sand and silt. Persons drowned were not reported. Over a hundred persons had to leave there homes and/or were isolated. Some persons lost there houses and cattle. A lot of damage was done to banana plantations. This was largely caused by trees, transported by the river all the way from the damaged catchment area, and by the thick sediment deposits in the drainage channels, which had to be cleaned. Although no precipitation amounts of the 11-12th of August are available for the catchment area of RChA-RM, the distribution is considered to be the same as in the RTA-RT and other catchment areas, but the

Photo 3.3 Temporarily reconnection of RTA with RT caused damage to roads and bridges.

Photo 3.4 Temporarily reactivation of Quebrada Agua Fría caused much damage to roads and plantations; before the 12-08-91 flood a banana plantation was present at this location.

total amount will be a little less (also according to Vahrson et al.). Total precipitation on the 10-11[th] and 12[th] of August in 28 Millas, situated in the alluvial plain, was 156 mm (73.3+82.5).

3.4 The Toro Amarillo-Tortuguero system (TTS)

3.4.1 *Introduction*

Studying airphotos of 1952 and 1981, as well as topographic and geologic maps made it possible to interpret the geomorphology of the Toro Amarillo-Tortuguero system and to divide the study area in four sectors: alluvial fan (TT*af*), inactive alluvial plain (TT*ip*), active alluvial plain (TT*ap*), and coastal plain (TT*cp*). The division of the alluvial plain was done in order to make a distinction between the area where RT may inundate large areas and deposit fresh sediment during high water discharges (TT*ap*), and the area where inundations of RT are restricted to a narrow low-lying floodplain along RT (TT*ip*). The major, high-lying, part of TT*ip* does not receive fresh RT sediment anymore. Generally such parts would be called river terraces. In this report they are called inactive floodplains, because in time they might become activated again (if for example RT would become reconnected with RTA, due to a disastrous event).

Because Kesel and Lowe (1987) already studied geomorphological and sedimentological aspects of the RTA alluvial fan, this fan is described only briefly. Also the coastal plain is described briefly, because the undersigned did not have the opportunity to visit that area. Information about this sector was derived from Battistini & Bergoeing (1984), who studied the geomorphology of the Caribbean coast of Costa Rica, Nieuwenhuyse & Kroonenberg (submitted), who studied the volcanic origin of Holocene beach ridges along the Atlantic coast of Costa Rica, and the Minesterio de Obras Públicas (1961), who did a preliminary study on the canalization of the Atlantic lagoons.

In sections 3.4.2 to 3.4.5 the geomorphology, as derived from the aerial photo interpretation and topographic maps, is described (see maps Ia-b). In sections 3.4.3.2 and 3.4.4.2 the cross sections RT1 and RT2 are presented and described (figs 3.2 and 3.3). The legend of the cross sections can be found before fig 3.2, and can be unfolded in order to study it together with the pictures.

3.4.2 *Alluvial fan* (TT*af*)

At the place where RTA leaves the Cordillera Central (near the bridge of the Carretera Braulio Carillo), a fault parallel to the mountain front occurs. Upstream of this intersection point the river is incised in adjacent older fan surfaces. Downstream of this intersection point the present RTA fan begins. The present alluvial fan may be divided in an active and an inactive part (after Kesel & Lowe). The active part is made up by RTA and a number of inactive channels which only become active during extreme floods (see section 3.3.2). During high water discharges RTA has a combined braided and anabranching character. At low discharges RTA is confined to a single channel, except for a small part near sample location 1 (fig 2.2), where RTA shows a more braided pattern. The gradient of the active RTA channel decreases from 27 m/km at the intersection point to 3 m/km at the transition alluvial fan-alluvial plain (at the confluence with Río Chirripó). The present active fan includes, besides active and inactive channels and braid complexes (term after Kesel & Lowe), also densely vegetated islands. They rise 1-4 m above the active channel and will seldomly be flooded. The inactive channels show a developing vegetation cover that may be removed during floods. Sediments in the active part are dominated by pebbles, cobbles and boulders; boulders with diameters up to 2 m occur. Sandy and finer sediments make up a minor part of the active fan. These sediments are generally moderately to well sorted. During floods overbank deposits may occur, mainly sand trapped by the vegetation on higher surfaces.

The inactive part of the alluvial fan on the east side of RTA is more elevated than the part on the west side; the west side is not described because it was not part of the study area. The inactive alluvial fan on the east side of RTA is drained in a radial pattern by a great number of small brooks. Some of them are only active during high precipitation. Features of intense fluvial, or possibly laharic, activity are quite abundant, meaning remnants of cobble/boulder deposits or old, aggraded, stream channels. Most of these channels are nowadays occupied by small brooks. Especially in the transition area of active-inactive alluvial fan, remnants of Pleistocene fluvial and/or laharic activity were found. They are in fact terrace remnants and are called "red hills". They occur as bodies of dissected terraces or as isolated hills, and can be up to 10 m high. Pieces of natural forest vegetation can still be seen along the active fan, and along the brooks at the inactive fan. The area between the brooks is dominated by grass lands/pastures.

Airphotos of 1952 showed clearly that RT formerly was a major branch of RTA. Nowadays RT also is a small, nearly straight, brook that runs in its old riverbed, that has been filled up nearly completely. At the distal part of the fan the ancient riverbed is clearly recognizable for the first time. Here at both sides the old riverbanks rise about one meter above the current river. The channel gradient of RT decreases from 28 m/km near its rise to 5 m/km at the transition TT*af*-TT*ip*. Suspended and bed load of RT at the distal part of the fan is still very low. At this point RT transports and resorts small amounts of the "old Tortuguero" deposits. The resorted deposits are medium to very coarse sands with many pebbles and cobbles.

3.4.3 *Inactive alluvial plain* (TT*ip*)

3.4.3.1 General

From the transition alluvial fan-inactive alluvial plain to the confluence with Río Guápiles, RT is a misfit river. This part can be characterized by parts where RT is jammed between the steep, 10-15 m high, riverbanks of the inactive floodplain 1, alternated by parts where RT runs between the 1-3 m high riverbanks of the, relatively broad, floodplain 2 (see also section 3.4.3.2). In the parts where RT is jammed, the river most of the time has a straight channel. In the other parts, the RT has a single phase meandering character with stable meanders. At some sites along RT, floodplain 2 may be separated in more than one level. However, the scale of the geomorphologic map (map Ia) made it impossible to make a further subdivision. The lower levels of floodplain 2 are still becoming inundated during high discharges. Floodplain 1 will not become inundated, at least not in the present-day situation (in which RT is not connected with RTA anymore). Especially in the area between RT and Río Guápiles, upstream from their confluence, a clearly denditric drainage pattern of small channels can be seen. Most of them are inactive. If they are situated in banana plantations, they are used as drainage channels and are not vegetated. Otherwise they are not used and generally will be vegetated (mainly grasses). During rainfall the vegetated channels will discharge clear rainwater, whereas the non-vegetated ones will also carry significant amounts of sediment (table 3.3).

In the upstream part of TT*ip*, also fragments of old, major channels can be traced. One fragment runs west-north of the village of Cariari. Another fragment was found on the other side of RT, in between the settlement of Sagrada Familia and RT. This fragment is not depicted on map Ia, because it has not been discovered on the airphotos, but by augering. It is not clear whether both fragments were formed by an ancient RT, or by neighbouring rivers.

Besides a small part near the settlement of Vegas de Tortuguero where RT is meandering, RT runs in a straight channel downstream from the confluence with Río Guápiles. After this confluence floodplain 2 does not occur anymore. In this part RT generally runs between the high banks of floodplain 1, or of dissected Pleistocene terrace remnants (red hills). On map Ia only the larger bodies of red hills were distinguished, because especially the isolated red hills could hardly be recognized on the airphotos. Moreover, they are to small to depict on the map.

The channel gradient of RT decreases from 6 m/km near cross section RT1, to 0.5 m/km near the transition TT*ip*-TT*ap*.

In the upstream part of TT*ip*, floodplain 1 is largely covered by banana plantations. The downstream part is largely covered by grass land and some isolated patches of forest (especially on the red hills, and along the rivers), although in the near future this situation will probably rapidly change with an increasing area covered by bananas.

3.4.3.2 Cross section RT1

Especially at the northwestern side of RT it seems that sand has been dug off, which would mean that some parts do not have the original topography anymore. It was tried to auger at spots where the topography has not been disrupted. Floodplain 2, as mentioned in section 3.4.3.1, has been further subdivided into the floodplains 2, 3 and 4. Lack of height measurements made it difficult to determine the exact number of floodplain levels and to match the levels on both sides of the river. That's why floodplain levels on the south-eastern side of RT were numbered with suffix *a*, and on the north-western side with addition of *b*.

Figs 3.2a-b show that in this part of the sector RT is a misfit river with on both sides remnants of older floodplains. Near this cross section more floodplain levels can be recognized. However, it was impossible to describe all levels in one cross section. The highest remnants, floodplains 1a and 1b, have within the upper 4 m three types of deposits, each type representing a different river regime. The deepest and oldest deposit is probably a riverbed deposit, consisting of moderately sorted, medium to coarse sands with pebble/cobble interlayers. The middle deposit shows a transition to a calmer environment. Loamy and sandy sediments alternate each other, indicating a natural levee deposit. The loamy sediments may also partly be the result of soil development. The upper deposit is probably a one-time-deposit (probably a sheetflood), which may occur after a disastrous event. This deposit consists of loamy, medium to coarse sands sometimes with pebbles. In this deposit a thick soil (>1 m) has developed. Floodplain 1b looks quite similar to floodplain 1a. However, floodplain 1a seems to be slightly higher. Moreover, near floodplain 1b seem to be other slightly higher parts.

Augerings in floodplain 2a (not part of the cross section) show two types of deposits. The lower deposits (1.70- ~2 m) are probably riverbed deposits consisting of moderately to well sorted, coarse sands with pebbles. The upper deposits (0-1.70 m) seem to be natural levee deposits: alternating (heavy) loamy and sandy sediments, with soil development in the first meter.

Floodplain 3a has at >1.20 m gravel sediments (probably pebbles), which may be interpretated as an old riverbed. Above lies a fining-upward deposit (ca 0.80-1.20 m): well sorted, medium sand that is gradually getting loamier, indicating a transition to a calmer environment. Some soil development in this layer is not excluded. In between the topsoil (ca 0-0.70 m) and the fining-upward deposit is a layer of coarse sand, probably indicating a flood deposit.

The surface of floodplain 2b/3b shows the signs of a calmer period: (cut-off) meanders, natural levees and point bars are the relicts of a meandering system. The sediments in the old riverbeds are moderately to well sorted, medium to coarse sands with pebbles. The sediments in the natural levees and point bars are alternating sandy and loamy. Within 2 m sediments change to coarse sands and pebbles, probably a transition to a more dynamic period. Soils in the old riverbeds are very shallow (< 0.10 m), while at the natural levees and the oldest point bar soils are well developed (up to 1 m).

Augering 20 is in a little alluvial fan of an erosion gully in floodplain 1b. This gully has filled up part

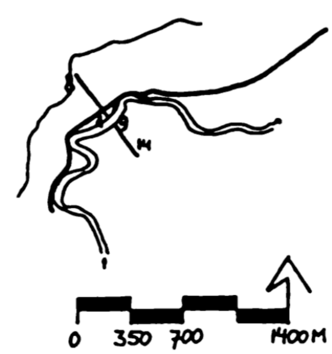
of an old riverbed. This happened probably after the riverbed had already been cut off from the major stream, considering the peat layer occurring underneath the deposits of the erosion gully.
Floodplain 4a and 4b are the youngest floodplains. The lower deposits are moderately to well sorted, coarse sands, sometimes with pebbles, probably indication riverbed deposits. In 4a and 4b still shallow, not active, channels are present with typical channel infillings: poorly sorted, thin layers of sand, loam and clay, on top of pebbles. The upper deposits are mostly loam layers or layers of slightly loamy to loamy, medium to coarse sand, sometimes alternated by well sorted, coarse sand layers.
Floodplain 4a and 4b show few soil development.

3.4.4 *Active alluvial plain* (TT*ap*)

3.4.4.1 General

In this sector the levees are gradually becoming lower: from 3-4 m above river level (normal discharge) at the transition TT*ip*-TT*ap*, to about 1 m above normal river level in the downstream part of TT*ap*. So floodplain 1 is gradually passing into the current active floodplain of RT, and the area along RT changes in a natural levee-backswamp landscape with some isolated red hills. Swampy grass lands with still many trees, and patches of forest are the dominant vegetation.
In the upper part of TT*ap*, RT is a two phase, bimodal meandering river with quite stable meanders. In this part cut-off meanders and former courses of RT (map Ib) were found. Downstream of the village of Ceibo a transition occurs to a single phase meandering river, also with stable meanders. Here RT is accompanied by a small, active, channel at about 0.5-1.5 km from the west bank. This might have been an old channel of RT. Near Ceibo also other small, almost completely vegetated, channels were found (not on the airphotos). Dominant vegetation in this area will be a swampy forest. Near the settlement of Zacatales crevasses were found (from the airphotos). Downstream of Zacatales until the Lomas de Sierpe, RT is gradually becoming less wide, and splits itself into a number of small channels, showing a more anastosoming pattern. This area is probably more or less one big river swamp. Old topographic maps and airphotos show that this area formerly began near Ceibo. From Lomas de Sierpe to the coastal plain, RT still has an anastosoming pattern, but is a little wider again. Here RT has to bend around the Lomas de Sierpe, remnants of basaltic Tertiary volcanoes, which form a natural barrier.
The channel gradient is decreasing to 0.3 m/km upstream from the confluence with Río Agua Fría, and increases slightly after this confluence until the transition TT*ap*-TT*cp* (1.8 m/km).

Fig 3.3 Cross section (a) and site description (b) of RT2.



3.4.4.2 Cross section RT2

This cross section is in a natural levee-backswamp landscape with coarse sediments close to the river passing into fine sediments with increasing distance from the river (fig 3.3a). Hardly any soil development in both backswamp and natural levee occurred so far, probably largely due to the poor drainage conditions. Coarse sediments at a depth of ca 1.5 m on both sides of the river, with a maximal extension of 100 m on either side, indicate old riverbeds. This implies that in an earlier stage the river bed may have been much wider than it is today (ca 25-30 m). The old, wider, riverbed has been filled up, and no signs are left in the present landscape (figs 3.3a-b). The fining-upward deposits in both levees suggest that the position of the present channel did not change much during infilling. This may confirm the idea of a meandering river with low activity. The accompanying channel (augering RT2.8 is in its levee) at the western side of RT, and channel relicts in RT2.6 and RT2.7, are suggestions that RT was (and perhaps still is) an anastosoming river. Augerings RT2.10 and RT2.11 have layers with signs of soil development, suggesting a (perhaps drier) period in which RT was calmer. Interpretation of such layers was often difficult. They may be the result of soil formation in a one-time-deposit, or of a gradual accumulation of thin layers of fine sediments on a vegetated surface causing the presence of small amounts of organic matter.

3.4.5 *Coastal plain* (TT*cp*)

In this sector the sea is the dominating factor for the geomorphology of the landscape. River influence will be very low, except after volcanic eruptions in the Cordillera Central when the increased sand supply may result in the formation of beach ridges (Nieuwenhuyse & Kroonenberg, submitted). In TT*cp* RT first runs through extensive coastal swamps, and is hardly traceable on the airphotos. Closer to the coast RT discharges into a lagoon, part of the Lagunas del Tortuguero. The lagoons are lying between old beach ridges, parallel to the coast. The mouth, near the village Tortuguero, forms besides of RT, the outlet of a number of rivers, which all first drain into the lagoons before they reach the sea. The location of this outlet has changed a number of times during the last century (fig 3.4 and map Ia). The channel gradient in this sector decreases to 0.2 m/km near the mouth.

3.4.6 *Discussion*

The major influences in the geomorphology of the study area in the Toro Amarillo-Tortuguero watershed seem to be relatively short lasting disastrous events (after Kesel & Lowe, 1987). Such disastrous events may occur during periods of volcanism. Besides eruptions of lava and ashes, volcanism accompanied by earthquakes and intense rainfall may produce lahars, (sheet)floods, and landslides. The huge boulders, present at the fan, are transported in lahars and (sheet)floods.

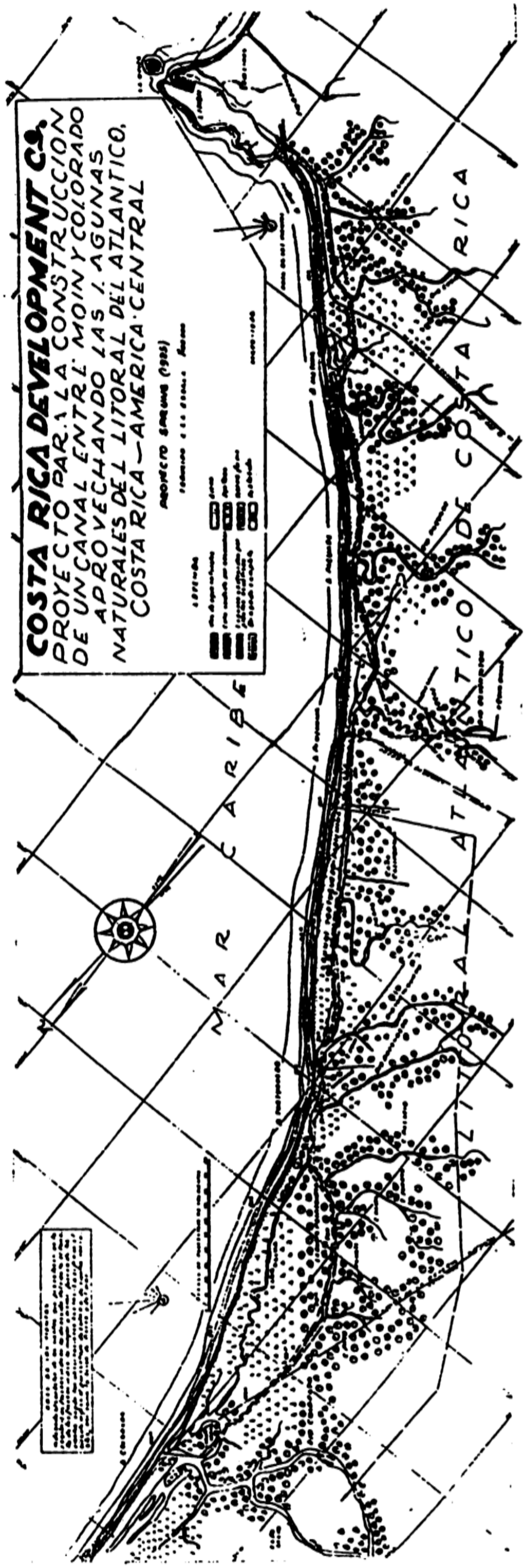


Fig 3.4 1925 Map of the north eastern part of the Caribbean coast of Costa Rica.

Perhaps also forest-fires occurred, in this way further increasing the hazard of landslides. All this will result in enormous sediment discharges and thick sediment deposits in large parts of the watershed. A large alluvial fan will develop. Due to the large sediment discharges, rivers at the fan may block their course, and will be forced to migrate or to shift to other channels. In this light the more elevated east side of the alluvial fan, and the several misfit rivers downstream of the transition TT*af*-TT*ip* (RT, Río San Ráfael, Río Guápiles, Queb Conga/Bejuco) suggest that RTA formerly completely discharged into RT and Río San Ráfael etc., and consequently during that period was not a tributary of Río Chirripó-Sucio.

At the transition with the alluvial plain a rapid decrease of channel gradient and sediment load occurs. Due to steepening of the river bed after heavy supplies of bed load, incision of the channel will occur in the upper part of the alluvial plain, shortly after the sediment discharges have reached normal values again (after Mangelsdorf et al. (1990) and Jiongxin (1991)). The incision will be made easier due to a decrease of resisting power against degradation of the stream channel, caused by the destruction of the stream bed armouring and the removal of vegetation along this channel. After a relative short period the area will be covered by vegetation again, and also the stream bed armouring will recover. Then incision will stop, the more because this region still is slowly subsiding. This process has repeated itself several times, resulting in the different floodplain levels along RT in the upstream part of the alluvial plain. Although the number of levels also will depend on the fact whether RT is connected to RTA or not. A similar process for the formation of a series of terraces along the Charwell river, New Zealand, is reported by Bull & Knuepfer (1987).

The small channels in floodplain 1 in the upper part of the alluvial plain, were probably all erosion gullies which formed in the freshly deposited sediment after a disastrous event. Due to a rapid recovery of vegetation, and formation of soils, the erosion gullies will only be discharging rainwater after a while, and thus will not further incise anymore.

The low sediment load of RTA and RT and the densely vegetated banks, during the calm periods in between the disastrous events, are probably major causes of the stable meanders of RT (after Chorley et al., 1984). It should be noted that during the calm periods also major floods may occur due to excessive precipitation. Generally such floods will probably not result in extreme sediment discharges and deposits, and major changes of stream channel.

Due to the very low sediment load and the poor drainage conditions in the coastal plain, RT nearly disappears in the big river swamps in the downstream part of the alluvial plain. This probably happens because at that point RT does not have enough sediment anymore to build up levees high enough to maintain a distinct stream channel.

The Pleistocene terrace remnants (red hills) have probably been formed in the same way as the present floodplains are being formed, with the distinction that the drop of sea level during the ice ages in the temperate zones, has lead to a deep incision of the old floodplains. This caused the formation of these terraces. With the ending of the ice age in the temperate zones, a gradual rise of sea level started, causing the infilling of the incised parts, which is still continuing nowadays.

3.5 <u>The Chirripó-Matina system (ChMS)</u>

3.5.1 *Introduction*

Airphotos and topographic maps show very clear that the area of interest in the Chirripó-Matina system may be divided into two sectors: alluvial fan (ChM*af*) and alluvial plain (ChM*ap*).
Unlike in the TTS, a subdivision of the alluvial plain was not necessary. And because RM does not disappear in a huge coastal swamp and the location of its river mouth probably is not dominated by sea influence, nor a coastal plain has been distinguished. Nevertheless, beach ridges and coastal swamps do occur in the neighbourhood of the study area.
In section 3.5.2 and 3.5.3.1 the geomorphology, as derived from the aerial photo interpretation and topographic maps, is described (see maps IIa-b). In section 3.5.3.2 cross section RM1 is presented and described (figs 3.5a-b).

3.5.2 *Alluvial fan* (ChM*af*)

Although the alluvial fan of RChA is clearly visible in the field, its form is different and less pronounced than the RTA fan. This is reflected by the smaller channel gradients, less large cobble/boulder deposits, and the agricultural use of the fan (especially on the east side), which does not differ much from the alluvial plain. Apart from these difference the RChA fan may be described in a similar way as the RTA fan was.
An intersection point occurs where RChA enters its alluvial fan. Before this intersection point RChA runs in a broad valley, incised in older fan deposits; it is uncertain whether these terraces consist of Quaternary or Tertiary (Suretka) deposits. Here at normal discharges RChA occupies only one straight channel. With high discharges several accompanying inactive channels may become active too. Nowadays the confluence with Río Zent is situated before the intersection point. Before 1970 the confluence was at the alluvial fan, which can clearly be seen on the 1963 topographic map. After several floods in 1970 the main channel of RChA shifted 600 m into the Zent valley (Vahrson et al., in press). Before the confluence RZ has already a clearly meandering channel. According to Vahrson et al. this is caused by a backwater effect generated by RChA, due to its higher bed load and

sedimentation rate at that point. The different channel patterns of RChA and RZ before their confluence is also reflected by their channel gradients: RChA ≈ 8.9 m/km and RZ ≈ 1.5 m/km.
The alluvial fan itself was divided in an active part and an inactive part. At the active fan RChA has a braided to anabranching character. During high discharges accompanying inactive channels may become active. In the active fan a number of, sometimes densely vegetated, islands are present. They are remnants of older deposits and may rise 1-4 m above the active channel. Most of them are made up of large coarse sand-pebble deposits on top of cobble-boulder deposits; the boulders mostly do not have diameters >50 cm. These deposits are probably of extremer floods than the 12-08-91 flood. During that last flood, besides pebble and coarse sand deposits in formerly inactive channels, mainly loamy fine to medium sands were deposited, even at the proximal part of the fan.
Nowadays the main channel is in the centre of the active fan. On the east side the inactive channels have a meandering character. The upstream parts of these channels have been formed by RZ. Whether the oxbow lakes near the village Zent have been made by RZ is uncertain. On the west side of the main channel, the inactive channels are nearly straight. Most of the active and inactive channels confluence in one major channel just before the bridge over RChA (near the village Line B). Here is the transition to the alluvial plain. The channel gradient of the main channel decreases from 6.7 m/km at the proximal part of the fan to 2.2 m/km at the transition ChM*af*-ChM*ap*.
The inactive part of the fan was subdivided in a part west and east of the active fan. The transition active-inactive fan on the east side is marked by height differences of 2-3 m higher, whereas on the west side no distinct height differences were found. The east side is probably completely covered by thick deposits of fine sediments with no pebbles, cobbles, or boulders close to the surface. This side is largely covered by banana plantations, even near the proximal part of the fan and on the banks along the transition active-inactive fan. Near the village Zent an old branch is visible, nowadays called Queb Boston, which formerly discharged directly to the east. A 1925 topographic map (fig 3.4) showed that this branch together with Río Cuba discharged in Río Moín, with an outlet near the village Moín. The results of a bulk geochemical analysis on a sand sample taken in the bed of this branch (app G), suggest that Queb Boston was a former branch of RChA, not of RZ.
On the inactive fan on the west side of the active fan, more inactive channels of RChA were found than on the east side (for example Quebrada Agua Fría). Most of these channels were activated during the 12-08-91 flood. At this side of the fan less banana plantations occur, possibly because of an, expected, bigger inundation hazard.

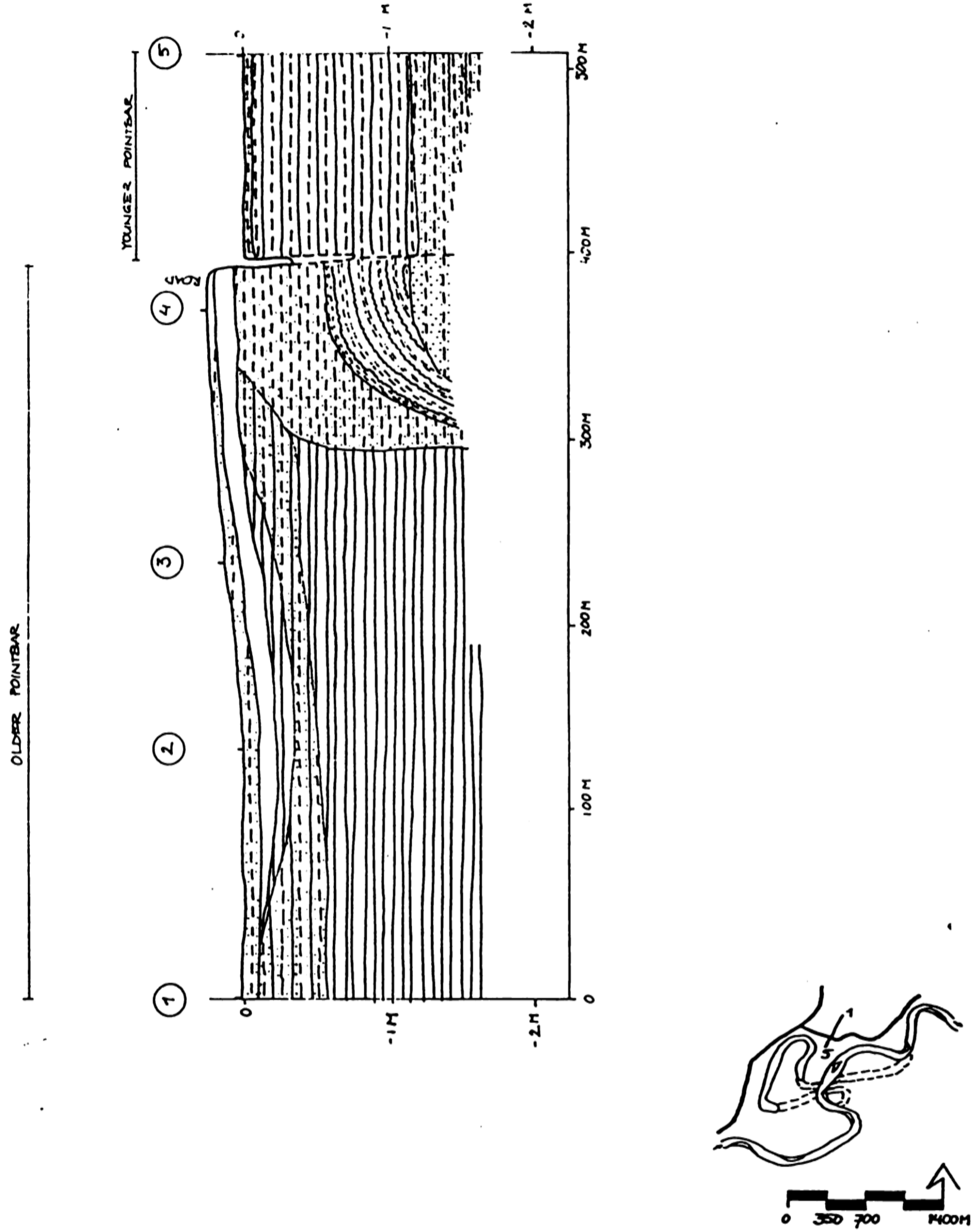


Fig 3.5 Cross section (a) and site description (b) of RM1.

3.5.3 *Alluvial plain* (ChMap)

3.5.3.1 General

From the transition point downstream, the alluvial plain rapidly changes into a natural levee-backswamp area. Here RM is a single phase meandering river with unstable meanders. Cut off meanders, oxbow lakes and parts of old courses were found on the airphotos and in the field. Especially the convex banks of the downstream meanders were made up of series of point bars. Near the confluence with Río Barbilla the levees rise 2-3 m above the river level. During times of inundation the largest deposits will occur at this point; after the 12-08-91 inundation deposits with thicknesses of up to 1 m were found here. Moreover, many former courses of both RM and RB were found near their confluence, indicating a high chance on channel migration at this point. Further downstream the height difference between the levees and the river level gradually becomes less (<1 m). Deposits in the alluvial plain generally range from fine/medium sands near the river to very fine sediments with increasing distance from the river. The channel gradient of RM decreases from 0.9 m/km near the confluence with RB to 0.4 m/km near the mouth.

When comparing the different topographic maps and airphotos, some points along RM seemed to have stayed quite stable compared to other parts: for example where Matina village is situated, or the large and broad meander in the middle-downstream part of RM. It is possible that RM cannot freely develop along these points because of occurrence of stagnant bodies in the subsurface (for example remnants of small volcanoes).

The area east of RM is largely covered by bananas. Some of the plantations are protected against inundations by dikes. In most cases these dikes did not prove to be a big success, considering the deposits found after the 12-08-91 inundation. In the area west of RM not so much large banana plantations are present, perhaps partly caused by worse drainage conditions. At this side more natural-like vegetation (swamp, forest) is left, than on the east side.

3.5.3.2 Cross section RM1

At present the location of this cross section is at a concave bank of a RM meander. However, until some years after 1952 when a cut off took place, it has been the convex bank of another meander (fig 3.5b). Apart from the recent mud deposits (12-08-91), the state of soil development (5-30 cm) indicates that not much sedimentation took place after the cut-off (fig 3.5a). So the augerings at this location can best be explained by the old - convex bank - situation, when point bars were actively formed. Augerings RM1.1 to RM1.4 show a laterally coarsening of the sediments in the upper meter in the direction of RM1.4. RM1.5 consists mainly of fine sediments. This implies a shift of the river channel in southeastern direction, with RM1.1 to RM1.4 at an older point bar, and RM1.5 at a younger one. The road (formerly an old rail-way) near RM1.4 appears to confirm the suggestion of an old point bar system. People living in wet areas will always search for the highest (and driest) locations to build their houses and (rail-)roads on. Such places are often the higher elevated levees along abandoned channels.

Most of the layers are slightly calcareous, except the topsoil layers which are non calcareous. The sandy deposits of RM1.4, probably crevasse deposits, as well as the 12-08-91 deposit, are calcareous.

3.5.4 *Discussion*

The geomorphology of the study area in the Chirripó-Matina system is also a result of relative short lasting disastrous events. In the ChMS watershed a disastrous event will be triggered by heavy earthquakes together with intense rainfall, causing liquefaction and major landslides in the catchment area. This will result in an enormous increase in sediment discharge of the rivers, causing migration of stream channels or shifting to other stream channels, cut off meanders, and large sediment deposits in the downstream area. In the years after the earthquake repeated floods with much sediment may occur after periods of high rainfall, due to the slow recovery of vegetation in the catchment area. During the generally long lasting calmer periods, floods may occur too. These floods are primarily caused by excessive rainfall. They will produce major inundations, but they generally will not trigger major channel migrations because the sediment discharge will not increase very much during such events.

The shape of the alluvial fan of RChA is markedly different from the RTA fan. One reason for the difference will be the confluence of RChA with Río Zent, causing a backwater effect in the RZ valley (Vahrson et al., in press). This backwater effect resulting from the smaller sediment load and sedimentation rate of RZ, causes a rapid decrease of channel gradient of RZ, and consequently a rapid deposition of its sediment and formation of a meandering channel pattern. This effect has probably produced the meandering form of the channels and the deposition of largely fine sediments on the east side of the alluvial fan.

Another reason for the different shapes of the RChA and RTA fan, may be the different grain size of the load carried by these rivers. According to Skinner & Porter (1987) a small stream carrying a load of coarse particles (RTA) builds a shorter, steeper fan than a larger stream carrying a load of finer particles (RChA). That the RChA fan is less steep may also be due to less frequent occurring disastrous events in this watershed, or to a higher subsiding rate of this part of the Atlantic Zone compared to the part where the RTA fan is situated.

4 MINERALOGY AND GEOCHEMISTRY

4.1 Introduction

Except for publications of Johnsson (1990) and Davies et al. (1978), little is known about mineralogy and bulk geochemical composition of river sediments in Central America, and more specifically the Atlantic Zone of Costa Rica.
In this chapter the mineralogical and geochemical composition of sediments of the Toro Amarillo-Tortuguero and the Chirripó-Matina system is studied. Key-minerals and/or key-elements, characteristic for individual rivers or river systems, can be identified by linking bulk geochemical data to mineralogical data. Studying the geochemical variation between the sediments can give information about source area characteristics, or about differentiation during sedimentary transport (Kroonenberg, 1990). To achieve a wider perspective concerning geochemistry of recent river sediments in the Atlantic Zone, samples from sediments were taken of Río Reventazón and Río Sucio too.
Finally it was tried to link the geochemical and mineralogical data to soil development and fertility along Río Tortuguero and Río Matina.

4.2 Material and methods

Geochemical and mineralogical data of river sediments were obtained by sampling different grain sizes at a single spot at a number of sites alongstream, thus covering for the effect of sorting (Kroonenberg, 1990). All sample sites consisted of fresh and undisturbed sediments and nearly all samples were taken by hand, else by knife or trowel. Due to floods after the 22-04-1991 earthquake it was difficult to find well sorted sand deposits of RChA, RM, RZ, and RB, because nearly all sands were covered with thick layers of mud and debris. Samples to determine clay mineralogy were taken with a jerry-can at places with high stream velocities. The samples were held moist in order to prevent changing of 10 Å halloysite into kaolinite or 7 Å halloysite. Clast-counts were carried out at undisturbed pebble/cobble beds at both the RTA and RChA alluvial fan. Randomly selected clasts were classified, and checked for presence of calcite by adding a few drops 2 N HCl. Soil samples were taken with an Edelman auger at two sites alongstream. Bulk samples of each 20 cm of soil, up to 120 cm, were taken to determine physical and chemical

Table 4.1 Explanation of classification of groupings, their abbreviations, and diagnostic criteria and examples referring to this study; modified after Johnsson (1990).

Abbr.	Groupings	Diagnostic criteria and examples
M	Monomineralic grains	> 95% of grain made up of a single mineral species
Qt	total Quartz	monocrystalline and polycrystalline forms
Qm	monocrystalline Quartz	> 95% of grain made up of a single crystal
Qp	polycrystalline Quartz	no single crystal makes up > 95% of grain; in this study Qp could also be part of Alt
Ft	total Feldspar	monocrystalline and polycrystalline forms
Fk	potassium Feldspar	includes microperthite
Fp	plagioclase Feldspar	includes albite
Acc	Accessory minerals	monocrystalline and polycrystalline forms; pyroxene (pyr), amphibole (Amph), Volcanic glass (Vg), Calcite (Calc), Clay body (Clay), Opaques (Opa), Mica, Epidote (Epi); Calc and Clay could also be part of Alt
L	Lithic fragments	no mineral species makes up > 95% of grain (polymineralic grains); genetic classification made largely on the basis of texture
Ls	sedimentary lithic fragm.	detrital textures, any birefringent micas clearly detrital; sandstones, conglomerates
Lp	plutonic Lithic fragments	coarse grain size, interlocking crystal texture; mainly granites
Lv	volcanic Lithic fragments	phenocrystic, microlitic, lathwork or glassy textures; mainly andesites
Lamb	ambiguous min. assemblage	unambiguous genetic classification cannot be made with confidence
Alt	Alterite	grain is altered beyond possible identification of precursor; in this study Alt refers to hydrothermally, and for a minor part to pedogenic, altered fragments

properties. Roots and litter were removed. To obtain a well mixed sample, each sample was sieved over a 2 mm sieve. After putting at least 300 g of each sample into plastic bags, these bags were sealed, to keep them at field moisture, in this way preventing textural and chemical changes. Field moisture was determined for use as a correction factor. The soils were classified according to FAO-Unesco (1988) and US Soil Survey Staff (Cornell University Agronomy Department, 1985). The sample sites are depicted on fig 2.2. Additional data on the individual samples can be found in appendix C.

Mineralogical and geochemical analyses

The bulk geochemical composition (major and selected trace elements) was determined by X-ray fluorescence spectrometry (XFRS). Air-dried samples were pounded in a tungsten-carbide mill. After having the powders oven dried (105 °C) and ignited (900 °C) in china cups, to determine the contents of crystalline water and organic material, glass disks were obtained by melting 0.6000 g of the pounded samples with 2.4000 g lithium tetraborate. These glass disks were analyzed on a Philips PW1404 XRFS assembly, using a scandium X-ray tube for the major elements and a rhodium X-ray tube for the trace elements. The sum of analytical results of each sample was lying between 98% and 102%. Statistical treatment of the geochemical data was carried out by principal component analysis (PCA) using the FACTOR software package, developed by A. Stein (Department of Soil Science and Geology). With PCA was attempted to identify clusters or associations within the data set. Application of PCA, results in a simplification of the complex data set by creation of new variables or principal components, each representing a cluster of interrelated variables within the data set (Moura & Kroonenberg, 1990). In this study principal component extraction is based on the correlation matrix of the 20-25 elements analyzed.

Mineralogical composition of sand deposits was determined by standard optical mineralogical study of thin sections. The distinguished categories were classified after Johnsson (1990) (table 4.1). Quantitative estimation of the mineralogical composition was carried out by counting 700-800 points, ignoring voids. According to Van der Plas & Tobi (1965) this number of points is sufficient to diminish errors caused by the point counts to acceptable values (1-3% at 95% confidence interval).

The mineralogy of the clay fraction was determined by X-ray diffraction (XRD). Oriented mounts were made by placing a porous plate in a suction apparatus and passing through a clay suspension. The samples were scanned in a Philips PW1050/PW1710 diffractometer with cobalt radiation, at 45 kV and 40 mA. To facilitate mineral identification samples were analyzed moist (to detect any 10 Å halloysite), air dried and magnesium saturated, glycolated, potassium saturated and oven dried (105 °C). Amorphous components, including allophane or imogolite, are not detected by this method. Relative abundance was estimated by peak height measurements. The clay fractions had to be separated rather inaccurate due to the rather small amounts of sample available. In this way also small amounts of fine silt were present in the suspensions.

Physical analyses

Texture of the sediments was determined after destruction of organic matter with H_2O_2 in the field moist samples, and dispersion using a mixture of sodium polymetaphosphate and NH_4. Clay (< 2 µm) and silt (2-53 µm) contents were measured with the hydrometer method (Gee & Bauder, 1986). After the measurements, the suspension with clay and silt was discarded, and the remaining sample was oven dried in order to weigh the sand fraction and to calculate the percentage of clay, silt and sand in the samples.

Particle-size distribution of the sand fraction (>0.053 mm) was determined by sieving (Gee & Bauder, 1986). Sand samples were oven dried (105 °C), weighed, and separated using nested sieves of 2 mm, 1 mm, 0.5 mm, 0.25 mm and 0.053 mm. The individual sand fractions were weighed and the percentage of each fraction calculated. The amounts of sample lost by sieving were all < 1.2%.

Chemical analyses

Soil pH was determined in field moist samples in a 1:2.5 (wt/wt) soil to water suspension after five minutes of intensive stirring.

Exchangeable bases were measured in the leachates obtained by leaching the field moist samples with 1 N ammonium acetate (NH_4OAc) at pH 7.0. Thomas (1982) stated that the results for Ca^{2+}, in soils containing free $CaCO_3$, may not be very accurate when using this method. However, this is also true when using other methods to determine Ca_{2+} in calcite containing soils.

Calcite was determined by the Modified Van Slyke Manometric Method (Nelson, 1982), a volumetric method. The volume of CO_2 that evolves from the reaction of inorganic carbonates with excess 4 N HCl, was measured at a definite temperature (20 °C) and atmospheric pressure. The weight of CO_2 is then calculated from its volume at standard temperature and pressure and is used to calculate the content of calcite equivalent. Before the calcite content of fresh rocks could be determined, they were first crushed to powder.

Phosphate retention was determined according to Blakemore et al. (1987) in air-dry samples.

Table 4.2 Petrographic composition of a pebble/cobble deposit (%) at the alluvial fan of Río Toro Amarillo (n = 252) and Río Chirripó Atlántico (n = 287), including the geology of their catchment area; n = number of clasts counted.

Petrographical composition	Río Toro Amarillo Total (%)	Río Toro Amarillo Geology (%)	Río Chirripó Atlántico Total (%)	Río Chirripó Atlántico Geology (%)
Volcanic rocks[a]				
Coarse-grained andesites	55.6		-	
Fine-grained andesites	35.3		-	
Basalt-like rocks	2.0		-	
Andesites, basalt-like rocks	-		16.4	
Sum	92.9	100	16.4	1
Hydrothermal rocks				
Completely altered	7.1		5.9	
Slightly altered volcanics	-		35.2	
Sl.alt.brec., conglomerates	-		10.1	
Sum	7.1	-	51.2	71
Plutonic rocks				
Granites, granite-like rocks	-		3.8	
Sum	-	-	3.8	6
Sedimentary rocks				
Sand/silt/clay/lime-stone	-		25.8	
Sum	-	-	25.8	22
Not determined	-		2.8	

[a] Andesites and basalt-like rocks were not subdivided for RChA.

4.3 Mineralogy

4.3.1 *Clast counts*

Results

The results of the clast counts are presented in table 4.2. The counting on the alluvial fan of RTA took place in an active branch (fig 2.2). A mixture of 252 pebbles and cobbles was identified. The clasts were divided in two major groups, both belonging to the magmatic rocks: volcanic rocks and volcanic rocks altered by hydrothermal action. The group of volcanic rocks could be divided in coarse- and fine grained andesites, and basalt-like rocks. The separation of the andesites in a fine- and coarse grained type depended on the size of the phenocrysts. Andesites with clearly visible phenocrysts (> 0.5 cm) were identified as coarse-grained, and andesites with hardly visible phenocrysts (<0.5 cm) as fine-grained. The phenocrysts in the andesites were mainly pyroxenes, plagioclases, hornblendes and olivines. The hydrothermally altered rocks contained sometimes pyrite and sulphur.

The counting on the alluvial fan of RChA took place in a recently active branch (fig 2.2). A total of 287 clasts was counted. Most of them were pebbles, some were cobbles. The clasts were classified in two major groups of different origin: sedimentary and magmatic rocks. The sedimentary rocks were all of marine origin (limestones, calcareous sand-, silt-, and claystones). The magmatic rocks were divided in plutonic rocks (granites, and granite-like rocks), unaltered volcanic rocks (andesites and basalt-like rocks), and hydrothermal rocks. The hydrothermal rocks were subdivided in slightly altered rocks, whose origin could still be recognized, and completely altered rocks. Also belonging to this group, but probably of fluvio-laharic origin, are conglomerates and breccias.

Discussion

Comparing the results of RTA with the geology of its catchment area, it is obvious that they represent the geology very well. The only missing rock type is dacitic rock, a light-coloured more acid volcanic rock. Dacites do occur however, but in such small amounts that they were not represented in the clast count. Although hydrothermal altered volcanic rock has not been depicted on the geologic map, it is not a big surprise to find this rock type, since hydrothermal processes often are associated with volcanic and plutonic activity. The same is true for the hydrothermal rock found in the RChA deposit.

The composition of rock types found in a gravel deposit of RChA at first sight does not seem to be a good representation of the geology of its catchment area. At the 1:200,000 geologic map of the area a distinction was made between Tertiary sedimentary volcanic rock and Tertiary-Quaternary volcanic rock. To separate both rock types in a RChA deposit is a rather ungrateful job to do, because they both are mainly of andesitic origin. In order to differentiate between them a distinction was made between slightly altered volcanic rock (presumably Tertiary sedimentary) and unaltered volcanic rock (presumably Tertiary-Quaternary). It is plausible that this distinction may have caused some errors in the clast count, because the amount of unaltered volcanic rock seems rather high (16.4%) compared to the amount expected according to the geology of the catchment area (1%). But summing all volcanic rocks, including slightly altered volcanic rocks, and breccias and conglomerates, the deposit turns out to be a quite good reflection of the geology of its catchment area after all (61.7% versus 72%). The sedimentary (25.8% vs 22%) and plutonic rocks (3.8% vs 6%) are good representations too. Especially for the sedimentary rocks this was surprising, because 30-40% of the area underlain by this rock type (fig 2.2) is made up of the Uscari formation, which consists of easily weatherable and erodible claystones (Sprechmann, 1984). Besides these claystones, probably also part of the volcanic rock is easily erodible. Altogether this resulted in a coincidental good representation of the geology of the catchment area, the more, considering the highly unreliable (=incomplete) geologic map of large parts of the Cordillera de Talamanca.

The distinction between unaltered and altered volcanic rock in the RChA deposit is furthermore of importance for the presumably different chemical composition of the two types of volcanic rock, the altered rocks being more weathered and having lost nearly all phenocrysts. Moreover, the cavities of a great number of these weathered phenocrysts were in a later stadium filled in with calcite, quartz and/or feldspar. Often this was caused by hydrothermal processes, giving rise to even bigger chemical differences.

The total amount of rocks containing some calcite in the RChA deposit is 56.8%. Beforehand this was not expected when looking at the amount of (marine) sedimentary rock in the catchment area (22%), and taking in account the prevailing very favourable conditions (humid tropics) for rapid chemical weathering of minerals, calcite in particular.

4.3.2 *Optical mineralogy*

Samples of the alluvial fan deposits of Río Toro Amarillo (3) and Río Chirripó Atlántico (3), were taken to obtain information about the mineralogical composition of the sediments and to be able to compare the results with the bulk geochemical composition (section 4.4.2). RTA-3 and RChM-1.5 are coarse, RTA-1 and RChM-1.2 are medium, and RTA-2 and RChM-1.3 are fine sands. In this paragraph the abbreviation RChM stands for Río Chirripó Atlántico.

Table 4.3 Mineralogical composition (vol %) of six different alluvial fan deposits of Río Toro Amarillo and Río Chirripó Atlántico, with MED = median of grain size, and n = number of points counted; see table 4.1 for meaning of abbreviations.

Sample	MED (μm)	n	Qp	Qm	Fk	Fp	Ls	Lp (vol %)	Lv	Lamb	Acc	Alt
RTA-1	357	732	2.6	0.3	0.0	13.1	0.0	0.0	57.2	0.7	12.8	13.3
RTA-2	221	753	0.4	0.0	0.0	10.4	0.0	0.0	60.2	0.1	10.2	18.7
RTA-3	926	795	1.9	0.4	0.1	6.2	0.0	0.0	60.6	0.0	6.0	24.8
RChM-1.2	378	724	0.0	0.1	0.4	4.0	1.1	1.4	9.0	0.0	10.4	73.6
RChM-1.3	150	772	0.0	1.2	2.5	6.1	0.4	0.9	3.8	0.0	20.1	65.2
RChM-1.5	543	726	0.1	0.0	0.4	2.2	2.3	2.3	16.8	0.0	6.7	69.0

Table 4.4 Composition of the group of accessory minerals (vol %) of the six samples of table 4.3; see table 4.1 for meaning of abbreviations.

Sample	Pyr	Amph	Vg	Calc	Clay	Opa (vol %)	Mica	Epi	Oliv	Sum =Acc
RTA-1	6.0	0.3	0.7	0.7	3.0	1.9	0.3	0.0	0.0	12.8
RTA-2	2.7	0.1	0.4	0.9	4.5	1.6	0.0	0.0	0.0	10.2
RTA-3	2.8	0.4	0.0	0.9	1.4	0.6	0.0	0.0	0.0	6.0
RChM-1.2	0.7	0.6	0.0	1.7	5.1	1.4	0.0	0.8	0.1	10.4
RChM-1.3	2.1	1.3	0.1	1.8	10.1	1.9	0.9	1.7	0.1	20.1
RChM-1.5	0.7	1.0	0.1	0.6	3.6	0.6	0.0	0.3	0.0	6.7

Results

The results of the point counts are presented in table 4.3. In all three samples of RTA the lithic fragments are exclusively composed of volcanic lithic fragments of andesitic origin. Their groundmass is dominated by fine grained materials (volcanic glass, plagioclase, etc.) with large phenocrysts of plagioclase, ortho-/clinopyroxene, opaques (probably magnetite/ilmenite), and pieces of volcanic glass. A small part of the rock fragments shows alteration. They consist mainly of hydrothermally formed chert, plagioclase and calcite, and 1:1, 2:1 and 2:1:1 clay pseudomorphs after primary minerals (also called clay bodies when occurring as monomineralic grains; more detailed information about the neo-formation of clay minerals by hydrothermal action can be found in Jongmans et al. (in prep.)). A minor part of the altered fragments are, probably pedogenic, goethite-pseudomorphs after primary minerals.

The monomineralic grains are dominated by plagioclase and accessory minerals. The quartz fraction (Qp+Qm) is low. The accessory minerals are (ortho-/clino-)pyroxene, clay bodies, opaques (probably magnetite/ilmenite), and traces of amphibole, volcanic glass, calcite and mica (table 4.4).

Besides some volcanic lithic fragments, the RChM-samples contain most of all altered fragments. Also small amounts of plutonic (granite) and sedimentary (sandstone, conglomerate) lithic fragments were observed. The volcanic fragments are mainly of andesitic origin with a fine, plagioclase-rich groundmass with phenocrysts (often strongly weathered) of plagioclase, alkali feldspar and (clino-)pyroxene. The altered fragments are mainly fragments of volcanic origin with hydrothermally formed calcite- and clay pseudomorphs (probably 2:1 clays) after primary minerals (phenocrysts), and fragments of chert and feldspars. A minor part of the altered fragments are, probably pedogenic, goethite-pseudomorphs after primary minerals.

Plagioclase is an important contributor to the monomineralic grains. In RChM-1.3 also a significant amount of alkali feldspar and monocrystalline quartz occurs. The largest part of the monomineralic grains, however, is made up by the accessory minerals. A substantial amount is contributed by clay bodies, especially in RChM-1.3. And besides (clino-)pyroxene, amphibole, calcite, opaques, and traces of mica and volcanic glass, also epidote and traces of olivine are present (table 4.4).

In the RChM-samples the fraction of the altered fragments that contained calcite, were counted. Together with the percentage of single calcite grains this resulted for RChM-1.2, RChM-1.3, and RChM-1.5 in a total of calcite containing grains of 7%, 4% and 7%. The total of calcite containing grains of the RTA samples is estimated to be less than 2%. However, this estimation is not based on exact counting.

Discussion

Sediments of both river systems contain mainly lithic fragments. This content tends to decrease in the finer sediments, due to progressive fragmentation of the lithic fragments into monomineralic grains, also confirmed by Davies and Vessell (1978).

The composition of lithic fragments and monomineralic grains of the RTA samples reflects the source-rock very good. This does not hold for the RChM samples, because they hardly contain any sedimentary and plutonic lithic fragments. Still, the diverse mineralogical composition of the sediment reflects a diverse composition of the source-rock in the catchment area.

The lack of sedimentary and plutonic lithic fragments was expected. The sedimentary source-rock consists largely of easily weatherable and erodible claystones, often also containing the easily weatherable calcite. The weathering products of such rock will not be found in sandy sediments, but in very fine sediments (section 4.3.3) or in the dissolved load (section 4.5). The smaller erosivity of plutonic rock compared to the other rock types in the catchment area may be an explanation for the under-representation of plutonic lithic fragments in the sediments. Part of the lack of sedimentary and plutonic rock can also be explained by the contents of monomineralic grains like quartz, alkali feldspars, amphiboles and mica, which are important constituents of granites and sandstones. Because the sedimentary rock largely consists of the weathering and erosion products of the Tertiary volcanic source-rock in the catchment area, the mineralogical composition of the sedimentary rock will be quite similar to the volcanic source-rock. That's why part of the sedimentary lithic fragments may not be recognized as such in the point counts, thus introducing counting errors.

The pyroxene amount of the RChM samples is considerably lower than that of the RTA samples, while the more basic volcanic source-rock of the RChM sediments would suggest the opposite. This difference may be explained by the higher age/degree of weathering of the source-rock of the RChM sediments, and the poly-cyclicity of part of these sediments, causing a further decrease of the easily weatherable pyroxenes. Studying the thin sections confirmed this suggestion, for the RTA lithic fragments and monomineralic grains were nearly all fresh to slightly weathered, while the RChM fragments and grains were nearly all at least slightly to moderately weathered.

The occurrence of clay bodies in the sand fraction in both RTA and RChM samples is probably caused by the fact that they act as sand grains when transported by rivers. They get rounded, but do not easily fall apart.

The abundance of clay bodies in the RChM samples may seem strange as nowadays no magmatic activity (with accompanying hydrothermal processes) is present in the ChMS catchment area. The abundance may be explained by plutonic and volcanic activity during the Tertiary, as well as volcanic activity during the Pleistocene (Weyl, 1980; Van Uffelen, 1991). However, these sources of hydrothermal processes can only explain a minor part of the abundance of the clay bodies (and in fact all altered fragments). A major part may be explained by Tertiary submarine volcanism (Kroonenberg, personal comment). From Weyl (1980) and others it is known that in the early Tertiary the Talamanca region was still a sea. Kroonenberg suggested that initial volcanism would be submarine and that the lava in contact with the salt water may have resulted in hydrothermal processes, which in turn may have produced the large amounts of hydrothermally altered volcanic rock.

When comparing the results of this study with the results of the study of Johnsson (1990) on river sediments in the Atlantic Zone, it appears that they agree very well. However, a good comparison with Johnsson's study cannot be made, because he studied samples of several sites alongstream, while in this study all samples were taken at one site. Moreover, the number of samples in this study is quite low, which makes it rather tricky to draw conclusions from them.
Johnsson states that the ratio more stable monomineralic components (quartz, feldspar) to unstable monomineralic components (pyroxene, amphibole, magnetite) increases as rivers cross the alluvial plains. It is strange, however, that Johnsson represents his division of mineral groups as stable:unstable, for calling magnetite unstable is doubtful. A better division might be low density:high density minerals (or:light/heavy minerals). When looking at the ratio (Qt+Ft):(Pyr+Amph+Opa), the RChM samples show an increasing ratio with decreasing grain size. RTA also has the highest ratio in the fine sediment (RTA-2). The lowest ratio, however, is not in the coarse sediment (RTA-3), but in the medium sediment (RTA-1).
From so few samples no conclusions should be drawn. However, the possible influences on the ratio light:heavy minerals can be discussed. A very important influence for both river systems will be the availability of the different minerals and their dominant grain size. Unfortunately no precise information about this subject is available. Other influences on the ratio will be chemical weathering and mixing with older sediments. Besides the regularly occurring landslides, these influences will hardly affect the mineralogical composition of RTA sediments, because they all are first-cycle sediments. RChM, however, contains at least partly second-cycle sediments. Together with landslides this may have a significant effect on the ratio light:heavy minerals. Mixing with other tributaries is probably another important influence on the ratio light:heavy minerals of RChM sediments. This effect will not be noticed in RTA sediments, because all tributaries have the same source-rock. According to Davies and Vessell (1978) a differential rate of rock fragment breakdown may also be of influence on the ratio light:heavy minerals in the sediments in the downstream part of both river systems. Riezebos (1979), in his study on compositional downstream variation of heavy residues in modern sand deposits, partly confirmed this suggestion. A differential rock fragment breakdown largely depends on the stream velocity of the streams in the upper reaches. Because neither these stream velocities are known, nor the critical stream velocities for the different rock fragments to be transported in the bed load or suspended load, nothing about the influence of the differential rate of rock breakdown can be said.

Table 4.5 Qualitative identification of clays in fine sediment samples of Río Tortuguero, Toro Amarillo, Chirripó Atlántico, and Matina.

Sample Nr	Description	Clay (%)	Clay types Kaol	Mica	Smec	Verm	Chlor
KM-5	Sedload of RT	nd	++	t	+++	-	-
KM-2	Fine deposit of RT	15	++	t	+++	t	t
KM-3	Sedload of RTA	nd	++	-	+++	-	-
KM-4	Sedload of RChA	nd	t	-	t	-	-
KM-1	Fine deposit of RM	5	t	-	+++	+++	-

Relative abundance is estimated by X-ray diffraction: +++ = much, ++ = considerable, + = some, t = trace and - = not detected; nd = not determined.

4.3.3 *XRD analyses*

Results

The results of the XRD-analyses are presented in table 4.5. The results of the TTS-samples (KM-2, KM-3 and KM-5) are nearly identical. The dominating clay minerals are smectite and kaolinite, with traces of mica, vermiculite and chlorite. Halloysite (10 Å) occurs in KM-2 and KM-5. Feldspar or cristobalite peaks (4.05 Å) occurred in all TTS-samples. A quartz peak was present in KM-2. Of the two ChMS-samples KM-4 hardly showed any peaks. In KM-1 the dominating clay minerals are smectite and vermiculite, with traces of kaolinite or 10 Å halloysite (not very clear). This sample showed a clear quartz peak too. Interstratifications could not be detected.

Discussion

In all samples the peaks were rather low and broad, which may be due to the poor crystallinity of the layer silicates, and to occurrence of significant amounts of short-range-order-materials. That KM-4 showed hardly any results, may also be due to occurrence of significant amounts of calcite. Inaccurate separation of the clay from the silt fraction, may have caused the feldspar and quartz peaks in some of the samples.

The presence of smectite and vermiculite in humid tropical, and volcanic regions is not unusual (Mizota & van Reeuwijk, 1989). However, the relative abundance of smectite and vermiculite is rather strange. Mizota & van Reeuwijk state that under humid and perhumid conditions and a neutral to mildly acid soil environment, volcanic ash mainly weathers to allophane and imogolite and in smaller amounts to ferrihydrite and more or less poorly cristalline layer silicates. More substantial amounts of layer silicates are formed under less humid conditions. Unfortunately, though, the allophane content was not determined. So a real statement about the abundance of smectite and vermiculite cannot be made.

In this region 2:1 clay minerals may occur due to transformation of primary minerals by weathering in sub soils at slopes in the middle reaches of the cordilleras, caused by the smaller dilution effect of the drain water in sub soils. The transformation of primary minerals may also occur in soils in the higher reaches of cordilleras (> 2500 m), where the climate is temperate and less humid. Other sources may be neo-formation of clay minerals by hydrothermal processes (Jongmans et al., in prep.), and eruptions of volcanic ash. Moreover, an important source of 2:1 clay minerals in the RChA-RM sediments is probably the Uscari formation, which according to Sprechmann (1984) largely consists of montmorillonitic clay minerals.

Heavy rainfall and light earthquakes will cause run off of the loose material, and will sometimes cause landslides. In this way, eventually all, 2:1 clay mineral containing material will be carried away by a river.

KM-1 is an affirmation that the 2:1 clay minerals were supplied by the river and not formed by in situ transformation of primary minerals by weathering in soils in the alluvial plain. KM-1 was taken in a backswamp. The soil was very wet and hardly any soil formation had occurred so far. Under the prevailing conditions the original sediments could not have undergone chemical weathering and neo-formation of secondary minerals.

Clay mineralogical data, provided by Kesel & Spicer (1985), from a recent age profile on the Río Cañas-Ceibo fan, draining the Pacific side of the Cordillera de Talamanca, do not fully agree with KM-1 and KM-4. They also found 1:1, 2:1 and 2:1:1 clay minerals, but not in similar ratios and not the same groups. Kaolinite (some), gibbsite (traces-some), chlorite (some), and illite (traces) were found. Presence of smectite, vermiculite and halloysite was not reported, although the latter probably was not searched for. In view of the similarity of the geology of both water sheds these results are quite remarkable.

When comparing clay mineralogical results of a study on a chronosequence of soils formed on lahars of the Turrialba volcano by Van Dooremolen (1990) with KM-2, KM-3, and KM-5, it appears that they differ in the occurrence of 2:1 clays. Besides some illite, he found merely traces of other 2:1 clay minerals, and those traces did not even occur in the youngest soils. A possible explanation of the different results is the excess of allophane and amorphous material compared to the 2:1 (and other) clay minerals. In this way the crystalline clay minerals are hardly traceable. Other possibilities are the different type of deposits or degree of sorting (laharic versus fluviatile), a possible dominant occurrence of smectite and vermiculite in the fine silt fraction (as clay bodies), compared to the clay fraction. On the other hand comparison of the results of Van Dooremolen and Kesel & Spicer with the results of this study may be rather questionable, looking at the small number of samples and the different geographic position of the sample sites.

4.4 Geochemistry

4.4.1 *Introduction*

In order to determine ranges of bulk chemical composition, and to carry out principal component analyses, only recently deposited sediments were used. The samples A-1/A-14/A-25, RT2-0.4/Rev-4, and RT2-5.4/RChM-1.6/RChM-XX/Z-1/Z-2 were skipped, because they were either suspended loads, placer deposits, or not recent sediments (app C). The contents of the major elements were determined in weight percentages of the oxides; loss on ignition (L.O.I.) was accounted for. The contents of the minor elements were determined in parts per million of the elements.

e 4.6 Bulk chemical composition of sediments from the Toro Amarillo-Tortuguero and the Chirripó-Matina system, and Río Reventazón, with n = number of samples, and M- = minimum, M = mean, and M+ = maximum value found for the corresponding element; SiO_2 to P_2O_5 in wt% of the oxides (L.O.I. accounted for), and Ba to Zr in ppm of the elements.

	RTA (n=4)			RTA (n=5)			RT (n=6)			RS (n=4)			RChApre (n=6)[a]			RChApost (n=5)[b]			RM (n=4)			RZ (n=3)			RB (n=3)			RR (n=3)		
	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+	M-	M	M+
$_2$	58.58	59.11	60.17	56.94	57.96	58.97	57.00	58.76	60.20	55.27	59.30	63.19	56.74	59.13	60.87	58.97	59.49	60.60	57.62	58.41	59.78	54.99	56.99	58.35	60.00	60.39	60.61	51.14	55.11	58.35
$_2$	1.21	1.31	1.41	1.07	1.18	1.28	1.16	1.33	1.71	1.20	1.26	1.42	0.98	1.19	1.47	0.98	1.09	1.21	0.98	1.06	1.13	0.71	0.92	1.11	1.13	1.23	1.42	1.08	1.48	2.22
)$_3$	16.50	17.88	19.76	16.32	17.46	19.03	15.35	17.81	21.34	16.32	17.97	21.47	15.19	16.20	18.04	15.89	17.11	18.44	16.55	17.04	17.57	13.12	14.09	14.88	14.36	15.14	15.56	14.05	15.97	19.22
O$_3$	7.44	8.21	8.90	7.30	7.71	8.24	7.29	8.20	10.47	6.82	8.43	10.50	8.65	9.71	11.13	8.25	9.20	9.78	9.03	9.46	9.90	8.67	9.21	9.61	8.89	9.20	9.76	8.14	11.08	15.75
)	0.05	0.10	0.12	0.10	0.11	0.12	0.09	0.12	0.15	0.08	0.12	0.19	0.14	0.19	0.35	0.12	0.17	0.26	0.15	0.17	0.24	0.12	0.12	0.13	0.21	0.21	0.22	0.12	0.16	0.17
)	2.56	3.40	3.95	3.04	3.91	4.57	2.40	3.44	4.59	2.55	3.31	4.05	3.22	4.17	4.87	3.48	3.81	4.27	3.65	4.54	4.92	5.61	7.06	9.12	3.87	3.89	3.93	2.87	4.36	5.60
)	3.18	5.20	6.20	5.86	6.48	7.13	4.01	5.25	5.75	3.93	4.70	5.69	3.11	5.47	6.61	4.14	5.02	5.76	5.21	5.63	5.87	6.86	8.48	10.54	5.60	5.80	6.03	6.25	8.04	10.05
O	1.76	2.47	2.86	2.84	2.93	3.03	2.14	2.69	3.06	2.15	2.53	2.78	1.62	2.52	3.02	2.04	2.65	3.08	1.50	2.28	2.59	1.69	1.73	1.82	2.48	2.58	2.77	2.04	2.16	2.33
)	1.77	1.93	2.10	1.78	1.91	2.03	1.63	2.04	2.49	1.74	2.02	2.45	1.04	1.21	1.45	1.12	1.25	1.40	1.15	1.20	1.35	0.90	1.18	1.38	1.32	1.34	1.37	1.21	1.36	1.63
)$_5$	0.34	0.38	0.44	0.32	0.34	0.38	0.31	0.35	0.45	0.31	0.36	0.48	0.19	0.21	0.25	0.19	0.21	0.25	0.17	0.20	0.24	0.15	0.21	0.26	0.21	0.21	0.22	0.26	0.28	0.31
	632	687	729	593	655	735	585	665	709	630	721	816	208	312	448	282	348	414	274	327	456	208	322	435	383	396	420	391	479	599
	69	73	78	69	84	101	70	91	130	52	68	79	34	112	205	51	75	104	57	102	130	342	378	400	100	115	141	57	126	202
	49	58	67	47	61	89	34	48	81	48	72	115	47	51	58	44	60	77	59	63	67	29	35	38	37	42	48	29	40	53
	15	16	17	15	15	16	15	17	19	16	17	18	11	14	15	13	14	15	12	14	15	10	11	12	11	12	12	12	14	15
	10	13	14	11	12	12	11	14	16	13	15	18	10	14	22	10	12	15	10	12	14	10	11	12	11	12	13	10	13	14
	16	30	39	31	35	40	29	35	44	21	26	31	12	21	28	12	17	21	20	26	32	45	54	70	22	26	29	24	37	45
	13	17	22	13	18	25	13	15	18	17	19	23	10	11	14	10	12	14	11	12	14	10	14	16	12	13	14	13	14	16
	34	44	52	36	42	47	38	49	65	35	51	64	10	16	23	18	21	25	14	19	22	13	17	23	12	17	22	11	22	29
	744	789	840	793	842	895	672	742	806	631	709	790	323	363	394	354	386	423	354	368	392	229	311	393	351	389	408	638	691	738
	178	192	202	159	175	198	164	196	288	172	185	197	157	194	263	160	174	199	158	172	192	132	157	179	174	196	236	159	268	4
	29	44	53	37	41	48	39	52	71	40	59	95	48	59	77	51	55	61	45	52	65	23	40	54	55	61	71	55	77	1
	201	212	219	197	207	218	207	226	243	199	227	255	102	124	189	92	108	120	92	105	137	62	91	116	121	123	126	127	155	170

efore confluence with RZ.
fter confluence with RZ.

Principal component analyses (PCA) with all elements were done on the complete data-set (TOT), and on the separated data-sets of the TTS and ChMS. In all analyses three principal components were considered. In order to see the relation of the chemical composition with grain size, also principal component analyses with all elements, including the median of the sand fraction (MED), were carried out. Finally, to get an indication of the relation between the chemical and the mineralogical composition, principal component analyses were carried out on samples of RTA (3) and RChA (3). In these analyses only elements showing high and/or many overall correlation coefficients in the correlation matrix were considered (Kroonenberg et al., 1987). So were all minerals/rock fragments that occurred in significant amounts. The results of the mineral determination were already presented in section 4.3.2. Also the relation of elements and minerals/rock fragments with grain size was evaluated. Considering the small number of samples (6), not too many conclusions may be derived from these final analyses, the more because the other rivers were not examined on mineralogy, and mineralogical results of other studies about these rivers were not available.
Samples with grain sizes ranging from very fine to coarse were not available for all rivers (RS, RZ, RB and RR). This should be kept in mind with the interpretation of the results.

4.4.2 *Bulk geochemical composition*

Results
Table 4.6 shows the ranges of the bulk chemical composition of sediments of individual rivers. The sediments have grain sizes varying from very fine to very coarse (app F). The bulk chemical compositions of all individual samples are shown in appendix G.
Looking for example at the Al_2O_3 content the total range is 13% to 21%. Although this is not a very wide range, the rivers draining the Cordillera Central show clear differing values of Al_2O_3 content compared to the rivers draining de Cordillera de Talamanca. Other differentiating elements between the river systems are Fe, K, P, Ba, Rb, Sr, and Zr. Especially Sr and Ba show a good separation of the river systems (fig 4.1). Element contents of RR lie as a rule between element contents of the ChMS, and TTS, including RS. Exceptions to the rule are the Ca, and to a lesser extent, the Fe content, for they both have highest values in RR sediments. The Ca content of RZ sediments is also high. Other differentiating elements for RZ are Ti, Mg, Cr, Ni, and V. RB can be distinguished from the other rivers in the Si content. RTA, RT and RS are hardly distinguishable from each other.
The ranges of the bulk chemical composition of the sediments of the individual rivers are somewhat smaller when skipping the element contents of the very fine sediments, but the mean values are staying nearly the same.

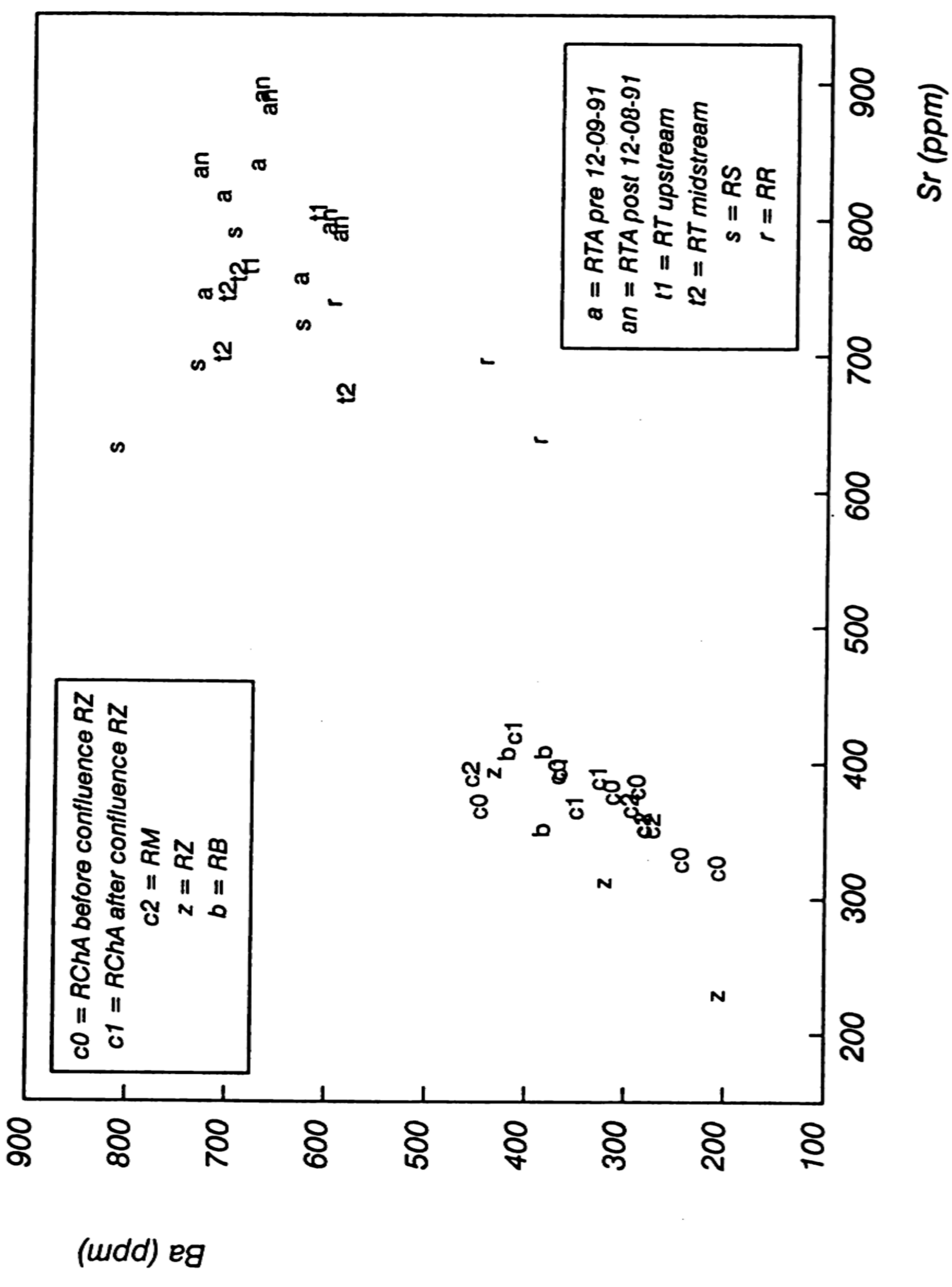


Fig 4.1 Sr and Ba contents (ppm) of all samples.

Discussion

Table 4.6 and fig 4.1 show already a clear distinction between the three river systems, with RR mostly in an intermediate position. This is obvious regarding the location of the catchment areas of TTS (Cordillera Central), ChMS (Cordillera de Talamanca), and RR (both Cordillera Central and Cordillera de Talamanca). The higher content of Al, K, Ba, Rb, Sr and Zr in the TTS, indicates a higher content of alkali feldspars and mica in these sediments (Kroonenberg et al., 1988). This was not expected, taking in account the age, i.e. the degree of weathering, of the parent rock of the TTS and ChMS catchment area, which is Quaternary vs. Tertiary or slight vs. moderate. Also the results of the mineral determination in section 4.3.2 suggest a higher content of alkali feldspars and mica in the ChMS sediments, although in both river systems the contents were very low. A possible explanation could be that the fine groundmass of the volcanic fragments of TTS contains slightly more alkali feldspars and mica than the volcanic fragments of the ChMS. So the volcanism of the Cordillera Central is probably more acid than the volcanism in the Cordillera de Talamanca was. This has been confirmed by Weyl (1980), who stated that magmatic activity in Costa Rica has been marked by a continuous rise in the SiO_2 content of the volcanic products and the development of alkaline rock types.

The high Mg and Ca content, and the very high Cr content in the RZ sediments may indicate a high content of pyroxenes and calcic plagioclase. Together with a relatively low K, Sr and Ba content, this implies that the RZ sediments are more basic than sediments supplied by RChA or RB.

RB can hardly be distinguished from RChA. This could be expected, because the RB catchment area, like the RChA watershed, for the greatest part is underlain by volcanic rocks. The same explanation is true for the similarity of the element contents of RTA, RT and RS.

4.4.3 *PCA with all elements*

Results

In table 4.7 the results of PCA with all elements are shown. This table shows the three principal components PC1, PC2 and PC3, with between brackets the percentage of the total variance accounted for by each principal component, and the principal component loadings of all elements after varimax rotation. All elements with rotated principal component loadings |<0.50| were skipped; this applies to the other tables with results of PCA too.

The three principal components of the total data set together explain 73.3% of the total variance. Principal component scores for PC1 and PC2 were calculated for all samples and plotted in fig 4.2. This picture shows nearly the same picture as fig 4.1. Three clusters become visible, viz. the a/an/t1/t2/s, r, and c0/c1/c2/z/b cluster. The c0/c1/c2/z/b cluster can again be separated in the

Table 4.7 Principal component loadings (after varimax rotation) of all analysed elements in PC1, PC2 and PC3, with between brackets the percentage of total variance explained by the particular principal component; PCA with all sampled rivers (TOT), Toro Amarillo-Tortuguero system (TTS), and Chirripó-Matina system (ChMS), with n = number of samples.

	TOT (n=43)			TTS (n=19)			ChMS (n=21)		
	PC1(40.1)	PC2(17.2)	PC3(16.0)	PC1(32.2)	PC2(23.5)	PC3(17.5)	PC1(44.8)	PC2(18.8)	PC3(14.8)
SiO_2		-0,56	0,74		0,67	0,71	0,92		
TiO_2			-0,93		-0,96			0,89	
Al_2O_3		-0,85		0,97			0,57		0,76
Fe_2O_3	0,89				-0,95			1,00	
MnO	0,67				-1,00		0,97		
MgO		0,94		-0,88			-0,90		-0,80
CaO		0,99		-0,73		-0,67	-0,79		-0,82
Na_2O	-1,00			-0,87					0,97
K_2O	-0,85					0,81	0,97		
P_2O_5	-0,68		-0,62	0,94			0,96		
Ba	-0,79			0,92			0,93		
Cr		0,95			-0,79		-0,56		-0,80
Cu		-0,96		0,96					1,00
Ga	-0,58	-0,64	-0,50	0,98					0,90
Nb		-0,99				0,98	0,96		
Ni		0,89		-0,86			-0,68		-0,73
Pb	-0,76		-0,52	0,99			0,70		-0,70
Rb	-0,86					0,79		-0,91	
Sr	-0,79		-0,58		0,55	-0,79	0,83		
V	0,53		-0,84		-0,95			0,98	
Zn	0,76		-0,55			0,80	0,81	0,54	
Zr	-0,89		-0,58			0,99	0,96		

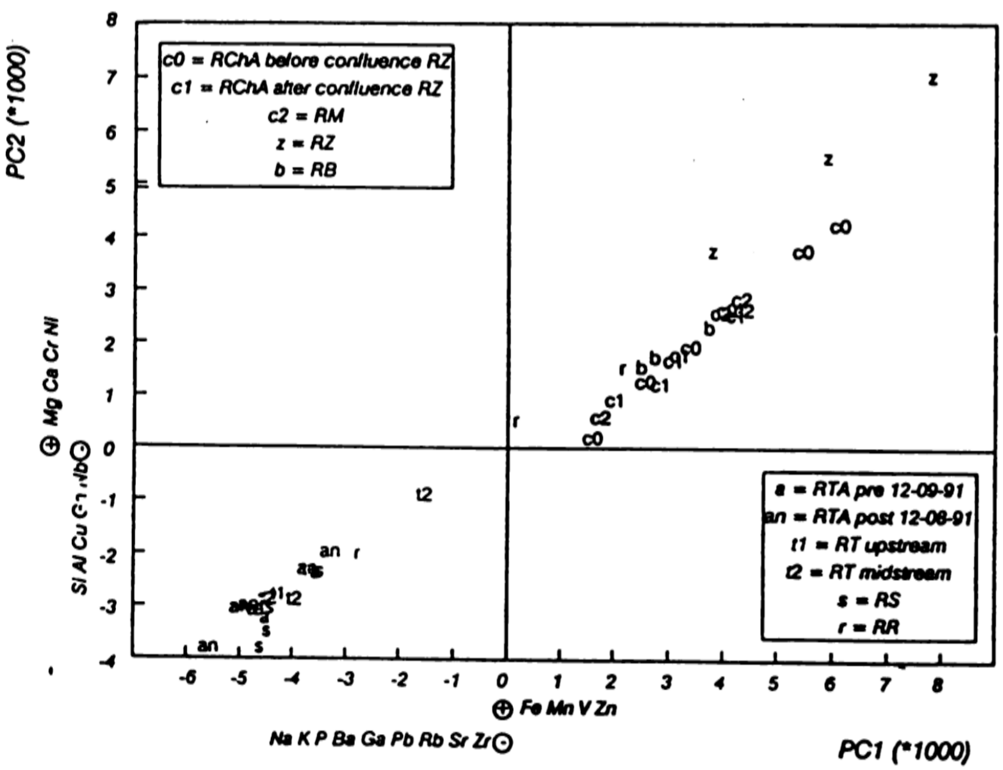


Fig 4.2 Principal component scores of all samples for PC1 and PC2.

c0/c1/c2/b and z cluster. A distinction between the individual rivers in the a/an/t1/t2/s cluster was not made yet.
The three principal components of the TTS data set explain 73.2% of the total variance. Principal component scores of the TTS data set can best be shown with PC2 and PC3. In total four clusters were separated, viz. a, an, t2 and s (fig 4.3); t1 was not separated. The clusters are mainly separated from each other in PC3. The t2 cluster has a large spread in PC2. The a and an clusters, RTA deposits before and after the 12-08-91 flood, together with the t1 scores form one big cluster of alluvial fan deposits. The t2 and s clusters form a big cluster of alluvial plain deposits.
The three principal components of the ChMS data set explain 78.4% of the total variance. Principal component scores of the ChMS data set can best be shown with PC1 and PC3 (fig 4.4). Again, as in fig 4.2 the z cluster is very obvious, having a large spread in PC1. In this picture also the b cluster can be distinguished. The c0/c1/c2 cluster, however, is very hard to separate, due to the large spread of the c0 cluster in both PC1 and PC3.

Discussion
With the application of PCA it was tried to obtain more information about sorting and weathering effects on the sediments, and to get a (better) differentiation between the rivers of each river system.
PC1 of the total data set has positive contributions of Fe, Mn, V and Zn, and negative contributions of Na, K, P, Ba, Ga, Pb, Rb, Sr and Zr. The first group suggests heavy minerals like Fe-opaques and Fe-oxides, the second group relatively stable minerals like mica, alkali feldspars and zircon (Kroonenberg et al., 1988; Moura & Kroonenberg, 1990). PC2 includes positive principal component loadings of Ca, Mg, Cr and Ni, reflecting basic minerals like olivine, pyroxene, epidote and Fe-opaques (Kroonenberg et al., 1988), and negative loadings of Si, Al, Cu, Ga and Nb, reflecting more stable minerals such as clay minerals. Because both PC1 and PC2 are largely volcanic principal components, fig 4.2 is reflecting the type of volcanism. The Cordillera de Talamanca had a more basic type, with the relative abundance of Ca, Mg, Cr, Fe, etc., the Cordillera Central has a more acid type of volcanism, with relative abundance of Na, K, etc.. The different element abundances of sediments of both river systems may not be subscribed to chemical weathering, considering the ratio (K+Na):(Ca+Mg) which does not change with chemical weathering.
The four clusters in fig 4.3 can best be explained by the variation in PC3. PC3 represents the effect of transportation time/distance or in fact the effect of weathering, with a relative abundance of Ca and Sr in alluvial fan sediments (an, a and t1), and of Si, K, Nb, Rb, Zn and Zr in alluvial plain sediments (t2, s). The first group of elements is probably reflecting easily weatherable

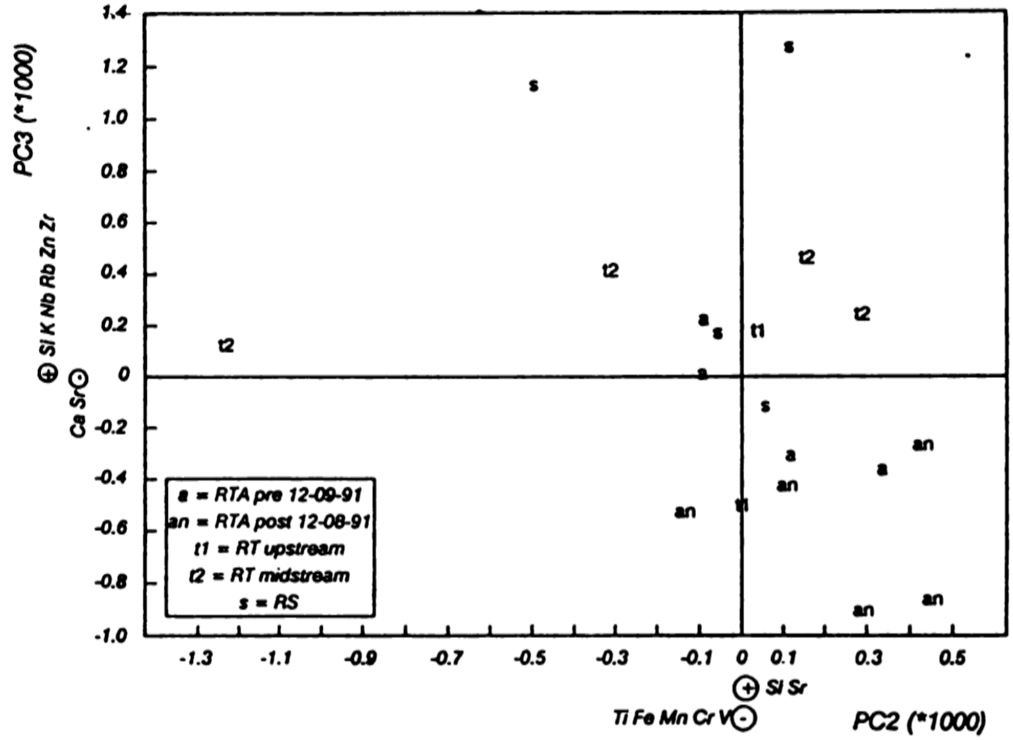


Fig 4.3 Principal component scores of the TTS samples (including Río Sucio) for PC2 and PC3.

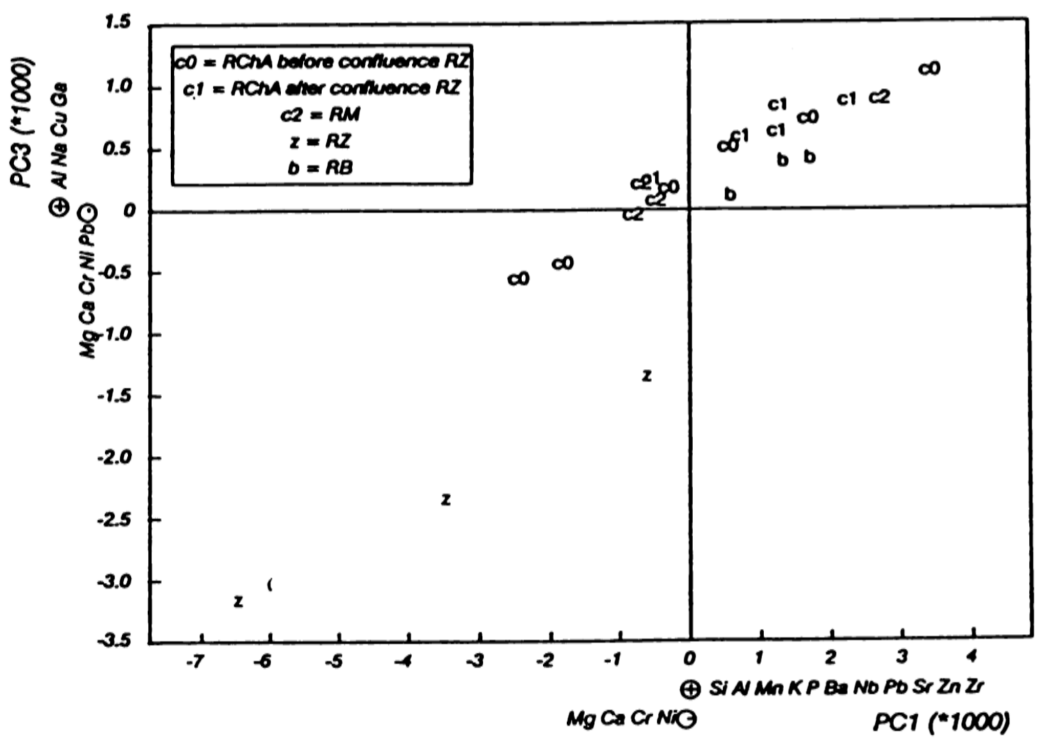


Fig 4.4 Principal component scores of the ChMS samples for PC1 and PC3.

minerals such as calcic feldspars. The second group of elements in PC3 is reflecting more stable minerals such as alkali feldspars and mica. The occurrence of Nb, Zn and Zr in the second group also suggests a relative abundance of stable, heavy minerals, like rutile and zircon (Moura & Kroonenberg, 1990). Because as well very fine as coarse sediments of t2 and s have high principal component scores, the relative abundance of Si, K, Nb, Rb, Zn and Zr might be a longitudinal sorting effect and/or mixing with older sediments. The different direction of the s and t2 clusters implies a different weathering and/or longitudinal sorting effect in both rivers. However, it may be expected that the different direction of both clusters is caused by the outermost score of t2. In this particular sample probably more heavy minerals were concentrated. To get a complete picture about the longitudinal sorting, samples should be taken more downstream, and near the mouth of RT and RS.

PC1 of the ChMS data set has positive loadings of Si, Al, Mn, K, P, Ba, Nb, Pb, Sr, Zn and Zr, reflecting stable minerals such as alkali feldspar, mica, zircon and clay minerals, and negative loadings of Mg, Ca, Cr and Ni, reflecting easily weatherable minerals such as olivine, pyroxene, epidote and Fe-opaques. PC3 is also divided in a part with positive loadings of elements mainly occurring in stable minerals, and an opposite part with elements mainly occurring in easily weatherable minerals. These principal components both are volcanic principal components, although a plutonic contribution in PC1 and a (calcareous) sedimentary contribution in both PC1 and PC3 may not be excluded. A pure plutonic principal component cannot be distinguished, probably due to the very small amounts of plutonic rock fragments transported by RChA (tables 4.2 and 4.3). Also a pure sedimentary principal component does not occur, because the sedimentary rock will largely be made up of the same volcanic rock that is still present in the Cordillera de Talamanca. The c0/c1/c2 cluster cannot be divided in three separate clusters, probably due to the short distances between the sample locations. So a longitudinal sorting effect as in the TTS, cannot be distinguished in the c0/c1/c2 cluster. From the discussion about the ratio light:heavy minerals (section 4.3.2) it may be expected that a longitudinal sorting effect will become visible in the downstream part of RChA-RM. However, the short distance from the apex of the alluvial fan to the coast (35 km), the part where net deposition takes place, may diminish the effect of longitudinal sorting. To be sure of this suggestion, samples should be taken near the mouth of RM.

4.4.4 *PCA with all elements and grain size*

Results

The results of PCA with all elements, including MED, are summarized in table 4.8. The new principal components were called PC1', PC2' and PC3'.

Table 4.8 Principal component loadings (after varimax rotation) of all elements including median of the sand fraction (MED) in PC1', PC2' and PC3', with between brackets the % of total variance explained by the particular principal component; PCA with all sampled rivers (TOT), Toro Amarillo-Tortuguero system (TTS), and Chirripó-Matina system (ChMS), with n = number of samples.

	TOT (n=43)			TTS (n=19)			ChMS (n=21)		
	PC1'(38.4)	PC2'(17.4)	PC3'(15.6)	PC1'(32.1)	PC2'(24.0)	PC3'(18.0)	PC1'(43.8)	PC2'(19.1)	PC3'(14.3)
SiO_2		-0,51	0,77		0,72	-0,66	0,95		
TiO_2			-0,95			0,97			-0,90
Al_2O_3		-0,94		0,97			0,64	0,71	
Fe_2O_3	0,85		-0,51			0,95			-0,99
MnO	0,90					1,00	0,96		
MgO		0,96		-0,88			-0,87		
CaO		0,99		-0,74	-0,65		-0,84	-0,53	
Na_2O	-1,00			-0,88				0,99	
K_2O	-0,87				0,82		0,94		
P_2O_5	-0,67		-0,57	0,94			0,92		
Ba	-0,79			0,92			0,90		
Cr		0,96				0,79	-0,67	-0,72	
Cu		-1,00		0,96				1,00	
Ga	-0,55	-0,70		0,98			0,52	0,85	
Nb		-0,99			0,97		0,99		
Ni		0,87		-0,86			-0,77	-0,64	
Pb	-0,73	-0,50		0,99			0,61	-0,78	
Rb	-0,89				0,79				0,91
Sr	-0,81		-0,54		-0,78	-0,56	0,89		
V			-0,88			0,96			-0,98
Zn	0,72		-0,65		0,88		0,82		-0,55
Zr	-0,71		-0,54		0,99		0,98		
MED	-0,71	0,68		-0,60	0,79			-0,86	

The cumulative variance explained by PC1', PC2' and PC3' for the total data set (71.4%) is smaller than the cumulative variance explained by PC1, PC2 and PC3 of the total data set. MED is included into both PC1' and PC2'. In fig 4.5 the principal component scores for PC1' and PC2' were plotted. Again the three clusters, viz. a/an/t1/t2/s, r, and c0/c1/c2/z/b, appear. These clusters can be subdivided in clusters of equal grain size. Fig 4.5 shows that a positive correlation of a number of elements with MED exists in the TTS in PC1', and in the ChMS in PC2', although in both river systems with different elements.
PC1', PC2' and PC3' of the TTS data set explain 74.1% of the total variance, a slight increase compared to the fraction explained by PC1, PC2 and PC3. Table 4.8 shows that MED is included into both PC1' and PC2'. Principal component scores for PC1' and PC2' were calculated for all samples and plotted in fig 4.6. This plot shows besides a clustering in grain size also a clustering in location of deposition (alluvial fan/plain). Individual rivers cannot be distinguished.
The cumulative variance explained by PC1', PC2' and PC3' for the ChMS (77.2%) is smaller than the cumulative variance explained by PC1, PC2 and PC3. MED is only included into PC2'. This principal component is comparable with PC2' for the total data set. Therefore this principal component does not give extra information and neither do plots of principal component scores. PC1' of the ChMS data set is comparable with PC1' of the TTS data set. Although MED is not included in the former, still some correlation between element contents and MED can be seen.

Discussion

Principal component analyses with all elements, including grain size, were carried out to study variation at single sampling sites or in other words lateral sorting effects (Kroonenberg et al., 1988).
The results of the total data set (fig 4.5) suggest for PC1' an increasing content of elements of stable as well as easily weatherable minerals with grain size in the TTS. This seems rather strange, but may be explained by the relative low contribution of MED to PC1', which makes it hard to deduce a real lateral sorting effect in this principal component. A large part of the variance explained by PC1' is simply due to the different source material of the sediments of both river systems. Another part may be due to longitudinal sorting and/or mixing with older sediments, with an increasing content of elements concentrated in stable minerals in the alluvial plain sediments (t2 and s). This results in a very small part of the variance of PC1' that may be explained by lateral sorting.
The results of the total data set suggest for PC2' an increasing content of elements concentrated in clay minerals with decreasing grain sizes, and an increasing content of elements concentrated in easily weatherable minerals with increasing grain size (or a decreasing content of elements concentrated in stable minerals). The latter is not necessarily an entire lateral sorting effect. An

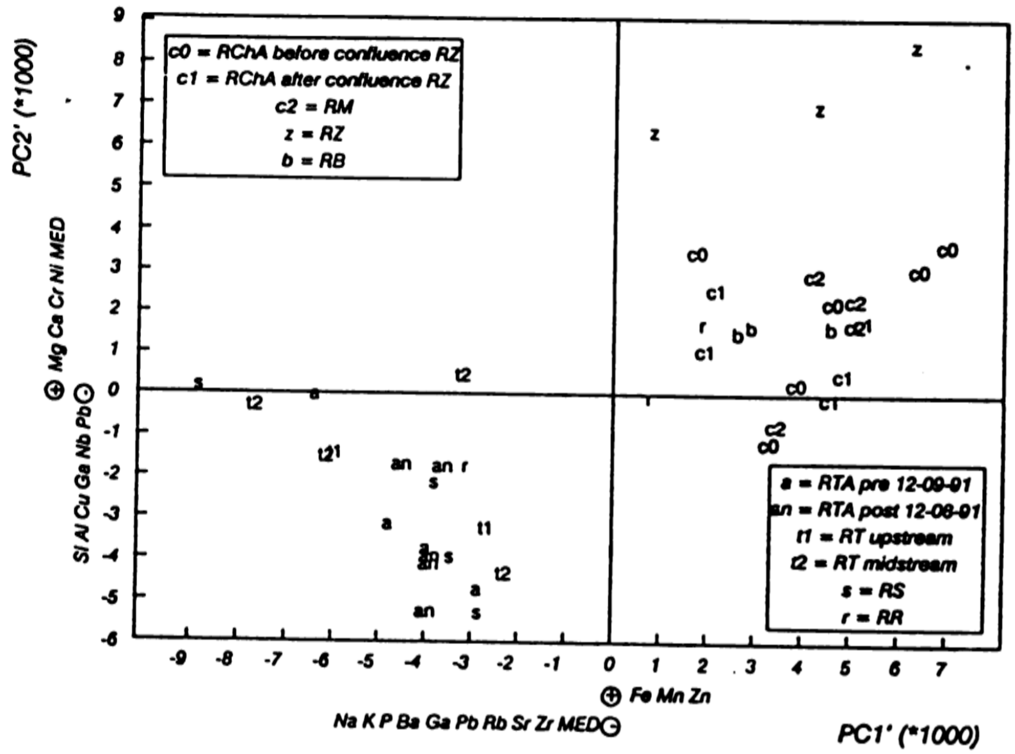


Fig 4.5 Principal component scores of all samples for PC1' and PC2'.

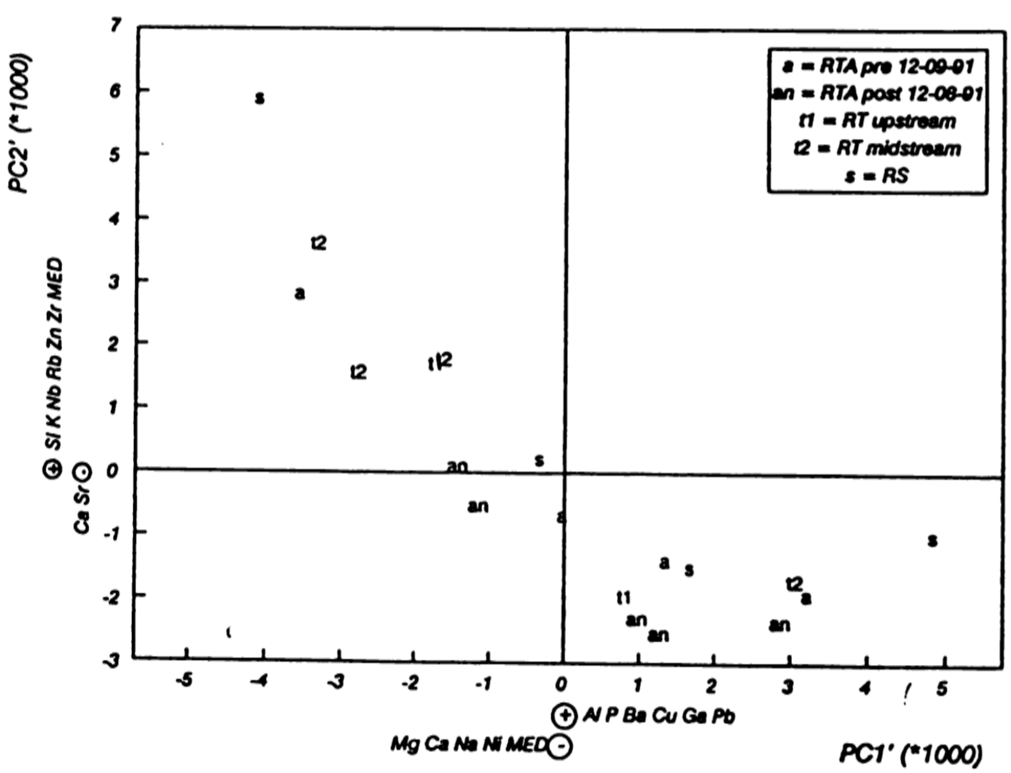


Fig 4.6 Principal component scores of the TTS samples (including Río Sucio) for PC1' and PC2'.

increasing content of elements concentrated in easily weatherable minerals with increasing grain size may be explained by the presence of phenocrysts, which are always more basic (=easily weatherable) than the groundmass. On the contrary, several stable minerals (like zircon) will almost never occur with a diameter >0.5 mm, and therefore will automatically be less abundant in the coarse sediments. Because also the increasing content of elements concentrated in clay minerals with decreasing grain size is not a lateral sorting effect, only a small part of the variance of PC2' may be explained by lateral sorting. The largest part of the variance explained by PC2' is due to the different source material of the sediments of both river systems. The variance of PC2' cannot be explained by longitudinal sorting and/or mixing with older sediments. This is shown in fig 4.5. In this picture principal component scores of sediments of the same river systems with identical grain sizes, but taken at different locations alongstream, appear to be nearly the same.
The results for the TTS are quite remarkable for PC2'. This principal component suggests an increasing content of elements concentrated in easily weatherable minerals with decreasing grain sizes, and an increasing content of elements concentrated in stable minerals with increasing grain size. No real explanation for the composition of PC2' in terms of lateral sorting can be given, except that both MED, and Ca and Sr do not contribute much to PC2'. The same holds for the contribution of MED to PC1', although this principal component is better to understand, suggesting an increasing content of elements concentrated in clay minerals with decreasing grain sizes, and an increasing content of elements concentrated in easily weatherable minerals with increasing grain size (MED > 250 μm). Fig 4.6 confirms the suggestion from PCA without MED, that longitudinal sorting and/or mixing with older sediments may occur, here completely reflected by PC2'. So in the TTS lateral sorting, if present at all, is hard to detect. Longitudinal sorting and/or mixing with older sediments, however, is reflected by an increasing fraction of elements concentrated in stable minerals with increasing transportation time/distance (PC2'), in spite of the presence of MED in this principal component.
When carrying out PCA with all elements and MED, for the ChMS, it would be of interest to see whether a specific grain size class would have high correlation with a specific petrographic principal component or not. However, the results do not show great differences with the results of PCA without MED. No specific petrographic principal component occurs, besides the volcanic ones but they are not pure volcanic (see discussion section 4.4.3). Thus no clear correlation between specific grain sizes and specific petrographic principal components can be found. Nevertheless like in the TTS, a positive correlation of elements, concentrated in easily weatherable minerals, with MED does occur (in PC2'). And although MED is not included in PC1', from the way the clusters in fig 4.5 have been arranged, it may be noted that a negative correlation of elements concentrated in stable minerals, with grain size class exists.

Table 4.9 Principal component loadings (after varimax rotation) of selected elements and minerals/rock fragments in PC1, PC2 and PC3, and including grain size (MED) in PC1', PC2' and PC3'; between brackets the percentage of total variance explained by the particular principal component; analyses at 6 samples.

	PC1(63.2)	PC2(16.0)	PC3(10.7)	PC1'(60.9)	PC2'(16.3)	PC3'(11.7)
SiO_2			0,74	0,72		
TiO_2			-0,92		-0,83	
Al_2O_3	-0,93			-0,87		
Fe_2O_3	0,77	0,64		0,72		-0,68
MgO		1,00				-0,99
CaO			-0,86	-0,63	-0,75	
K_2O	-0,65		-0,62	-0,67	-0,63	
Ba	-0,69	-0,51	-0,51	-0,73		0,52
Cr		1,00				-0,97
Ga	-0,97			-1,00		
Ni	-0,86		-0,50	-0,92		
Rb	-0,78		-0,54	-0,78	-0,57	
Sr	-0,76		-0,53	-0,81		
Zr	-0,72		-0,60	-0,76	-0,56	
Qt	-0,86			-0,87		
Ft	-1,00			-0,98		
Lp	0,98			0,98		
Lv	-0,67		-0,67	-0,74	-0,60	
Alt	0,82		0,54	0,88		
Pyr	-0,94			-0,98		
Amph	0,57	0,74		0,57		-0,75
Calc			0,97		0,96	
Clay		0,63	0,78		0,86	-0,50
Epi		0,60	0,77		0,78	-0,55
MED					-0,97	

4.4.5 *PCA with elements, minerals and grain size*

Results

The results of PCA with as well a selection of elements and minerals/rock fragments, as this selection and grain size, are shown in table 4.9.

The results of both analyses look very similar, apart from the switch of PC2 to PC3' and PC3 to PC2'. The total variance accounted for by PC1, PC2 and PC3 is 89.9%, of which PC1 the largest part explains. PC1', PC2' and PC3' explain a slightly smaller fraction of the total variance (88.9%). Again the first principal component explains by far the largest part.

Discussion

The results of PCA with a selection of elements and minerals/rock fragments confirm what already in the preceding discussion was mentioned, that no principal component reflects one specific rock type. Besides that, the three principal components are rather inconsistent. PC1 has negative loadings for the elements Al, K, Ba, Ga, Ni, Rb, Sr and Zr, and for the minerals Qt, Ft, Lv and Pyr. The fact that Qt and Pyr have negative loadings, while neither Si, nor Ca, Mg or Cr have, makes PC1 hard to understand or explain. Moreover, the presence of PC loadings of both quartz, feldspars, and pyroxenes in one principal component (all with the same sign) is not to be expected, certainly not after the preceding discussion of the results of PCA without minerals/rock fragments. PC3 is with a positive loading of Calc and a negative loading of Ca, also inconsistent.

The results of PCA with a selection of elements and minerals/rock fragments, and grain size are almost similar. MED is included in PC2'. However, a negative correlation of epidote with MED seems rather odd, considering the relatively easy weathering of epidote. In the same principal component a negative correlation of Calc with Ca seems even stranger. Even though the fraction of the total variance accounted for is high, this does not immediately mean the results are 'good and interpretable.

It should be obvious that from PCA with a selection of elements and mineral/rock fragments, as well as with this selection and grain size, with this small data set no conclusions may be derived. Thin sections of sandy sediments of more rivers and of more locations alongstream should be studied, before PCA with both elements and minerals/rock fragments may give results that are more consistent and of which conclusions may be derived.

Table 4.10 Selected physical and chemical properties of profiles along Río Tortuguero (T1 and T2) and Río Matina (M1 and M2); profile locations are depicted on fig 2.2; no texture analyses for M1 and M2 were available.

	Horizon	Depth (cm)	% Sand[a] (2000-50)	% Silt (50-2)	% Clay (<2 µm)	pH-H_2O (1:2.5)	Exchang. cations (meq/100 g)[b] Ca^{2+}	Mg^{2+}	K^+	Na^+	$CaCO_3$ (wt%)	P-ret (%)
Profile T1												
FAO: Eutric Fluvisol												
USST: Tropofluvent												
	Ah (0-5)	0-20	17	59	24	6,3	7.1	3,1	0,2	0,2	nd[c]	75,0
	BC (5-50)	20-40	19	61	20	6,4	6.8	2,8	0,5	0,2	nd	69,5
	2C	40-60	55	35	10	6,7	5.2	2.2	0,5	0,3	nd	55,0
	(50-90)	60-80	71	21	8	6,3	5.1	1,9	0,7	0,2	nd	43,5
	3C	80-100	75	17	8	6,2	5.5	2,0	0,8	0,2	nd	40,0
	(90-120)	100-120	87	5	8	6,9	4.4	1,7	0,6	0,2	nd	34,0
Profile T2												
FAO: Eutric Fluvisol												
USST: Tropofluvent												
	Ah (0-5)	0-20	39	47	14	6,4	7.2	4,0	0,5	0,3	nd	44,0
	Bw (5-20)	20-40	19	63	18	6,8	7.8	4,5	0,2	0,3	nd	51,0
	Cg (20-68)	40-60	53	41	6	6,8	6.4	2,4	0,1	0,3	nd	41,0
	2Cg	60-80	29	63	8	6,4	4.3	2,3	0,2	0,3	nd	46,0
	(68-120)	80-100	33	53	14	6,9	6.9	3,6	0,1	0,4	nd	41,0
		100-120	21	59	20	6,8	10.4	5,8	0,2	0,4	nd	45,0
Profile M1												
FAO: Eutric Fluvisol												
USST: Tropofluvent												
	Ah (0-30)	0-20	Silt loam[d]			6,8	41.1	5,3	1,1	0,4	0,2	38,5
	Bw1	20-40	Silt loam			7,1	43.1	4,8	0,5	0,4	0,1	37,0
	(30-80)	40-60	Silt loam			7,6	46.2	4,6	0,2	0,5	0,1	39,0
		60-80	Silt loam			7,5	46.6	4,5	0,2	0,4	0,1	37,0
	Bw2	80-100	Silt loam			7,4	40.9	3,8	0,2	0,5	0,1	33,0
	(80-120)	100-120	Silt loam			7,4	39.2	4,5	0,2	0,5	0,1	31,0
Profile M2												
FAO: Eutric Fluvisol												
USST: Tropic Fluvaquent												
	Ah (0-3)	0-20	Loamy fine sand			7,4	33.9	1,9	0,6	0,4	0,7	31,0
	C (3-50)	20-40	Loamy fine sand			7,6	48.8	2,5	0,3	0,4	0,6	31,0
	2Cg(50-60)	40-60	Sl.loamy fine/med sand			7,4	37.3	2,9	0,2	0,4	0,1	29,0
	3Cgr	60-80	Loamy fine sand			7,5	29.2	2,4	0,2	0,4	0,1	26,5
	(50-120)	80-100	|			7,3	37.2	3,8	0,3	0,4	0,1	35,0
		100-120	Silty clay			7,1	44.7	3,7	0,3	0,4	0,1	33,0

[a] Texture analyses appeared to be slightly inaccurate.
[b] Exchangeable cations were measured in duplo.
[c] nd = not determined.
[d] According to USDA classification (Gee & Bauder, 1986).

4.5 <u>Soils</u>

In order to obtain a first impression of the type of soils along RT and RM, two soil profiles along both rivers were described, and samples were taken to determine selected physical and chemical properties. The obtained results were also linked with the mineralogical and geochemical results.

Results

The results of the physical and chemical analyses, including a horizon description were summarized in table 4.10. The soils were classified according to FAO-Unesco (1988) and US Soil Survey Staff (Cornell University Agronomy Department, 1985). Because profile descriptions were rather brief, and not all physical and chemical properties were included, the soils could not be classified very accurate. The calcite content (weight %) of the RTA and RChM-samples can be found in appendix H.

All profiles (table 4.10) are situated on natural levees, with T1 and M1 in the upstream part, and T2 and M2 in the downstream part of the alluvial plain (fig 2.2). The levees are all under grassland, and are periodically inundated.

Considerable amounts of exchangeable cations are available, especially Ca^{2+} in M1 and M2. These amounts do not significantly decrease in the downstream soils, except perhaps K^{+} in T2. Small quantities of free $CaCO_3$ are present in M1 and M2. The pH-H_2O values are neutral (T1 and T2) to slightly basic (M1 and M2). The P-retention values of T1 and T2 are higher than the values of M1 and M2. Nevertheless, T1 and T2, like M1 and M2, do not have andic properties.

Discussion

Considering the dominance of (mainly andesitic) volcanic rock in both the ChMS, and the TTS catchment area, the considerable higher amounts of exchangeable Ca^{2+} in M1 and M2, must be largely due to the presence of limestone and calcareous sand-/silt-/claystones in the ChMS catchment area.

The texture of the horizons in M2 and their calcite content, suggest that the calcite content is positively correlated with the grain size of the sediments. Studying the calcite content of a number of sediments of RChA, RM, RZ and RB (app H), this suggestion appears to be rather doubtful. The calcite content ranges of coarse, medium and fine sediments appear to cover each other completely: coarse = 0.6-0.9%, medium = 1.0-1.3% and fine = 0.1-2.0%. With the calcite content of the dominant rock types present in the ChMS catchment area, and the petrographical composition of an alluvial fan gravel deposit of RChA (table 4.2), the potential calcite content of any perfectly mixed RChA deposit may be calculated, not taking in account sorting, chemical weathering, and differential breakdown effects. This would result in a potential calcite content of a perfectly mixed RChA deposit of 3-3.5% (app H). From this it may be concluded that the calcite content decreases with progressive breakdown of rock fragments > 2 mm. The decrease of calcite may be explained as a chemical weathering effect, for breakdown of a calcitic rock fragment would not result in a decrease of the total calcite content. In the fraction < 2 mm no further decrease of the calcite content with progressive breakdown occurs.

The high Ca^{2+} content in M1 and M2 will be the result of in situ weathering of Ca^{2+} containing minerals, particularly calcite. Another part may be supplied as dissolved Ca^{2+} in the river water. During inundations, besides dissolved Ca^{2+}, also sediment with fresh (Ca^{2+} containing) minerals will be supplied by the river. Generally however, without preceding earthquakes, the suspended load of RM is not high (Vahrson et al., in press), and inundations of RM will not always result in large depositions of sediment. In order to maintain the high content of exchangeable Ca^{2+}, and regarding the relatively slow weathering of primary minerals, it is probable that a significant part will be supplied by the river water. Considering data of dissolved elements in river water (Schlesinger, 1991; Stallard et al., 1991), it may expected that Ca^{2+} accounts for the largest part of the dissolved basic cations in the river water of RM. From agricultural point of view it would be of interest to know more about which part of the exchangeable Ca^{2+} may be contributed to in situ weathering of primary minerals, particularly calcite, and which part to the supply by river water. For such a study also the calcite weathering rate under the prevailing conditions, and the chemical composition of the river water should be determined.

From table 4.5 a dominance of vermiculite and smectite in the young soils along RM, and of smectite and kaolinite along RT, may be expected. Although Ca^{2+} and Mg^{2+} are the dominating cations at the adsorption complex of both RT and RM soils, the presence of vermiculite and smectite may cause difficulties in the uptake of these cations by plants (Van Diest, 1986). From agricultural point of view, another reason to know as well the bulk chemical composition of the sediments, as the chemical composition of the river water.

5 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The geomorphology of TTS watershed is a result of short-lasting periods of series of disastrous events in which large amounts of sediment are deposited, separated by long-lasting relatively calm periods in which the sediments become weathered, reworked and transported. The short-lasting disastrous periods coincide with reactivation of Irazú and Turrialba volcano. Eruptions of ash and lava, lahars/sheetfloods, landslides, and floods result in enormous sediment deposits and in enormous increases of sediment discharge of the rivers draining these volcanoes. During these periods rivers change their course and inundations occur. In the long-lasting calm periods rivers do not carry much sediment. In these periods landslides, floods and inundations occur too, but do not have the same dramatic effect as during the short-lasting periods.

For the geomorphology of ChMS watershed the same explanation is true, except that the short-lasting disastrous periods do not coincide with reactivation of volcanism, but with major earthquakes in the Cordillera de Talamanca. Such earthquakes cause liquefaction and, together with rainfall, trigger landslides.

RTA-RT and RChA-RM both have developed a high profile concavity, which is the result of the rapid downstream increase of water discharge and their generally low sediment load. This implies that heavy earthquakes and periods of active volcanism have not occurred often during the beginning of the Holocene.

The sediments at the proximal part of the RTA alluvial fan are dominated by cobbles and boulders (diameter range 7.5-200 cm), at the RChA fan by sands and pebbles. The different size of the sediments is partly caused by the higher stream channel gradient of RTA at the proximal fan, partly by the different source rock of the sediments of both rivers, and partly by the different distances over which these sediments are transported before they reach the alluvial fan (RChA longer than RTA).

Principal component analyses of the bulk chemical composition of TTS and ChMS sediments suggest that present volcanism in the Cordillera Central is slightly more acid than the volcanism in the Cordillera de Talamanca was. This was not expected from optical mineralogy.

With PCA of the bulk chemical composition of sediments a longitudinal sorting effect was found for sediments of TTS. In sediments of ChMS no longitudinal sorting effect was found. In both TTS and ChMS sediments no or hardly any lateral sorting effect was found.

A good distinction between volcanic and sedimentary rock in the RChA sediments, with both optical mineralogy and PCA of the bulk chemical composition, was not possible, due to the comparable mineralogical composition of both rock types.

Rivers in the ChMS watershed all appear to carry calcite containing sediment. Soils along the rivers still contain small amounts of calcite and they have high amounts of Ca^{2+} and Mg^{2+} at their adsorption complex.

Recommendations

Rivers draining the Cordillera de Talamanca and rivers draining the Cordillera Central carry sediments with a clearly different mineralogical and chemical composition, resulting in different physical and chemical properties of the soils. In this study a first indication of the different properties of the soils is given. To achieve a complete picture of the differences more soils, especially along RChA-RM, should be described and analyzed.
Furthermore for agricultural purposes it is important to know whether soils become inundated (and how often) and achieve fresh sediment. From this study the chemical composition and several chemical properties (pH, exchangeable cations, $CaCO_3$) of a number of fresh overbank deposits of RChA are determined. Together with the thickness of the layer of fresh deposits, it is for example possible to calculate the amount of Ca, Mg, K and Na, that the natural fertilizer has deposited at a certain area (ton/ha). Knowing that the thickness of the layer of fresh deposit will decrease with increasing distance from the river, it is also possible to calculate the area where the natural fertilizer still has a significant contribution. This may play a role, for example in the decision whether dikes should be build or not. Of course also other purposes than agricultural should be reckoned with (viz. protection) then.
To achieve more information about mineralogy and geochemistry of sediments of rivers in the Atlantic Zone more rivers should be sampled. RTA-RT and RChA-RM should be sampled downstream. Moreover, especially for the understanding of the sediments of the ChMS and other watersheds in the Cordillera de Talamanca, it would be very helpful to study the source rock in its original position. This means that more expeditions should be made in the Cordillera de Talamanca.

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SUMMARY

The purpose of this study was to characterize and compare geomorphology, mineralogy and geochemistry of the Toro Amarillo-Tortuguero (TTS) and the Chirripó-Matina river system (ChMS) in the Atlantic Zone of Costa Rica. The study is concentrated on the lower reaches, and part of the middle reaches of the river systems.

River systems in this region are very dynamic. To understand better what produces the considerable dynamics, it is necessary to know more about the landforming processes that were active in the past and still are active today. The Toro Amarillo-Tortuguero system drains part of the eastern side of the active volcanic Cordillera Central with mainly andesitic rocks. The Chirripó-Matina system drains part of the eastern side of Cordillera de Talamanca with highly variable rock types, varying from calcareous sedimentary to plutonic rocks, in which active volcanism is absent. The Atlantic Zone has a humid tropical climate, with sometimes periods of extreme rainfall.

The geomorphological study included collecting river characteristics (longitudinal profile, water/sediment discharge, flood record), studying airphotos, topographic and geologic maps, field work and drawing geomorphologic maps. For more detailed study both river systems were subdivided in sectors. In the TTS four sectors were distinguished: alluvial fan, inactive alluvial plain, active alluvial plain and coastal plain. In the ChMS two sectors were distinguished: alluvial fan and alluvial plain. The geomorphology of both the TTS and the ChMS watershed is a result of short-lasting periods of series of disastrous events (volcanism, earthquakes, landslides, excessive rainfall) in which large amounts of sediment are deposited, separated by long-lasting relatively calm periods in which the sediments become weathered, reworked and transported. In the calm periods both rivers generally have a low sediment discharge, except during floods, caused by excessive rainfall. In the disastrous periods such floods are accompanied by earthquakes, volcanism, and/or landslides. Then they have a disastrous impact on the watershed (changing of river course, inundations). RTA-RT and RChA-RM both have developed a high profile concavity, which is the result of the rapid downstream increase of water discharge and their generally low sediment load.

Geochemical and mineralogical data of river sediments were obtained by sampling different grain sizes at a single spot at a number of sites alongstream, thus covering for the effect of sorting. The results of the bulk chemical composition of the sediments were statistically treated with principal component analysis. Soils along RT and RM were described and sampled to study the differences. RTA pebble clasts consist of andesites (90.9%), basalts (2%) and hydrothermal rock (7.1%). RChA pebble clasts consist of fresh volcanic rock (16.4%; andesites, basalts), hydrothermal rock (51.2%; slightly altered volcanics and completely altered rocks), plutonic rock

(3.8%; granites) and sedimentary rock (25.8%; sand/silt/claystones, limestones). RTA sands consist of volcanic lithic fragments (60%), altered fragments (18%) and monomineralic fragments (22%; mainly plagioclase, pyroxene, quartz). RChA sands consist of sedimentary, plutonic and fresh volcanic fragments (12%), altered fragments (69%) and monomineralic fragments (19%; mainly plagioclase, clay bodies, opaques and pyroxenes). Dominant clay minerals in fine sediments of RTA and RT are smectite and kaolinite, of RChA and RM smectite and vermiculite. Differentiating elements of TTS and ChMS sediments are: Al, Fe, K, P, Ba, Rb, Sr, and Zr. Sediments of rivers in the TTS cannot be distinguished at element content. RZ can be distinguished from the other rivers in the ChMS in Ca, Ti, Mg, Cr, Ni, and V. Dominant soil types along both RT and RM are Eutric Fluvisols (FAO)/Tropofluvent (US Soil Taxonomy). Principal component analyses of the bulk chemical composition of TTS and ChMS sediments suggest that present volcanism in the Cordillera Central is slightly more acid than the volcanism in the Cordillera de Talamanca was. This was not expected from optical mineralogy. PCA suggests furthermore a longitudinal sorting effect for sediments of rivers in TTS. In sediments of rivers in ChMS no longitudinal sorting effect was found. In both TTS and ChMS sediments no or hardly any lateral sorting effect was found. Rivers in the ChMS watershed all appear to carry calcite containing sediment. Soils along the rivers still contain small amounts of calcite and they have high amounts of Ca^{2+} and Mg^{2+} at their adsorption complex.

APPENDIX A: Precipitation distribution of selected weather stations

Weather stations[a]	Period of observation	Altitude (m)	Jan M-[b]	Jan M	Jan M+	Feb M-	Feb M	Feb M+	Mar M-	Mar M	Mar M+	Apr M-	Apr M	Apr M+	May M-	May M	May M+
Tortuguero	1979-1991	3	-	455	-	-	302	-	-	235	-	-	286	-	-	453	-
Jalova	1978-1985	3	146	336	570	197	282	490	70	128	211	3	198	449	85	362	761
Caribe	1971-1975	40	200	430	925	45	145	254	16	97	176	81	127	211	116	216	513
La Mola	1980-1986	70	73	233	334	45	169	237	27	138	310	52	186	364	146	319	579
Río Frío	1970-1985	100	88	257	672	85	183	340	32	139	351	42	185	632	127	326	564
Guápiles	1970-1987	262	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carillo[c]	1984-1988	730	241	515	646	188	359	453	112	369	687	229	431	602	367	545	780
La Montura	1984-1989	1000	305	556	779	232	417	573	144	421	827	153	367	584	376	513	711
Irazú	1964-1986	3400	4	86	191	0	57	185	0	33	165	3	97	456	42	208	386

Weather stations	June M-	June M	June M+	July M-	July M	July M+	Aug M-	Aug M	Aug M+	Sep M-	Sep M	Sep M+	Oct M-	Oct M	Oct M+
Tortuguero	-	403	-	-	591	-	-	499	-	-	326	-	-	420	-
Jalova	212	385	627	146	453	892	274	409	654	38	453	236	104	330	648
Caribe	123	295	472	312	555	775	204	389	598	75	275	553	230	339	451
La Mola	205	404	575	226	475	1064	293	446	519	125	261	411	188	337	723
Río Frío	223	470	1669	225	499	958	254	434	769	162	343	587	205	397	725
Guápiles	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Carillo	852	915	1071	474	673	785	572	872	1110	555	626	729	630	758	857
La Montura	543	731	909	582	763	889	576	782	1064	474	602	710	516	774	932
Irazú	120	223	373	59	171	344	120	206	367	166	229	336	143	275	423

Weather stations	Nov M-	Nov M	Nov M+	Dec M-	Dec M	Dec M+	Year M-	Year M	Year M+
Tortuguero	-	668	-	-	666	-	-	5345	-
Jalova	304	625	1405	6	488	1062	3771	4580	5106
Caribe	116	348	674	181	342	490	3269	3557	4685
La Mola	89	389	966	146	363	758	2716	3718	4413
Río Frío	263	489	927	137	386	1189	2663	4107	4935
Guápiles	-	-	-	-	-	-	3900	4500	6500
Carillo	436	572	722	294	425	561	5958	6848	7726
La Montura	306	614	948	352	602	862	6363	7120	7785
Irazú	99	281	622	20	162	443	1544	2085	2529

Source: Instituto Meteorológico Nacional (IMN) and Instituto Costarricense de Electricidad (ICE).

[a] Weather stations are depicted on fig 2.2

[b] M- = minimum, M = mean and M+ = maximum precipitation during the period of observation.

[c] Note that Carillo weather station is not Carillo discharge station.

APPENDIX B: Information about floods after the 22-04-1991 earthquake

Estimation of duration of increased sediment discharge in the Chirripó-Matina river system after the 22-04-1991 earthquake

Assumptions[a]:

- Total catchment area = 1200 km^2
- Percentage damaged in catchment area = 25%
- Average thickness of soil layer slided down = 0.5-1 m
- Average suspended load = 10 kg/m^3
- Average water discharge[b] = 200 m^3/s
- Average density of sediment = 2600 kg/m^3
- A linear decrease of the total amount of soil slided down (carried away by the rivers)
- Suspended load is constant

Calculations:

Total amount of soil slided down: 1200 10^6*0.25*{0.5,1} = {1.5-3} 10^8 m^3
Average sediment discharge: 10*200/2600 = 0.77 m^3/s
Duration of increased sediment discharge: {1.5 10^8,3 10^8}/0.77 = {1.95-3.9} 10^8 s

Conclusion:

With these assumptions the increased sediment discharge would last {1.95-3.9} 10^6 s, which is 6-12 years. In this estimation has not been accounted for certainly occurring drier periods in which RChA, RB and RZ hardly carry any sediment.

[a] Assumptions based on data of Vahrson et al. (in press), on personal comment of A. Nieuwenhuyse, on data of ICE, and on data of this report.
[b] An estimation of the sum of discharges of RChA, RB and RZ.

Selected newspaper articles about the 12-08-91 floods

EMERGENCIA EN EL ATLANTICO

Decenas de casas inundadas

Zozobra y pánico en Matina

NICOLAS AGUILAR

Redactor de La Nación

Naturaleza implacable

APPENDIX C: Location of sample sites, analyses and additional data

(Location numbers (example: 1 RTA-1) refer to numbers depicted on fig 2.2)

Toro Amarillo-Tortuguero system

Río Toro Amarillo	
Topmap	Guápiles, Hoja 3446 IV, Edición 3-IGNCR 1989, 1:50,000
Coordinates	N = $^{2}43^{7}$, E = $^{5}55^{5}$
Remarks	28-06-91; all samples taken by hand
1 RTA-1	medium sand (rounded), greyish brown, sandbank
1 RTA-2	fine sand, rounded, transition river/riverbank
1 RTA-3	coarse sand/pebble gravel (MED gravel 0.3 cm), on top of sandbank
1 RTA-4	very fine sand/silt in small depression, yellowish brown/grey, upper layer of coarse sand removed; some "pollution" with coars.sand
Coordinates	N = $^{2}44^{3}$, E = $^{5}55^{0}$
Remarks	26-08-91; all samples taken by hand
1 RTA-5	completely altered hydrothermal rock
1 RTA-6	coarse grained-andesite
1 RTA-N1	fine sand, very well sorted, grey
1 RTA-N2	fine sand, very well sorted, grey
1 RTA-N3	medium sand, very well sorted, grey
1 RTA-N4	coarse sand, very well sorted, grey
1 RTA-N5	silt/very fine sand, very well sorted, beige (grey after drying); maybe a little polluted with drying
1 A-2	12-08-91; ca 05.30 pm; discharge of RTA was a little more than usual, but sed.discharge was enormous (7 kg/m^3); this was after the disastrous inundation in the night of 11/12-08: Guápiles 95 mm, Carillo (11-08&12-08) 315.9 mm, La Montura (11-08&12-08) 226.4 mm
Coordinates	N = $^{2}43^{8}$, E = $^{5}55^{0}$
Remarks	A-15 and A-1 have been put together to get one sample for XRF-analyses (A-1)
1 A-15	09-05-91; ca 09.00 am; discharge of RTA was a little more than usual, however most of the (old) riverbeds still were dry; color of the water was yellowish brown; I suppose not much extra sediment was discharged (35 g/m^3)
1 A-1	09-05-91; ca 06.30 pm; discharge RTA was more than usual, moreover a number of formerly dry riverbeds were discharging again (400 g/m^3)
1 KM-3	reacted very strongly when adding peroxide to remove organic matter

Río Tortuguero	
Topmap	Río Sucio, Hoja 3447 III, Edición 2 IGNCR 1985, 1:50,000; Guápiles, Hoja 3446 IV, Ed3
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{9}$
Remarks	sample sites are part of cross section RT1
2 RT1-9.0	fine sand, current deposit; transition river/riverbank (easternbank)
2 RT1-10.0	coarse sand; sample taken in current riverbed; contains a number of little shales
Coordinates	N = $^{2}57^{1}$-$^{2}57^{8}$, E = $^{5}63^{0}$-$^{5}62^{4}$
2 RT1-1.1	medium sand, mod.sorted, grey
2 RT1-2.1	loamy, coarse sand, yellowish brown
2 RT1-7.1	loamy, medium sand, mod.sorted, red/grey
2 RT1-9.4	sandy (coarse) loam, brown
2 RT1-13.1	loamy, medium sand, poorly sorted, darkgrey
2 RT1-21.4	sandy (fine) loam, lightbrown/grey
Topmap	Agua Fria, Hoja 3447 II, Edición 2-IGNCR 1984, 1:50,000
Coordinates	N = $^{2}59^{6}$, E = $^{5}65^{0}$
3 A-21	09-05-91; ca 11.00 am; RT was discharging more than usual, the lower terraces were inundated; color of the water was reddish brown; I think more sed. was discharged than usual (70 g/m^3)
3 A-3	16-08-91; ca 06.00 pm; few discharge and hardly any sediment discharge (30 g/m^3); maybe still some influence of 12-08-91 inundation
3 KM-5	-
Topmap	Agua Fria, Hoja 3447 II, Edición 2-IGNCR 1984, 1:50,000
Coordinates	N = $^{2}61^{2}$, E = $^{5}66^{4}$
4 Profile T1	26-07-91; 1RT-P1 (0-20 cm)/P2 (20-40)/P3 (40-60)/ P4 (60-80)/P5 (80-100)/P6 (100-120); natural levee, river ca 2.5 m below levee, dist. river ca 5 m, well drained, fin.-upward profile: sand/loamy sand/sandy loam; sample P5 was very wet, but may have lost some soilwater
Topmap	Agua Fria, Hoja 3447 II, Edición 2-IGNCR 1984, 1:50,000
Coordinates	N = $^{2}63^{8}$, E = $^{5}72^{4}$
5 A-25	10-05-91; ca 10.00am; river level was already dropping; color of the water was reddish brown; I suppose more sediment was discharged than usual (75 g/m^3); A-21 and A-25 have been put together to get one sample for XRFS-measurements (A-25)
Topmap	Agua Fria, Hoja 3447 II, Edición 2-IGNCR 1984, 1:50,000
Coordinates	N = $^{2}71^{3}$, E = $^{5}76^{9}$
6 RT2-0.1	coarse sand (weighs heavy), transition river/riverbank, taken by hand
6 RT2-0.2	coarse sand at riverbank, taken by hand

5	RT2-0.3	silt/very fine sand, lightbrown, taken by knive; some "pollution" with coarse sand
5	RT2-0.4	medium sand at riverbank, black, placer deposit (weighs heavy), deposited next to/together with pebble gravel, taken by a knive; some "pollution" with coarse sand
5	RT2-0.5	coarse sand at riverbank (with pebble gravel on top), taken by hand
Coordinates		$N = {}^{2}71^{4}-{}^{2}71^{0}$, $E = {}^{5}76^{6}-{}^{5}77^{0}$
Remarks		sample sites are part of cross section RT2
5	RT2-1.10	slightly loamy, medium sand, well sorted, lightbrown/grey
5	RT2-1.18	sandy (very fine) loam, unripened, blueish grey
5	RT2-5.2	very loamy, medium sand, fairly sorted, greyish brown
5	RT2-5.4, KM-2	silty clay, unripened, red/grey
5	RT2-6.2	loamy, medium sand, greyish brown
5	RT2-8.4	sandy clay loam, red/grey
5	RT2-11.3	loam, lightgrey/brown
5	RT2-12.3	slightly loamy, fine sand, well sorted, grey
5	Profile T2	26-07-91; 2RT-P1 (0-20 cm)/P2 (20-40)/P3 (40-60)/ P4 (60-80)/P5 (80-100)/P6 (100-120); same augering as RT2.1, river ca 2 m below levee, distance to river ca 1 m, badly drained; P3 and P5 were wet and had some concretions; P4 had also some concretions, but was wetter; P4 as well as P2 may have lost some soilwater

Drainagechannel bananaplantation

Topmap		Agua Fria, Hoja 3447 II, Edición 2-IGNCR 1984, 1:50,000
Coordinates		$N = {}^{2}64^{3}$, $E = {}^{5}67^{7}$
Remarks		in a bananaplantation between Campo Cinco and Campo Dos, just after entering the bananaplantation coming from Campo Cinco, still before calle campo cuatro
7	A-27	10-05-91; ca 09.30 am; at the confluence of two drainage channels two different colors of water (=sediment) appear: reddish brown and yellowish brown; much sediment in these two channels (250 g/m^3)
7	A-5	24-05-91; ca 03.30 pm; very little discharge with no sediment (not detectable)

Río Sucio

Topmap		Río Sucio, Hoja 3447 III, Edición 2-IGNCR 1985, 1:50,000
Coordinates		$N = {}^{2}64^{1}$, $E = {}^{5}48^{2}$
Remarks		25-10-91; Su-1/4 were taken at a little beach; all samples taken by trowel
	Su-1	very coarse sand
	Su-2	medium sand, brown
	Su-3	fine sand, greyish brown
	Su-4	very fine sand/silt, brown

<u>Chirripó-Matina system</u>

Río Chirripó Atlántico

Topmap		Barbilla, Hoja 3545 IV, Edición 1-IGCR 1963, 1:50,000
Coordinates		$N = {}^{2}17^{5}$, $E = {}^{6}10^{0}$
Remarks		30-08-91; RChA before confluence with RZ; all samples taken by har accurate due to the things ł
9	RCh-N1	well sc very sn
9	RCh-N2	irly wel
9	RCh-N3	irly well sorted, brownish grey
9	RCh-N4	ll sorted, brownish grey
9	RCh-N5	nd, well sorted, brownish grey, ver/riverbank
9	RCh-N6	nd/silt, lightbrown; maybe some ith coarse sand

Topmap		Barbilla, Hoja 3545 IV, Edición 1-IGCR 1963, 1:50,000
Coordinates		$N = {}^{2}19^{7}$, $E = {}^{6}13^{0}$
Remarks		17-07-91; all taken by hand; coordinates may be inaccurate due to the incompleteness of the 1963 topmap, many things have changed after 1963
10	RChM-1.1	anic matter, green and cent deposit taken close of alluvial branch (not
10	RChM-1.2	; deposited ar in a dry ridge
10	RChM-1.3	well sorted earthquake; fluence dry
10	RChM-1.4	well sorted earthquake;
10	RChM-1.5	: deposited ar in a dry ridge

Topmap		3545 IV, Edición 1-IGCR 1963,
Coordinates		13^{5}
Remarks		ay be inaccurate due to the of the 1963 topmap, many things fter 1963
11	RChM-XX	ium sand, well sorted, grey, istocene terrace (fan deposit or

	pliocene deposit (suretka); taken at 1 m above road level
11 A-14	14-05-91; ca 12.00 pm (noon); compared with infrared aerial photos from 1984, at this spot RChA has a new branch; after the 22-04-91 earthquake much sediment and (especially) trees were deposited by the river; even now a lot of sediment is discharged (5 kg/m^3)
11 A-4	16-07-91; ca 10.00 pm; a considerable (sed.)-discharge (14 kg/m^3); RChA was (still) inundated after heavy rains
11 KM-4	reacted very strongly when adding peroxide to remove organic matter (and some calcite)
Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	$N = {}^{2}25^{3}$, $E = {}^{6}14^{4}$
Remarks	16-07-91; these samples were taken at the same site where the stonecount took place
13 RChM-1.8	andesite
13 RChM-1.9	conglomerate
13 RChM-1.10	completely altered hydrothermal rock
13 RChM-1.12	slightly altered volcanic rock with some calcite
13 RChM-1.13	sandstone/shale
13 RChM-1.14	limestone/calcareous claystone

Río Matina

Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	$N = {}^{2}28^{2}$, $E = {}^{6}13^{2}$
Remarks	RChM-X2/X3/X4 are very well sorted sands, they are part of a one-time-deposit of ca 1.5 m; all sands are calcareous; sand deposited after 12-08-91 inundation
14 RChM-X1	18-07-91; recent mud (after 22-04-91), fairly well sorted; at nearly the same spot as soil profile 2RM-K (transition river/riverbank)
14 RChM-X2	30-08-91; fine sand, very well sorted, brown, a little cross laminated
14 RChM-X3	24-10-91; medium sand, very well sorted, brown, cross lamination
14 RChM-X4	24-10-91; fine sand, very well sorted, brown, horizontally layered
14 Profile M1	16-07-91; 2RM-K1 (0-20 cm)/K2 (20-40)/K3 (40-60)/ K4 (60-80)/K4 (80-100)/K6 (100-120); natural levee, river ca 4 m below levee, distance to river ca 10 m, soil well developed (AB-profile), from 0-120 cm silty loam, well drained

Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	$N = {}^{2}29^{2}$, $E = {}^{6}13^{0}$
15 RChM-1.6, KM-1	18-07-91; heavy clay, not calcareous, grey; near Matina in a backswamp (at ca 80 cm); taken by auger; strong reaction when adding peroxide to remove organic matter and calcite
Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	$N = {}^{2}28^{8}$, $E = {}^{6}16^{1}$
16 IA-14/15/27	14-08-91; sandy (very fine) loam, brown; old, small streambed; two days after the inundation this spot was not inundated anymore
Topmap	Moin, Hoja 3546 II, Edición 3-IGNCR 1989, 1:50,000
Coordinates	$N = {}^{2}34^{2}$, $E = {}^{6}22^{3}$
18 Profile M2	16-07-91; 1RM-K1 (0-20 cm)/K2 (20-40)/K3 (40-60)/ K4 (60-80)/K5 (80-100)/K6 (100-120); natural levee, river ca 2.5 m below levee, distance to river ca 5 m, hardly any soil development, from 0-120 cm increasing loam content, badly drained

Río Zent

Topmap	Barbilla, Hoja 3545 IV, Edición 1-IGCR 1963, 1:50,000
Coordinates	$N = {}^{2}17^{8}$, $E = {}^{6}15^{3}$
Remarks	26-07-91; probably the samples were a little "polluted" with recent deposits (after 22-04-91 eartquake); all samples taken by hand; coordinates may be inaccurate due to the incompleteness of the 1963 topmap, many things have changed after 1963
12 Zent-1	coarse sand, brown, fairly well sort.; sandbar
12 Zent-2	coarse sand/pebble gravel, brown, fairly well sorted; Zent-2 underneath Zent-1
12 Zent-3	coarse sand, darkgrey, well sorted; other sandbar
Topmap	Barbilla, Hoja 3545 IV, Edición 1-IGCR 1963, 1:50,000
Coordinates	$N = {}^{2}19^{7}$, $E = {}^{6}13^{3}$
E1 Z-1	15-08-91; 15-30 cm, coarse sand with some pebble gravel, well sorted, brown, erosion terrace (an old riverbed); taken by auger; coordinates may be inaccurate due to the incompleteness of the 1963 topmap, many things have changed after 1963

Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	N = $^{2}23^{0}$, E = $^{6}16^{0}$
E2 Z-2	15-08-91; >150 cm, fine sand, gleymottling colors; old riverbed with peat (60-110) and pebble gravel (110-120); taken by auger

Río Barbilla

Topmap	Matina, Hoja 3546 III, Edición 2-IGNCR 1988, 1:50,000
Coordinates	N = $^{2}27^{7}$, E = $^{6}05^{6}$
Remarks	26-07-91; all samples taken by hand
19 Barb-1	slightly loamy, medium sand, greyish brown, fairly well sorted; sandbar
19 Barb-2	fine sand, well sorted, greyish brown; transition river/riverbank
19 Barb-3	medium sand, brownish grey, well sorted; sandbar, topsurface removed

<u>Reventazón system</u>

Topmap	Bonilla, Hoja 3446 II, Edición 2-IGNCR 1967, 1:50,000
Coordinates	N = $^{2}32^{3}$, E = $^{5}87^{9}$
Remarks	26-07-91; Rev-1/3 taken at little beach at line perpend. to river; Rev-1 nearest to river; Rev-4 ca 5 m upstream; all by hand
20 Rev-1	medium sand, greyish brown; transition river/riverbank
20 Rev-2	medium sand with pebble gravel, lightbrown, light colored minerals
20 Rev-3	fine sand, brown
20 Rev-4	fine sand, black, heavy minerals, placer deposit; some "pollution" with coarse sand

APPENDIX D: Augerings of cross sections RT1, RT2 and RM1

Remarks:
- topographic maps used for RT1: Guápiles, Hoja 3446 IV, Ed3-1989, and Río Sucio, Hoja 3447 III, Ed2-1985, IGN, 1:50,000;
- topographic map used for RT2: Agua Fria, Hoja 3447 II, Ed2-1984 IGN, 1:50,000;
- topographic map used for RM: Matina, Hoja 3546 III, Ed2-1988, IGN, 1:50,000;
- m-gl = meters below ground level;
- MED = estimated median of grain size (with a sandruler);
- ϕ = estimated maximum diameter.

CROSS SECTION RIO TORTUGUERO 1 - JUNE 1991

Especially at the northwestern side of Río Tortuguero sand has been dug off, which means that some parts do not have the original topography anymore. We tried as good as possible to auger at spots where the topography has not been disrupted.

Augering	RT1.1
Coordinates	$N = {}^{2}57^{1}$, $E = {}^{5}63^{0}$
Landuse	cattle/pasture
Geomorphological feature	floodplain 1

Layer (no.)	Thickness (m-gl)	Description
1	0-1.75	Ah (0-0.50), darkbrown/black, sandy loam, slightly smeary; Bw (0.50-1.10), yellowish
2	1.75-3.00	
3	3.00-3.50	
4	3.50-3.70	cobbles;
5	3.70-4.30	C, grey/red (glmott.), mod. sorted, slightly loamy medium sand with some very fine pebbles;
6	4.30-4.70	C, redd.brown (glmottl.), poorly sorted, slgh. lmy.med. sand with fairly many coarse pebbles;
7	4.70-5.30	C, grey, mod.sorted, loamy medium sand;
8	>5.30	gravel.

Samples: RT1.1.1-C, RT1.1.2-C, RT1.1.7; all taken by shovel, for more info see description.

Remarks:
- an explanation of this augering could be: layer 1,2,3 are some old sheetflood deposits with soil development; the A-horizon of layer 3 has probably been washed away by the next sheetflood, which is layer 2 (idem for the A-horizon of layer 2 by the next sheetflood, which is layer 1), layer 4 is an old riverbed of Río Tortuguero or another river;
- an other possible explanation could be: layer 1 is an old sheetflood, layer 2 and 3 are one fining upward sequence, and layer 4 is an old riverbed of Río Tortuguero or another river; so this explanation would give three different layers (one layer has the same type of deposits), instead of four.

Augering	RT1.2
Coordinates	$N = {}^{2}57^{1}$, $E = {}^{5}63^{0}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	floodplain 1

Layer (no.)	Thickness (m-gl)	Description
1	0-1.80	Ah (0-0.50), darkbrown/black, sandy loam, smeary; Bw (0.50-1.20), yellowish brown, loamy coarse sand, thixotropic; C (1.20-1.80), grey, loamy coarse sand, poorly/mod.sorted, unweathered;
2	1.80-3.10	buried soil (?): Bw (1.80-2.30), brown, sandy (medium) loam, smeary; C (2.30-3.10), brown, coarse sand with very fine/fine pebbles, mod./fairly sorted, unweathered;
3	3.10-3.80	buried soil (?): Bw (3.10-3.40), brown (but less dark than 2Bw), loamy sand with very fine/fine pebbles, thixotropic; C (3.40-3.80), brown, coarse sand, quite a few medium pebbles, mod.sorted;
4	>3.80	gravel.

Samples: RT1.2.1-Bw; by auger, for more info see remarks.

Remarks:
- equal to RT1.1;
- RT1.2.1-Bw: a number of little pieces of, probably, white kaolinitic clay.

ugering	RT1.3
oordinates	$N = {}^{2}57^{1}$, $E = {}^{5}62^{9}$
istance to former point (m)	35
anduse	cattle/pasture
eomorphological feature	edge of floodplain 1

Layer (no.)	Thickness (m-gl)	Description
1	0-2.00	Ah (0-0.50), darkbrown, loam, smeary; Bw (0.50-1.10), sandy (coarse) loam with medium pebbles, some gleymottling; C (1.10-2.00), grey, loamy coarse sand with very fine/fine pebbles, poorly sorted, some gleymottling;
2	2.00-3.00	buried soil (?): Bw (2.00-2.55), brown (you know the color!), loamy medium sand, thixotropic; C (2.55-3.00), brown, medium sand, fairly well sorted;
3	3.00-3.60	buried soil (?): Bw (3.00-3.20), brown, loamy coarse sand, thixotropic; C (3.20-3.60), brown, loamy coarse sand with medium/coarse pebbles, poorly/mod.sorted;
4	>3.60	gravel.

emarks:
looks very much the same as RT1.1 and RT1.2.

ugering	RT1.4
oordinates	$N = {}^{2}57^{2}$, $E = {}^{5}62^{9}$
istance to former point (m)	20
anduse	cattle/pasture
eomorphological feature	floodplain 2 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.20	Ah (0-0.20), darkbrown, loamy fine sand, thixotropic; Bw (0.20-1.10), brown, loamy medium sand, less loamy in lower part, thixotropic; C (1.10-1.20), grey, medium sand (rounded), fairly well sorted;
2	>1.20	gravel.

mples: RT1.4.1; by auger, for more info see description.

Augering	RT1.5
Coordinates	$N = {}^{2}57^{3}$, $E = {}^{5}62^{9}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	floodplain 2 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.85	Ah (0-0.20), darkbrown, loamy sand, thixotropic; Bw (0.20-0.70), brown, medium sand, thixotropic; C (0.70-0.85), brown, coarse sand;
2	0.85-1.30	buried soil (?): Bw (0.85-1.05), brown, loamy medium sand, thixotropic; C (1.05-1.30), grey, medium sand (rounded), well sorted;
3	>1.30	pebbles and cobbles.

Remarks:
- layer 2 is a buried soil or just another deposit with no soil development (hard to see).

Augering	RT1.6
Coordinates	$N = {}^{2}57^{3}$, $E = {}^{5}62^{9}$
Distance to former point (m)	35
Landuse	cattle/pasture
Geomorphological feature	edge of floodplain 2 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.80	Ah (0-0.15), darkbrown, loamy sand, thixotropic; Bw (0.15-0.70), brown, medium sand, thixotropic; C (0.70-0.80), brown, coarse sand;
2	0.80-1.20	buried soil (?): Bw (0.80-1.05), brown, loamy medium sand, thixotropic; C (1.05-1.20), grey, medium sand (rounded), well sorted;
3	>1.20	pebbles and cobbles.

Remarks:
- layer 2 is a buried soil or just another deposit with no soil development (hard to see).

Augering	RT1.7
Coordinates	N = $^{2}57^{3}$, E = $^{5}62^{9}$
Distance to former point (m)	21
Landuse	cattle/pasture
Geomorphological feature	old gully/channel in floodplain 3 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.50	Ah (0-0.10), darkbrown, loam, smeary; Bw (0.10-0.30), brown, loam (some fine sand), smeary; C (0.30-0.50), red/grey (gleymottling), loamy medium sand, mod.sorted;
2	0.50-1.00	C, brown/darkgrey (in lower part), coarse sand (MED 600 mu), well sorted;
3	1.00-1.15	C, probably an old riverbed with thin layers of clay (blue)/loam (lightbrown)/sand (red/grey, gleymottling), poorly sorted, "beekopvulling";
4	>1.15	gravel.

<u>Samples</u>: RT1.7.1, RT1.7.2; all taken by auger, sample RT1.7.1 is slightly affected by insects, for more info see description.

Augering	RT1.8
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{9}$
Distance to former point (m)	30
Landuse	cattle/pasture
Geomorphological feature	floodplain 3 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.10	Ah, darkbrown, loamy coarse sand;
2	0.10-0.50	BC, brown, loam (some fine sand), gleymottling, smeary;
3	>0.50	gravel.

<u>Remarks</u>:
- Layer 1 is probably an overbank deposit;
- A-horizon of layer 2 has probably been washed away; or BC is actually a C: a loamy sediment.

Augering	RT1.9
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{9}$
Distance to former point (m)	15
Landuse	cattle/pasture
Geomorphological feature	edge of floodplain 3 (?), natural levee, eastbank of RT

Layer (no.)	Thickness (m-gl)	Description
1	0-0.20	Ah, brown (few organic matter), sandy (medium) loam, smeary;
2	0.20-0.70	C, brown, loamy medium sand, well sorted, thixotropic;
3	0.70-0.90	C, brown, coarse sand, well sorted;
4	0.90-1.25	C, brown, sandy (coarse) loam, smeary, in lower part less loamy and gleymottling;
5	1.25-1.50	C, brown, coarse sand with quite a few medium pebbles (rounded), mod.sorted;
6	>1.50	gravel.

<u>Samples</u>: RT1.9.4 (by auger), RT1.9.0 (by hand); sample RT1.9.4 is slightly affected by insects, for more info see description or remarks.

<u>Remarks</u>:
- distance to Río Tortuguero: 3 m;
- RT1.9.0 was taken at the easternbank of Río Tortuguero (near to RT1.9), so it is a current deposit: fine sand;
- close to this point is another floodplain (2.5 (?)) too.

Augering	RT1.10
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{9}$
Distance to Río Tortug. (m)	5
Landuse	cattle/pasture
Geomorphological feature	floodplain 2.75 (?), westbank RT

Layer (no.)	Thickness (m-gl)	Description
1	0-0.70	Ah (0-0.10), brown (few organic matter), loamy medium sand, thixotropic; BC/C (0.10-0.70), brown, medium sand, fairly well sorted, gleymottling with concretions (iron, manganese) in the lower part;
2	0.70-1.00	C, brown, coarse sand, fairly well sorted;
3	>1.00	gravel.

<u>Samples</u>: RT1.10.0; by hand, for more info see remarks.

<u>Remarks</u>:
- RT1.10.0 was taken in the current riverbed of Río Tortuguero: coarse sand;
- at ca 30 m in the direction of RT1.11 is a small channel/gully.

Augering	RT1.11
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{8}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	floodplain 2.75 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.20	Ah, brown (few organic matter), sandy loam, smeary;
2	0.20-0.30	C, greyish brown, loamy medium sand, mod.sorted, gleymottling, slightly thixotropic;
3	0.30-1.50	C, brown, coarse sand, well sorted;
4	1.50-2.00	C, darkgrey/brown, coarse sand with much fine pebbles;
5	>2.00	no further because of groundwater.

Remarks:
- looks very much the same as floodplain 2.25;
- groundwater in layer 4.

Augering	RT1.12
Coordinates	N = $^{2}57^{5}$, E = $^{5}62^{8}$
Distance to former point (m)	65
Landuse	cattle/pasture
Geomorphological feature	floodplain 1.5 or 2 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.60	Ah (0-0.10), brown (few organic matter), sandy (medium) loam, smeary; BC (0.10-0.80), brown, loamy medium sand (less loamy in the lower part), mod./fairly sorted, thixotropic; C (0.80-1.60), grey, loamy medium sand, mod.sorted, thixotropic;
2	>1.60	gravel.

Remarks:
- at 10 m in the direction of RT1.11 is the floodplain edge.

Augering	RT1.13
Coordinates	N = $^{2}57^{5}$, E = $^{5}62^{8}$
Distance to former point (m)	60
Landuse	swamp/market-gardening, flowers (Ginger)
Geomorphological feature	old riverbed of Río Tortuguero in floodplain 1.5 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.00	Ah (0-0.10), greyish brown (few organic matter), gleymottling, thixotropic; C (0.10-1.00), darkgrey (few organic matter), loamy medium sand, poorly sorted, unripened;
2	1.00-1.10	C, brown/black/grey (dirty), loamy medium sand, with organic matter (peat);
3	1.10-1.50	C, darkgrey, very coarse sand (MED 1400 mu) with fine pebbles, well sorted;
4	1.50-1.55	C, darkgrey, loamy coarse sand with fine pebbles, mod.sorted;
5	1.55-2.00	C, darkgrey, fine/../very coarse pebbles, fairly well sorted;
6	>2.00	gravel.

Samples: RT1.13.1, RT1.13.C14, RT1.13.3; all taken by auger, sample RT1.13.1 is slightly affected by insects, for more info see description.

Remarks:
- deposits are stratified;
- groundwater is near groundlevel and at the surface shallow drains (depth and width: 0.20-0.30 m) have been dug.

Augering	RT1.14
Coordinates	N = $^{2}57^{5}$, E = $^{5}62^{7}$
Distance to former point (m)	20
Landuse	market-gardening, flowers (Ginger)
Geomorphological feature	natural levee of old riverbed of Río Tortuguero

Layer (no.)	Thickness (m-gl)	Description
1	0-1.50	Ah (0-0.25), darkbrown, loamy medium sand, thixotropic; Bw (0.25-1.00), brown, loamy medium sand, fairly sorted, thixotropic; C (1.00-1.50), brown, medium sand, fairly well sorted;
2	1.50-2.00	C, lightbrown to grey in the lower part, loamy medium sand (less loamy in the lower part), mod./fairly sorted;
3	>2.00	gravel.

Augering	RT1.15
Coordinates	N = $^{2}57^{6}$, E = $^{5}62^{7}$
Distance to former point (m)	50
Landuse	market-gardening, flowers (Ginger)
Geomorphological feature	old point bar, same level as RT1.14

Layer (no.)	Thickness (m-gl)	Description
1	0-0.60	Ah (0-0.35), darkbrown, very loamy coarse sand, thixotropic/smeary; Bw (0.35-0.60), brown, loamy coarse sand, thixotropic;
2	0.60-1.60	buried soil (?): Bw (0.60-1.00), lightbrown, very loamy medium sand with fine pebbles, thixotropic/smeary, some remainders of organic matter (roots); C (1.00-1.60), red/grey (gleymottling), slightly loamy medium sand (decreasing loam content with depth);
3	>1.60	gravel.

Remarks:
- other explanation: layer 2 could also be an old deposit;
- groundwater at approximately 1.50 m.

Augering	RT1.16
Coordinates	N = $^{2}57^{6}$, E = $^{5}62^{7}$
Distance to former point (m)	50
Landuse	market-gardening, flowers (Ginger)
Geomorphological feature	edge of old point bar, same level as RT1.15 but slightly sloping down

Layer (no.)	Thickness (m-gl)	Description
1	0-0.70	Ah (0-0.20), darkbrown, sandy (medium), loam, smeary; Bw (0.20-0.70), brown, loamy medium sand, thixotropic;
2	0.70-1.50	C, greyish brown, loamy medium sand, mod. sorted, gleymottling;
3	>1.50	gravel.

Remarks:
- groundwater at approximately 0.80 m;
- layer 2 could be the C-horizon of layer 1, but I expect it is another deposit.

Augering	RT1.17
Coordinates	N = $^{2}57^{7}$, E = $^{5}62^{6}$
Distance to former point (m)	20
Landuse	market-gardening, flowers (Ginger)
Geomorphological feature	old point bar, lower level than RT1.16

Layer (no.)	Thickness (m-gl)	Description
1	0-0.60	AC (0-0.30), red/grey (gleymottling), loam with very few medium sand, very smeary; C (0.30-0.60), grey, silty loam with very few medium sand, smeary, some organic matter (smells like manure);
2	0.60-0.90	C, grey, loamy medium sand with some fine pebbles, fairly sorted, very wet;
3	>0.90	gravel.

Remarks:
- inbetween RT1.16 and RT1.17, at a distance of 8 m to RT1.16 a gully/channel of a point bar occurs;
- very wet spot, comparable with RT1.13;
- this level is younger than level RT1.16.

Augering	RT1.18
Coordinates	N = $^{2}57^{7}$, E = $^{5}62^{6}$
Distance to former point (m)	20
Landuse	swamp/reed
Geomorphological feature	old channel of Río Tortuguero, same level as RT1.13

Layer (no.)	Thickness (m-gl)	Description
1	0-0.40	C, brown (dirty), peaty layer with loamy medium sand;
2	0.40-1.65	C, grey, coarse sand with loamy unripened interlayers (stratified), well sorted;
3	>1.65	gravel.

Remarks:
- an absolute channel deposit with the old riverbed at 1.65 m.

Augering	RT1.19
Coordinates	N = $^{2}57^{7}$, E = $^{5}62^{5}$
Distance to former point (m)	30
Landuse	cattle/pasture
Geomorphological feature	old channel, same level as point bar of RT1.14 en RT1.15

Layer (no.)	Thickness (m-gl)	Description
1	0-0.80	Ah (0-0.20), darkbrown, sandy (medium) loam, glmott., smeary; BC/C (0.20-0.80), lightbrown, silty/sandy (v. fine) loam, very smeary, some glmott., in upper part some soil development;
2	0.80-1.30	C, stratified layer of mod.sorted loamy medium sand with some very fine pebbles, and of silty clay loam with some medium sand, gleymottling, smeary;
3	>1.30	gravel.

Remarks:
- old channel deposit, probably an older channel than RT1.18 and a better drainage (less wet); no organic matter or peat;
- dist. to gully (between RT1.18 and RT1.19) from RT1.19 = 15 m.

Augering	RT1.20
Coordinates	N = $^{2}57^{8}$, E = $^{5}62^{5}$
Distance to former point (m)	45
Landuse	cattle/pasture
Geomorphological feature	small alluvial fan (see remarks)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.90	
2	0.90-1.45	
3	1.45-1.55	
4	1.55-1.90	
5	1.90-2.00	very coarse sand;
6	>2.00	gravel.

Samples: RT1.20.C14; by auger, for more info see description.

Remarks:
- this is a small alluvial fan of a gully that has made an incision into the level of RT1.21; this fan could have made Río Tortuguero change its course by damming its (ancient) channel (the channel of RT1.19), or else it could be a cut-off meander.

Augering	RT1.21
Coordinates	N = $^{2}57^{8}$, E = $^{5}62^{4}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	highest floodplain at this side of Río Tortuguero (see remarks)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.90	Ah [illegible] dium) loam, smea[illegible] dium sand, fair[illegible] ghtly loamy medi[illegible] rted;
2	1.90-2.30	C, [illegible] layer of mod. [illegible] sand/sandy clay loam, gleymottling, a few concretions (ironoxides);
3	2.30-3.10	C, [illegible], stratified (?) layer of [illegible] medium sand (largest part[illegible]
4	3.10-3.50	C, [illegible] (gleymottling), sandy (fi[illegible] ary;
5	3.50-3.60	C, [illegible] very rusty), coarse sand with[illegible]
6	>3.60	gravel.

Samples: RT1.21.3 (loamy medium sand), RT1.21.4; by auger, for more info see description.

Remarks:
- possible explanation (comparable to RT1.1/1.2/1.3): layer 1 is a sheetflood deposit; layer 2, 3 and 4 are natural levee deposits; layer 5 and 6 are riverbed deposits;
- other parts at this side of Río Tortuguero seem to be slightly higher.

Augering	RT1.3½
Coordinates	N = $^{2}57^{2}$, E = $^{5}62^{9}$
Distance to RT1.3 (m)	15
Landuse	cattle/pasture
Geomorphological feature	edge of floodplain 1.5 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.90	Ah (0-0.20), darkbrown, loam, smeary; Bw (0.20-0.90), brown, loamy med.sand, thix.;
2	0.90-1.50	buried soil (?): Bw (0.90-1.30), brown, loamy fine sand, thixotropic; C (1.30-1.50), grey, medium sand, gleymottling;
3	1.50-1.70	C, white/grey/brown, loamy clay (heavy), hardly any sand, gleymottling (Fe and Mn) and small pipes of rust, very smeary;
4	1.70-1.90	C, brown/grey, coarse sand with fine pebbles, fairly well sorted;
5	1.90-2.10	C, brown/red, coarse sand with much coarse pebbles (rounded);
6	2.10-2.20	C, gleymottling color, coarse sand with very fine/fine pebbles, poorly sorted;
7	>2.20	gravel.

Remarks:
- layer 2 is a buried soil or just another deposit with no soil development (hard to see);
- extra augering.

Augering	RT1.10½
Coordinates	N = $^{2}57^{4}$, E = $^{5}62^{9}$
Distance to former point (m)	30 (perpendicular to RT1.9)
Landuse	cattle/pasture
Geomorphological feature	floodplain 2.25 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.25	Ah (0-0.10), slht.loamy coarse sand with quite a few very coarse pebbles; C (0.10-0.25), ›arse sand (MED 1000 ıbbles, well sorted;
2	0.25-0.30	fairly well sorted;
3	0.30-0.80	h increas.med.pebbles in lower part), well
4	>0.80	gravel.

Samples: RT1.10½.1; by auger, for more info see description.

Remarks:
- extra augering;
- so far six floodplain levels can be found.

Augering	RT1.11½
Coordinates	N = $^{2}57^{5}$, E = $^{5}62^{8}$
Distance to former point (m)	50 (RT1.11)
Landuse	cattle/pasture
Geomorphological feature	old gully/channel in floodplain 1.5 or 2 (?)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.90	Ah (0-0.30), darkbrown, sandy (medium) loam, : compacted by cattle and trucks feels granular; Bw (0.30-0.55), sandy (medium) loam, smeary; C greyish brown, loamy medium sand, poorly sorted, slightly
2	0.90-1.60	rown, medium sand (MED 300 mu), orted;
3	1.60-2.00	coarse sand with fine/../coarse /fairly sorted;
4	>2.00	

Samples: RT1.11½.2; by hand, for more info see description.

Remarks:
- between layer 2 and 3 is a transitional rustlayer, which forms when the riverregime changes or when the river changes its course.

CROSS SECTION RIO TORTUGUERO 2 - JUNE 1991

Augering	RT2.1
Coordinates	N = $^{2}71^{2}$, E = $^{5}76^{8}$
Distance to Río Tortug. (m)	0.5
Landuse	cattle/pasture
Geomorphological feature	natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.20	Ah (0-0.05), darkbrown, loam with some fine sand, smeary, many roots; Bw (0.05-0.20), lightbrown, sandy (fine) loam, smeary;
2	0.20-0.22	C, lightbrown, medium sand (rounded), well sorted, crevasse (?);
3	0.22-0.26	C, lightbrown, loamy medium sand, some gleymottling;
4	0.26-0.28	C, lightbrown, medium sand (rounded), well sorted, crevasse (?);
5	0.28-0.45	C, lightbrown, loamy fine sand, gleymottling, slightly thixotropic;
6	0.45-0.48	C, grey/brown, medium sand (rounded), well sorted, crevasse (?);
7	0.48-0.68	C, alternating layers of lightbrown loamy medium sand with some gleymottling, and of greyish brown loamy fine sand;
8	0.68-0.82	C, red/grey (gleymott.), sandy (v. fine) loam;
9	0.82-1.38	B/C (?), lightbrown, sandy (fine) loam with decreasing sand content in the lower part, smeary, charcoal;
10	1.38-2.10	C, lightbrown/grey, slightly loamy medium sand, well sorted, still roots;
11	2.10-2.13	C, grey, slightly loamy medium sand, well sorted;
12	2.13-2.20	C, grey, loamy fine sand, fairly sorted;
13	2.20-2.50	C, lightbrown, loamy medium sand, mod.fairly sorted;
14	2.50-2.70	C, lightbrown, slightly loamy medium sand, well sorted;
15	2.70-2.80	C, lightbrown, loamy medium sand, gleymottling;
16	2.80-3.05	C, blueish grey, sandy (fine) loam, some rust, smeary;
17	3.05-3.20	C, lightbrown, sandy (medium) loam;
18	3.20-3.25	C, blueish grey, sandy (very fine) loam, very smeary, unripened;
19	3.25-3.55	C, alternating brown/blue (more blue in the lower part), loamy medium sand, fairly sorted;
20	3.55-4.40	C, blueish grey, coarse/very coarse sand with some very fine pebbles, well sorted;
21	4.40-4.70	C, blueish grey, very coarse sand with much medium pebbles, well sorted;
22	>4.70	gravel.

<u>Samples</u>: RT2.1.10 (by hand), RT2.1.18 (by hydraulic auger); for more info see description.

<u>Remarks</u>:
- the first 1.5 m were described at a profile in an outside bend of Río Tortuguero, that is the reason why I could distinguish crevasse-splays; the next 3.2 m were described by augering;
- layer 2, 3, 4, 5, 6 and 7 is one stratified deposit;
- layer 9 might be a buried soil.

Augering	RT2.2
Coordinates	N = $^{2}71^{2}$, E = $^{5}76^{8}$
Distance to former point (m)	35
Landuse	cattle/pasture
Geomorphological feature	natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-1.20	Ah (0-0.05), darkbrown, loam with some fine sand, smeary; C1 (0.05-0.45), brown, silty loam, very smeary; C2 (0.45-1.20), brown, sandy (very fine) loam, some gleymottling, very smeary; AC and C with thin interlayers of medium sand;
2	1.20-1.35	C, lightbrown, sandy (fine) loam, some gleymottling, slightly smeary;
3	1.35-2.70	C, brown/grey, slightly loamy coarse to very coarse sand (MED 1000 mu) with thin interlayers of loam, fairly well sorted, stratified;
4	2.70-3.50	C, greyish blue/brown, very coarse sand, some very fine pebbles, fairly/well sorted, maybe old riverbed;
5	3.50-3.70	C, greyish blue/brown, very coarse sand with hardly any gravel, well sorted;
6	3.70-4.20	C, greyish blue/brown, very coarse sand with quite a few very fine pebbles, fairly/well sorted;
7	4.20-4.40	C, brown, very coarse sand, well sorted;
8	4.40-4.80	C, greyish blue/brown, very coarse sand with some very fine pebbles, well sorted.

<u>Samples</u>: RT2.2.3; by auger, for more info see description.

<u>Remarks</u>:
- 1C1 and 1C2 are fining-upward deposits with traces of soil development;
- layer 2 could also be the C-horizon of layer 1.

Augering	RT2.3
Coordinates	N = $^{2}71^{2}$, E = $^{5}76^{8}$
Distance to former point (m)	40
Landuse	cattle/pasture
Geomorphological feature	transition natural levee/backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.60	Ah (0-0.05), darkbrown, sandy (fine) loam, smeary; C1 (0.05-0.35), lightbrown, sandy (fine) loam; C2 (0.35-0.60), greyish brown (gleymottling), very loamy fine sand;
2	0.60-0.75	C, brownish grey, loamy medium sand, fairly well sorted;
3	0.75-1.60	C1 (0.75-1.30), lightbrown (yellowish), sandy (medium) loam, mod.sorted, very smeary; C2 (1.30-1.60), lightbrown (yellowish), loamy medium sand, mod.sorted, very smeary;
4	1.60-2.40	C, brown, medium sand with in the upper part a loamy interlayer and coarsening of the sand in the lower part, well sorted, stratified;
5	2.40-2.70	C, lightbrown/grey, coarse/very coarse sand with quite a few very fine pebbles (yellow, orange and red), well sorted.

<u>Remarks</u>:
- groundwater at ca 2 m;
- layer 3C1/C2 could also be part of a buried soil;
- too few water to go deeper with the hydraulic auger and too much water to go deeper with the "Edelman"-auger.

Augering	RT2.4
Coordinates	N = $^{2}71^{3}$, E = $^{5}76^{7}$
Distance to former point (m)	40
Landuse	cattle/pasture
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.70	Ah (0.0.05), darkbrown, sandy (fine) loam, smeary; C1 (0.05-0.35), lightbrown, sandy (fine) loam; C2 (0.35-0.70), greyish brown (gleymottling), very loamy fine sand;
2	0.70-1.45	C, red/grey (gleymottling), loam/silty clay loam with hardly any sand (in the lower part a slightly increasing medium sand content), fairly heavy;
3	1.45-2.00	C, lightbrown, sandy (medium) loam with interlayers of sandy (medium) clay loam at ca 1.80/1.90 m, in the lower part a slightly increasing medium sand content, smeary;
4	2.00-2.20	C, brownish grey, loamy medium sand with concretions, fairly sorted;
5	2.20-2.30	C, red/grey (gleymottling), sandy (fine) loam with concretions, smeary;
6	2.30-2.45	C, red/grey (gleymottling), sandy (fine) loam with many concretions (ϕ 2 cm), smeary;
7	2.45-2.70	C, red/grey (gleymottling), silty clay loam with concretions, very smeary;
8	2.70-2.80	C, lightbrown, sandy (medium) loam with concretions, very smeary;
9	2.80-4.50	C, blue, sandy (very fine) loam/silty clay loam with red concretions (ϕ 2 cm), unripened;
10	4.50-5.00	C, blue, silty clay loam, halfripened, some organic matter (maybe ^{14}C).

<u>Samples</u>: RT2.4.10; by auger, for more info see description.

<u>Remarks</u>:
- distance from RT2.3 to the other side of the road with verge: 18 m;
- groundwater within 1 m;
- real backswamp deposits;
- natural channel/gully at 2 m of RT2.4 in the direction of RT2.5.

Augering	RT2.5
Coordinates	N = $^{2}71^{3}$, E = $^{5}76^{7}$
Distance to former point (m)	40
Landuse	cattle/pasture
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.25	...oam, smeary; C (0.05- ...y (fine) loam/very ...orted, gleymottling,
2	0.25-0.60	... brown, loamy medium ... concretions, fairly ...C2 (0.35-0.60), idem ...r than C1;
3	0.60-1.10	...y loam with small ... very smeary;
4	1.10-2.80	... silty clay with many ...pened, very smeary;
5	2.80-3.20	... some fine sand, some ...y.

<u>Samples</u>: RT2.5.2-C2, RT2.5.4; by auger, RT2.5.4 is also used for clay mineralogy, for more info see description.

<u>Remarks</u>:
- we stopped at 3.20 m because it looked much like RT2.4.

Augering	RT2.6
Coordinates	N = $^{2}71^{3}$, E = $^{5}76^{7}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-1.50	Ah (0-0.03), greyish brown, silty clay with concretions (ϕ 0.5 cm), gleymottling, very smeary; C (0.03-1.50), greyish brown, silty clay with some fine sand and with concretions (ϕ 2 cm), gleymottling;
2	1.50-2.00	C, greyish brown, loamy medium sand, compact/dense, crevasse/old channel of RT/deposit of another river.

<u>Samples</u>: RT2.6.2; by auger, for more info see description.

<u>Remarks</u>:
- groundwater at the surface;
- too compact/dense to auger any further with an "Edelman"-auger and too few water to auger with an hydraulic auger.

Augering	RT2.7
Coordinates	N = $^{2}71^{4}$, E = $^{5}76^{6}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.20	C, red/grey (gleymottling), silty clay with some fine sand and with a few concretions (ϕ 0.5 cm), smeary;
2	0.20-0.30	C, greyish brown, loamy medium sand, fairly well sorted, gleymottling, crevasse;
3	0.30-0.50	C, red/grey (gleymottling), sandy (very fine)/silty loam with a few concretions (ϕ 0.5 cm), very smeary;
4	0.50-0.55	C, blue, loamy medium sand, well sorted, some rust, crevasse;
5	0.55-1.40	C, greyish brown, sandy (fine) clay loam with increasing sandcontent in the lower part and with concretions (ϕ 0.5 cm), gleymottling, smeary;
6	1.40-1.50	C, blue, sandy (fine) loam, hardly any rust, smeary;
7	1.50-2.20	C, red/grey (gleymottling), sandy (medium) clay loam with quite a few concretions (ϕ 1 cm), smeary;
8	2.20-2.40	C, blue, loamy fine sand, well sorted, charcoal;
9	2.40-2.80	C, blue, loam with some fine sand, charcoal.

<u>Remarks</u>:
- groundwater at the surface;
- this spot might be the backswamp of another river;
- we could not auger any further.

Augering	RT2.8
Coordinates	N = $^{2}71^{4}$, E = $^{5}76^{6}$
Distance to former point (m)	55
Landuse	cattle/pasture
Geomorphological feature	natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.15	Ah (0-0.05), darkbrown, loam with some medium sand, gleymottling, smeary; C (0.05-0.15), brown, loam with some medium sand, gleymottling, smeary;
2	0.15-0.35	C, brown, sandy (medium) loam/loamy medium sand with a sandy interlayer, fairly sorted, stratified;
3	0.35-0.80	C, brown, loamy fine sand, fairly well sorted, gleymottling;
4	0.80-1.50	C, red/grey (gleymottling), sandy clay loam with in the upper part a few small concretions (ϕ 0.4 cm) and in the lower part an increasing number of larger concretions (ϕ 2 cm), very smeary;
5	1.50-2.50	C, blue, loam with some fine sand and with quite a few concretions (ϕ 0.5 cm (0.4-2 cm)), unripened, some organic matter;
6	2.50-3.00	C, blue, loam with some medium sand, halfripened (some soil development), some organic matter.

Samples: RT2.8.3, RT2.8.4; by auger, for more info see description.

Remarks:
- natural levee of another river;
- this river could be an old channel of RT, although this river is not very wide compared to RT;
- layer 5 and 6 are probable backswamp deposits of RT;
- layer 5 contains an interlayer of (bright) lightblue clay and an interlayer of (dirty) blue clay (problably organic matter).

Augering	RT2.9
Coordinates	N = $^{2}71^{2}$, E = $^{5}76^{8}$
Distance to Río Tortug. (m)	8
Landuse	cattle/pasture
Geomorphological feature	natural levee at eastbank of RT (Atlantic side)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.20	AC (0-0.10), lightbrown, sandy (fine) loam, gleymottling, smeary; C (0.10-1.20), greyish brown, loamy fine sand with in the upper part a thin loam interlayer and at ca 1 m a thin interlayer of grey medium sand, fairly well sorted, stratified, slightly thixotropic;
2	1.20-1.35	C, red/grey (gleymottling), sandy (medium) loam/loamy medium sand, mod.sorted, thixotropic/smeary;
3	1.35-2.40	C, greyish brown, medium sand with in the upper part thin interlayers of loam, fairly well sorted, gleymottling and in the lower part more grey;
4	2.40-2.50	C, greyish brown/red, loamy medium sand, fairly well sorted;
5	2.50-2.60	C, greyish brown, slightly loamy medium sand, fairly well sorted;
6	2.60-2.85	C, greyish brown/red (gleymottling), loamy medium sand, fairly sorted;
7	2.85-3.00	C, blue, loam (in the upper part fine sandy), unripened, smeary, organic matter, channel deposit ("beekbezinksel");
8	3.00-3.65	C, blueish grey, very coarse sand with some very fine pebbles, well sorted;
9	3.65-3.70	C, blue, sandy (fine) loam with on top a thin red sand interlayer, unripened;
10	3.70-4.20	C, red (3.70-3.85)/blueish grey (3.85-4.20), very coarse sand with some very fine pebbles, well sorted.

Samples: RT2.9.C14; by auger, for more info see description.

Remarks:
- layer 8, 9 and 10 is probably one stratified layer;
- this bank lies probably a bit lower than the westbank.

Augering	RT2.10
Coordinates	N = $^{2}71^{2}$, E = $^{5}76^{8}$
Distance to former point (m)	35
Landuse	cattle/pasture
Geomorphological feature	natural levee (sloping)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.60	Ah (0-0.05), darkbrown, loam (heavy), gleymottling, very smeary; C1 (0.05-0.50), lightbrown, sandy (fine) loam, some gleymottling; C2 (0.50-0.60), lightgrey/brown, very loamy fine sand, fairly sorted, some gleymottling, thixotropic/smeary;
2	0.60-0.80	C, lightbrown, loam, very smeary;
3	0.80-2.00	buried soil: Ah (0.80-1.30), darkbrown, loamy coarse sand, feels granular, gleymottling, thixotropic; C (1.30-2.00), greyish brown, slightly loamy coarse sand, fairly well sorted, possibly some weathering, a loamy interlayer occurs at transition Ah/C;
4	2.00-4.50	C, grey/brown, coarse sand (MED 600 mu) with some very fine pebbles, well sorted;
5	4.50-4.80	C, very coarse sand with much very fine to medium pebbles, well sorted.

Samples: RT2.10.1-C1, RT2.10.4; by auger, for more info see description.

Remarks:
- layer 1 and 2 [illegible] d deposits of the current, small, Río Tortuguero [illegible] ning-upward deposits, with in the upper part soi[illegible] an older and, probably, broader RT; layer 1 ar[illegible] infillings of the current RT in an older and [illegible] of RT; thus at this point river other floodpla[illegible] occur anymore.

Augering	RT2.11
Coordinates	N = $^{2}71^{1}$, E = $^{5}76^{9}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	natural levee (sloping)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.35	Ah (0-0.05), darkbrown, loam (heavy), very smeary; C (0.05-0.35), yellowish brown, loam, very smeary;
2	0.35-0.40	C, grey, slightly loamy fine sand, fairly well sorted, crevasse;
3	0.40-0.60	C, lightgrey/brown, loam, gleymottling, very smeary;
4	0.60-2.30	buried soil: Ah (0.60-1.00), darkbrown (dirty), loamy coarse sand, thixotropic; C (1.00-2.30), greyish brown (dirty), coarse sand, in the upper part slightly loamy and with some very fine pebbles, a loamy interlayer occurs at transition Ah/C;
5	2.30-2.50	C, greyish brown, very coarse sand with quite a few very fine to medium pebbles.

Samples: RT2.11.3; by auger, for more info see description.

Remarks:
- groundwater at ca 0.8 m;
- RT2.11 resembles RT2.10;

Augering	RT2.12
Coordinates	N = $^{2}71^{1}$, E = $^{5}76^{9}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	transition natural levee/backswamp (sloping)

Layer (no.)	Thickness (m-gl)	Description
1	0-1.50	Ah (0-0.10), darkbrown, loam (heavy), smeary; C1 (0.10-0.90), brown, loam with slgh.increas. sand cont. in the lower part, glmott, very smeary, pieces of org.matter (?); C2 (0.90-1.50), lgtbrown/grey, loamy medium sand with loamy interlrs.(strat.), frly sorted, glmott.;
2	1.50-1.90	C, grey/brown, slightly loamy medium sand, fairly well sorted, gleymottling;
3	1.90-2.30	C, grey, sl.lm.fine sand, well sort., gl.mott;
4	2.30-2.60	C, grey/brown, medium sand, well sort., some glmott.;
5	2.60-3.00	C, br.grey, loamy med. sand, fairly sorted.

Samples: RT2.12.3; by auger, for more info see description.

Remarks:
- it seems a bit strange that no buried soil occurs at this spot when comparing this augering to RT2.11 and RT2.10; it could be that part of an old Ah is hidden in 1C1.

Augering	RT2.13
Coordinates	N = $^{2}71^{0}$, E = $^{5}77^{0}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.20	Ah (0-0.10), darkbrown, clay loam, gleymottling, very smeary; C (0.10-0.20), grey/lightbrown, clay loam, very smeary, gleymottling;
2	0.20-0.75	C, greyish brown, loam, charcoal, some organic matter;
3	0.75-1.20	C1 (0.75-0.95), lightbrown, sandy (fine) loam, gleymottling, very smeary; C2 (0.95-1.20), lightbrown, loamy fine sand, fairly sorted, gleymottling;
4	1.20-1.50	C, lightgrey/brown, loamy medium sand, fairly sorted;
5	1.50-1.70	C, lightbrown, sandy (fine) loam with some concretions, gleymottling;
6	1.70-1.85	C, whitish grey/brown, silty clay loam, gleymottling, very smeary;
7	1.85-2.60	C, lightgrey/brown, alternating layers of sandy (fine) loam/very loamy fine sand (stratified), fairly well sorted, gleymottling;
8	2.60-3.00	C, blue, loamy very fine sand, well sorted;
9	3.00-4.30	C, blue, loam with some fine sand, in the lower part slightly heavier, unripened.

Remarks:
- layer 2 is a typical fining-upward deposit with traces of soil development;
- layer 9 contains an interlayer of (bright) lightblue clay and an interlayer of (dirty) blue clay (problably organic matter);
- photo of transition natural levee/backswamp.

Augering	RT2.14
Coordinates	N = $^{2}71^{0}$, E = $^{5}77^{0}$
Distance to former point (m)	50
Landuse	cattle/pasture
Geomorphological feature	backswamp (just before a swampo)

Layer (no.)	Thickness (m-gl)	Description
1	0-0.90	Ah (0-0.05), reddish brown ((fine) clay loam, gleymott organic matter; C (0.05-0. (dirty), sandy (fine) clay] some (fresh?) organic matter
2	0.20-0.90	C, darkgrey/brown (dirty), halfripened, gleymottling, very smeary, some (fresh?) organic matter, charcoal;
3	0.90-1.20	C, brownish grey, sandy (very fine) loam with interlayers/bands of clay (heavy), unripened, gleymottling, very smeary, stratified;
4	1.20-2.20	C, red/grey (gleymottling), loamy fine sand with interlayers of loam and of rust/sand (stratified), fairly well sorted;
5	2.20-3.00	C, blue, loamy very fine sand with interlayers/bands of (dirty) darkblue loamy sand (problably organic matter) and interlayers/bands of loam (stratified), unripened (?!), well sorted;
6	3.00-3.30	C, blue/grey, sandy (very fine) loam, unripened, possibly some organic matter;
7	3.30-3.60	C, lightblue with some darker bands, clay loam, halfripened, smeary.

Samples: RT2.14.5 (analysis nr RT2.14.4!); by hydraulic auger, for more info see description.

Remarks:
- 1C and 2C are typical fining-upward deposits with traces of soil development.

CROSS SECTION RIO MATINA 1 - AUGUST 1991

This cross section lies in an inner curve of Río Matina. It should be possible that in such a place occur point bars. I did not notice these point bars because my augerings were rather far apart (due to lack of time). The point bar system could be an explanation for the transition backswamp/natural levee, which, I think, is quite long/broad.

Augering	RM1.1
Coordinates	N = $^{2}32^{7}$, E = $^{6}18^{4}$
Landuse	banana plantation (young)
Geomorphological feature	backswamp

Layer (no.)	Thickness (m-gl)	Description
1	0-0.10	C, greyish brown, loamy fine sand, fairly sorted, very calcareous, stratified, 12-08-91 inundation mud;
2	0.10-0.55	buried soil: AC (0.10-0.15), darkbrown with gleymottling, clay loam with some fine sand, ripened, not calcareous; C (0.15-0.55), darkbrown with gleymottling, clay loam with some fine sand, ripened, slightly calcareous;
3	0.55-0.95	C, greyish blue with rust mottles, clay, many roots and small branches, ripened, well developed structure (angular blocky), slightly calcareous;
4	0.95-1.15	C, darkblue with rust mottles, heavy clay, compact/dense, ripened, hardly any structure development, very slightly calcareous;
5	1.15-1.55	C, brownish grey with gleymottling, clay, many roots and small branches, ripened, well developed structure (rounded angular blocky), slightly calcareous.

<u>Samples</u>: Mat^{14}C-ondiep (upper part), Mat^{14}C (upper part); taken by hand, for more info see description.

<u>Remarks</u>:
- these samples were taken at a side of a ditch;
- only recent this plantation has a better drainage;
- Mat^{14}C-ondiep and Mat^{14}C have not been used for ^{14}C-dating.

Augering	RM1.2
Coordinates	N = $^{2}32^{6}$, E = $^{6}18^{4}$
Distance to former point	133 m
Landuse	banana plantation (young)
Geomorphological feature	transition backswamp/natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.10	C, greyish brown, loamy fine sand, fairly well sorted, very calcareous, stratified, 12-08-91 inundation mud;
2	0.10-0.35	AC, darkbrown/grey with rust mottles, heavy clay, ripened, not calcareous;
3	0.35-0.50	C, sandy (fine) clay loam, brownish grey with rust mottles, ripened, slightly calcareous;
4	0.50-1.60	C, loamy clay, brownish grey with rust mottles, ripened, slightly calcareous.

<u>Remarks</u>:
- in a ditch.

Augering	RM1.3
Coordinates	N = $^{2}32^{5}$, E = $^{6}18^{4}$
Distance to former point	100 m
Landuse	banana plantation
Geomorphological feature	transition backswamp/natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.10	C, greyish brown, slightly loamy fine sand, fairly well sorted, very calcareous, stratified, 12-08-91 inundation mud;
2	0.10-0.35	AC, darkbrown/grey with rust mottles, heavy clay with some sand, ripened, slightly calcareous;
3	0.35-0.50	C, sandy (fine) clay loam, brownish grey with rust mottles, ripened, slightly calcareous;
4	0.50-1.60	C, loamy clay, brownish grey with rust mottles, ripened, slightly calcareous.

<u>Remarks</u>:
- in a ditch;
- slightly better soil development than RM1.2.

==
Augering	RM1.4
Coordinates	$N = {}^{2}32^{3}$, $E = {}^{6}18^{3}$
Distance to former point	135 m
Landuse	banana plantation
Geomorphological feature	natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.05	C, greyish brown, loamy fine sand, fairly sorted, stratified, very calcareous, 12-08-91 inundation mud;
2	0.05-0.90	Ah (0.05-0.20), brown with rust mottles, sandy loam; C1 (0.20-0.55), brownish grey with rust mottles, sandy loam/sandy clay loam, slightly calcareous; C2 (0.55-0.90), grey with rust mottles, sandy loam/sandy clay loam, slightly calcareous;
3	0.90-1.40	C, layers (ca 0.03 m) of grey, well sorted, medium sand and layers (ca 0.06 m) of grey with rust mottles, loamy sand, crevasse dep.;
4	1.40-1.60	C, grey with rust mottles, loamy medium sand, mod.sorted, slightly calcareous.

Remarks:
- several very thin (ca 0.01 m) crevasse splays occur in the lowest part of layer 2;
- 2C1 is probably the product of natural sedimentation and some soil development.

==
Augering	RM1.5
Coordinates	$N = {}^{2}32^{2}$, $E = {}^{6}18^{2}$
Distance to former point	140 m
Landuse	banana plantation
Geomorphological feature	natural levee

Layer (no.)	Thickness (m-gl)	Description
1	0-0.05	C, greyish brown, loamy fine sand, fairly sorted, very calcareous, stratified, 12-08-91 inundation mud;
2	0.05-0.65	C, darkgrey/brown with rust mottles, clay loam, slightly calcareous;
3	0.65-1.15	C, grey with rust mottles, clay loam, slightly calcareous, charcoal;
4	1.15-1.60	C, greyish brown with rust mottles, sandy loam (heavy), slightly calc., thin (0.01-0.02 m) calc. sand interlayers (=crevasse deposit).

Remarks:
- fining-upward deposit: both soil forming processes and natural sedimentation; 2C is probably the product of these processes;
- 1A-hor. has probably been removed with plantation activities.

APPENDIX E: Airphotos

<u>Toro Amarillo-Tortuguero system</u>

Project	CRAC - Petrolera Limón
Date	24-04-1952
Scale/actual scale	1:40,000/1:48,984.2
Flying height	20,000 ?
Series	R83
Lines and numbers*	18: 646-<u>647</u>-648 19: 619-<u>620</u>-621-<u>622</u>-623-<u>624</u>-625-<u>626</u>-627-<u>628</u>-629-<u>632</u>

* underlined numbers are photos used to draw the geomorphologic maps

Project	Actualización Zona Atlántica
Date	17-03-1981
Scale/actual scale	1:35,000/1:37,437.8
Series	R177
Lines and numbers	248: 24865-<u>24866</u>-24867 254: 24897-<u>24898</u>-24899-<u>24900</u> 260.6: 24907-<u>24908</u>-24909-<u>24910</u> 266.5: <u>24930</u>-24931 272: 24953-<u>24954</u>-24955-<u>24956</u>-24957-<u>24958</u>-24959

Project	CRIRC/BID
Date	20-04-1984
Scale	1:80,000
Camera	SAG II 2087, f=88,19
Flying height	7360.9 metros
Series	R4
Line and numbers	17-E: 85-86-87-88

<u>Chirripó-Matina system</u>

Project	CRAC - Petrolera Limón
Date	17-03-1952
Scale/actual scale	1:40,000/1:48,984.2
Flying height	20,000 ?
Series	R84
Line and numbers	15: 25-<u>26</u>-27-<u>28</u>-29-<u>30</u>-31

Project	Actualización Hoja Matina
Date	18-01-1985
Scale/actual scale	1:50,000/1:56,000
Camera	Wild RC9, f=88.35
Series	R222
Line and numbers	222: 36420-<u>36421</u>-36422 230: 36376-<u>36377</u>-36378

Project	CRIRC/BID
Date	20-04-1984
Scale	1:80,000
Camera	SAG II 2087, f=88,19
Flying height	7360.9 metros
Series	R4
Line and numbers	15-O: 93-94-95

APPENDIX F: Particle size distribution of all samples

Sample	Particle size class (µm) in weight %						MED[a]
	<53	53-250	250-500	500-1000	1000-2000	>2000	(µm)
RTA-1	1.5	31.3	40.4	23.2	3.2	0.4	357
RTA-2	3.5	54.5	28.2	12.0	1.5	0.2	221
RTA-3	0.3	7.0	14.8	32.7	33.0	12.1	926
RTA-4[b]	-	-	-	-	-	-	25
RTA-N1	8.2	81.0	10.3	0.5	0.0	0.0	155
RTA-N2	23.6	75.1	1.3	0.0	0.0	0.0	122
RTA-N3	0.7	20.8	43.7	29.0	4.5	1.2	413
RTA-N4	0.2	14.5	34.6	36.5	12.2	2.0	509
RTA-N5	67.6	30.4	2.0	0.0	0.0	0.0	39
RT1-9.0	5.7	91.5	2.8	0.0	0.0	0.0	148
RT1-10.0	0.1	4.1	30.4	40.1	15.9	9.3	691
RT2-0.1	0.3	4.9	25.9	56.2	10.5	2.3	669
RT2-0.2	0.0	0.4	6.2	44.6	30.6	18.2	987
RT2-0.3[b]	-	-	-	-	-	-	25
RT2-0.4	0.2	32.3	50.9	13.0	3.4	0.2	336
RT2-0.5	0.1	1.0	25.2	61.9	10.8	1.0	691
Su-1	0.0	0.1	0.8	33.2	63.0	2.8	1251
Su-2	0.1	6.6	65.1	25.2	2.8	0.2	416
Su-3	5.5	79.8	11.9	2.8	0.0	0.0	163
Su-4	85.9	14.1	0.0	0.0	0.0	0.0	31
RChM-1.1[b]	-	-	-	-	-	-	25
RChM-1.2	0.2	19.9	58.2	21.1	0.6	0.0	378
RChM-1.3[b]	-	-	-	-	-	-	150
RChM-1.4[b]	-	-	-	-	-	-	25
RChM-1.5	0.2	11.3	34.5	46.6	7.3	0.1	543
RChM-1.6[b]	-	-	-	-	-	-	25
RChM-X1[b]	-	-	-	-	-	-	25
RChM-X2	1.7	66.2	23.4	8.3	0.4	0.0	197
RChM-X3	2.1	26.4	38.5	31.0	2.0	0.0	390
RChM-X4	23.6	75.1	1.0	0.4	0.0	0.0	122
RChM-XX	3.2	16.7	34.6	34.6	7.9	2.9	467
RCh-N1	0.5	10.4	21.5	45.0	15.5	7.1	696
RCh-N2	3.7	50.0	23.9	16.0	5.4	1.0	235
RCh-N3	13.0	78.7	6.5	1.5	0.3	0.0	146
RCh-N4	5.5	83.5	10.9	0.1	0.0	0.0	158
RCh-N5	35.5	64.2	0.1	0.1	0.0	0.0	97
RCh-N6[b]	-	-	-	-	-	-	25
Zent-1	0.8	10.8	26.0	52.3	7.6	2.5	619
Zent-2	0.4	3.8	13.2	39.4	25.3	18.0	914
Zent-3	0.1	2.5	36.6	54.7	5.7	0.4	599
Z-1	0.4	8.0	34.2	35.2	11.2	11.1	605
Z-2	4.7	57.8	27.9	8.3	1.3	0.0	207
Barb-1	1.0	36.4	50.0	12.4	0.2	0.0	313
Barb-2	5.1	76.3	18.0	0.5	0.0	0.0	169
Barb-3	1.0	36.2	45.7	15.5	1.5	0.2	320
Rev-1	0.5	25.8	51.4	22.1	0.2	0.0	365
Rev-2	0.5	6.9	58.8	33.5	0.3	0.0	431
Rev-3	0.4	65.9	33.6	0.1	0.0	0.0	201
Rev-4	0.6	78.5	17.0	3.9	0.1	0.0	177

[a] MED = median of grain size, based on the weight % of each part.size class

[b] RTA-4, RT2-0.3, RChM-1.1/1.3/1.4/1.6/X1 and RCh-N6 were not sieved, but were estimated in the field.

Remark:
particle size distr. of the suspended load samples (A-1/14/25) was not determined.

APPENDIX G: Bulk chemical composition of all samples

Su = Sucio, RChM = Chirripó-Matina, RCh = Chirripó Atlántico, Barb = Barbilla, Rev = Reventazón, A-no = suspended load, Z-no = Zent or Ch.Atl.; LOI accounted for.

Sample	Major elements (wt%)										Trace elements (ppm)											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ba	Cr	Cu	Ga	Nb	Ni	Pb	Rb	Sr	V	Zn	Zr
RTA-1	58.71	1.21	17.47	7.44	0.11	3.61	6.20	2.86	2.03	0.35	677	69	56	16	13	39	13	50	840	178	47	212
RTA-2	58.58	1.26	17.79	8.41	0.11	3.49	5.69	2.51	1.82	0.34	711	73	58	17	10	30	19	34	817	191	47	201
RTA-3	58.99	1.35	16.50	8.11	0.12	3.95	5.74	2.76	2.10	0.38	632	78	49	15	14	34	14	52	756	198	53	219
RTA-4	60.17	1.41	19.76	8.90	0.05	2.56	3.18	1.76	1.77	0.44	729	72	67	17	13	16	22	41	744	202	29	217
RTA-N1	57.77	1.07	17.61	7.30	0.11	3.99	6.91	3.03	1.88	0.32	666	78	58	15	12	35	13	36	886	164	39	197
RTA-N2	56.94	1.18	17.42	8.11	0.11	3.99	7.13	2.99	1.78	0.36	674	101	63	16	12	35	25	39	895	176	41	203
RTA-N3	57.96	1.28	16.32	8.24	0.12	4.57	6.44	2.84	1.90	0.33	593	95	49	15	12	40	16	47	793	198	48	204
RTA-N4	58.97	1.22	16.94	7.50	0.10	3.94	6.07	2.91	2.03	0.33	605	79	47	15	11	35	16	42	798	177	40	218
RTA-N5	58.13	1.15	19.03	7.41	0.12	3.04	5.86	2.69	1.98	0.38	735	69	89	16	11	31	18	47	839	159	37	215
A-1	56.68	1.24	20.18	10.32	0.17	2.60	4.49	2.08	1.73	0.50	700	92	239	17	11	50	36	28	690	183	253	204
RT1-9.0	58.38	1.24	19.92	7.51	0.09	3.17	5.23	2.51	1.63	0.31	615	96	56	18	11	32	15	38	806	175	54	207
RT1-10.0	59.26	1.27	17.15	7.80	0.11	3.68	5.49	2.81	2.10	0.34	682	85	45	19	16	34	15	51	766	184	50	234
RT2-0.1	57.00	1.71	15.35	10.47	0.15	4.59	5.75	2.66	2.00	0.32	585	130	34	15	12	44	13	41	672	288	71	218
RT2-0.2	59.88	1.23	16.43	7.56	0.12	3.39	5.48	3.06	2.49	0.36	705	79	34	16	14	34	16	65	746	178	45	243
RT2-0.3	57.85	1.39	21.34	8.60	0.13	2.40	4.01	2.14	1.70	0.45	709	87	81	18	13	35	18	40	702	186	54	226
RT2-0.4	37.80	5.65	7.01	32.06	0.31	9.49	5.89	0.85	0.55	0.39	50	400	35	17	13	126	11	18	238	1000	258	160
RT2-0.5	60.20	1.16	16.67	7.29	0.13	3.40	5.51	2.98	2.32	0.34	694	70	35	15	15	29	14	57	760	164	39	228
RT2-5.4	59.24	1.59	22.16	10.34	0.14	2.02	1.48	0.91	1.69	0.43	769	99	114	21	17	36	24	41	516	231	47	252
A-25	55.60	1.47	23.61	10.10	0.28	1.94	3.08	1.67	1.57	0.69	761	75	124	18	15	40	33	29	546	192	281	226
Su-1	63.19	1.20	16.68	6.62	0.08	2.55	3.93	2.78	2.45	0.32	736	52	53	16	15	24	18	64	692	172	95	255
Su-2	60.50	1.20	16.32	7.64	0.10	4.05	5.20	2.66	2.01	0.31	630	73	48	16	13	26	18	56	722	185	40	220
Su-3	58.25	1.22	17.40	8.76	0.11	3.97	5.69	2.52	1.74	0.34	700	79	70	16	18	31	17	48	790	185	52	199
Su-4	55.27	1.42	21.47	10.50	0.19	2.68	3.97	2.15	1.87	0.48	816	68	115	18	15	21	23	35	631	197	48	234
RChM-1.1	59.35	1.05	18.15	9.08	0.17	3.99	4.59	2.24	1.19	0.19	328	81	63	15	10	21	10	20	390	162	53	110
RChM-1.2	60.60	0.98	16.57	8.25	0.12	3.48	5.31	3.08	1.40	0.21	414	59	48	13	15	12	14	25	423	161	51	110
RChM-1.3	59.07	1.12	16.53	9.40	0.15	4.27	5.32	2.83	1.12	0.19	282	104	67	15	10	21	11	21	354	186	51	92
RChM-1.4	59.45	1.07	18.44	9.50	0.26	3.62	4.14	2.04	1.23	0.25	351	51	77	13	14	19	12	23	368	160	60	120
RChM-1.5	58.97	1.21	15.89	9.78	0.13	3.69	5.76	3.04	1.31	0.21	367	78	44	13	12	14	13	18	397	199	61	106
RChM-1.6	60.32	1.12	19.32	9.56	0.20	3.44	2.75	1.88	1.23	0.19	432	71	63	15	14	23	17	15	323	174	61	120
RChM-X1	59.78	1.10	17.57	9.36	0.24	3.65	5.21	1.50	1.35	0.24	456	57	59	15	14	20	14	19	392	158	65	137
RChM-X2	58.07	1.05	16.55	9.54	0.15	4.91	5.87	2.53	1.15	0.18	283	130	61	12	12	29	11	19	355	175	49	98
RChM-X3	57.62	1.13	16.79	9.90	0.15	4.70	5.79	2.59	1.15	0.20	274	103	67	14	10	23	13	14	354	192	50	92
RChM-X4	58.19	0.98	17.27	9.03	0.15	4.92	5.65	2.49	1.16	0.17	296	119	63	14	13	32	11	22	369	161	45	94
RChM-XX	60.27	1.43	16.32	10.77	0.14	3.87	3.38	2.29	1.28	0.24	327	98	66	14	11	22	14	20	356	242	71	106
RCh-N1	59.90	0.98	16.25	8.65	0.14	3.93	5.66	3.02	1.25	0.22	314	65	47	14	13	18	10	20	379	157	48	107
RCh-N2	58.74	1.11	15.82	9.28	0.15	4.49	6.22	2.78	1.21	0.20	289	118	51	15	10	23	10	14	383	183	49	102
RCh-N3	57.76	1.33	15.35	10.39	0.15	4.79	6.40	2.59	1.07	0.19	245	186	58	11	12	28	10	11	329	231	59	108
RCh-N4	56.74	1.47	15.19	11.13	0.16	4.87	6.61	2.60	1.04	0.19	208	205	54	14	11	28	10	10	323	263	64	104
RCh-N5	60.77	1.05	16.57	8.92	0.19	3.71	4.81	2.50	1.25	0.22	369	66	50	13	16	17	12	23	394	164	55	133
RCh-N6	60.87	1.21	18.04	9.86	0.35	3.22	3.11	1.62	1.45	0.25	448	34	48	15	22	12	14	15	368	167	77	189
A-14	54.70	0.89	18.92	10.11	0.16	6.75	5.02	2.04	1.20	0.21	303	112	89	12	10	53	10	14	309	149	53	79
Zent-1	57.63	0.95	14.29	9.35	0.12	6.45	8.05	1.69	1.26	0.22	322	393	29	11	10	47	16	16	312	160	43	96
Zent-2	58.35	1.11	14.88	9.61	0.12	5.61	6.86	1.82	1.38	0.26	435	342	38	12	12	45	15	23	393	179	54	116
Zent-3	54.99	0.71	13.12	8.67	0.13	9.12	10.54	1.69	0.90	0.15	208	400	38	10	10	70	10	13	229	132	23	62
Z-1	60.24	1.06	16.14	9.20	0.13	4.12	4.69	2.78	1.41	0.23	395	102	53	13	13	20	12	24	361	177	50	100
Z-2	61.24	1.10	16.76	8.72	0.10	3.62	4.35	2.58	1.36	0.18	386	109	51	14	10	21	13	27	392	177	56	113
Barb-1	60.58	1.14	15.49	8.69	0.21	3.69	5.78	2.48	1.32	0.21	383	104	41	11	12	27	14	22	408	174	55	121
Barb-2	60.00	1.42	14.36	9.76	0.22	3.87	6.03	2.77	1.37	0.21	384	141	48	12	11	22	13	12	351	238	71	126
Barb-3	60.61	1.13	15.56	8.93	0.21	3.93	5.60	2.48	1.32	0.22	420	100	37	12	13	29	12	17	407	177	58	121
Rev-1	51.14	2.22	14.63	15.75	0.17	4.62	7.82	2.12	1.25	0.29	391	202	39	15	14	45	13	27	638	453	113	170
Rev-2	58.35	1.08	19.22	8.14	0.12	2.87	6.25	2.04	1.63	0.31	599	57	53	15	14	24	16	29	738	159	55	168
Rev-3	55.85	1.14	14.05	9.35	0.17	5.60	10.05	2.33	1.21	0.26	446	118	29	12	10	42	13	11	696	193	63	127
Rev-4	23.48	7.81	6.95	50.94	0.40	5.11	4.28	0.58	0.23	0.23	50	400	78	21	17	106	12	12	203	1000	412	253

APPENDIX H: Selected physical and chemical properties of a number of sediment and rock samples

Sediment samples

Sample[a]	Geomorph. Unit[b]	Depos.after 22-04-91	% Sand[c] (2000-50)	% Silt (50-2)	% Clay (<2 μm)	pH-H_2O (1:2.5)	Exchang. cations (meq/100 g)[d] Ca^{2+}	Mg^{2+}	K^+	Na^+	$CaCO_3$ (wt%)	P-ret (%)
RTA-1	TT*af*	no	medium sand[e]			-[f]	-	-	-	-	0.1	-
RTA-2	TT*af*	no	fine sand			-	-	-	-	-	0.1	-
RTA-3	TT*af*	no	coarse sand			-	-	-	-	-	0.1	-
RTA-4	TT*af*	no	27	60	13	-	-	-	-	-	-	-
RT2-5.4[g]	TT*ap*	no	23	62	15	-	-	-	-	-	-	-
RChM-1.1	ChM*af*	yes	28	59	13	7	43.5	3.3	0.4	0.6	0	40.0
RChM-1.2	ChM*af*	no	medium sand			-	-	-	-	-	1.0	-
RChM-1.3	ChM*af*	?	Slightly loamy fine sand			8	30.9	3.2	0.3	0.4	1	21.5
RChM-1.4	ChM*af*	?	24	66	10	8	48.5	3.5	0.5	0.7	0	40.5
RChM-1.5	ChM*af*	no	coarse sand			-	-	-	-	-	0.9	-
RChM-1.6[g]	ChM*ap*	no	9	86	5	7	46.1	5.0	0.2	0.5	0	35.0
RChM-X1	ChM*ap*	yes	23	64	13	8	59.7	4.2	0.9	0.6	2.0	46.5
RChM-X2	ChM*ap*	yes	fine sand			-	-	-	-	-	0.9	-
RCh-N1	ChM*af*	yes	coarse sand			-	-	-	-	-	0.7	-
RCh-N2	ChM*af*	yes	fine sand			-	-	-	-	-	0.9	-
RCh-N3	ChM*af*	yes	fine sand			-	-	-	-	-	0.9	-
RCh-N4	ChM*af*	yes	fine sand			-	-	-	-	-	0.9	-
RCh-N5	ChM*af*	yes	very fine sand			-	-	-	-	-	0.6	-
RCh-N6	ChM*af*	yes	very fine sand/silt			-	-	-	-	-	0.1	-
Zent-1	na	yes	coarse sand			-	-	-	-	-	0.7	-
Zent-2	na	yes	coarse sand			-	-	-	-	-	0.7	-
Zent-3	na	yes	coarse sand			-	-	-	-	-	0.6	-
Z-1	ChM*af*	no	coarse sand			-	-	-	-	-	0.0	-
Z-2	ChM*af*	no	fine sand			-	-	-	-	-	0.0	-
Barb-1	na	?	medium sand			-	-	-	-	-	1.3	-
Barb-2	na	?	fine sand			-	-	-	-	-	1.2	-
Barb-3	na	?	medium sand			-	-	-	-	-	1.2	-
Rev-1	na	?	medium sand			-	-	-	-	-	1.8	-
Rev-2	na	?	medium sand			-	-	-	-	-	1.8	-
Rev-3	na	?	fine sand			-	-	-	-	-	2.6	-
Rev-4	na	?	fine sand			-	-	-	-	-	0.6	-

Rock samples

Sample[a]	Geomorph. Unit[b]	Depos.after 22-04-91	% Sand[c] (2000-50)	% Silt (50-2)	% Clay (<2 μm)	pH-H_2O (1:2.5)	Ca^{2+}	Mg^{2+}	K^+	Na^+	$CaCO_3$ (wt%)	P-ret (%)
RTA-5	TT*af*	no	compl.alt.hydroth.rock			-	-	-	-	-	nr[h]	-
RTA-6	TT*af*	no	coarse-grained andesite			-	-	-	-	-	nr	-
RChM-1.8	ChM*af*	no	andesite			-	-	-	-	-	nr	-
RChM-1.9	ChM*af*	no	conglomerate			-	-	-	-	-	0.4	-
RChM-1.10	ChM*af*	no	compl.alt.hydroth.rock			-	-	-	-	-	1.3	-
RChM-1.12	ChM*af*	no	sl.alt.hydroth.rock			-	-	-	-	-	2.1	-
RChM-1.13	ChM*af*	no	sandstone/shale			-	-	-	-	-	7.0	-
RChM-1.14	ChM*af*	no	limestone/calc.claystone			-	-	-	-	-	56.7	-

[a] See appendix C for additional data on samples.
[b] See sections 3.4 and 3.5 of this report; na = not applicable.
[c] Texture of RTA-4, RT2-5.4 and RChM-1.1/1.4 was measured in duplo (slightly inaccurate).
[d] Exchangeable cations were measured in duplo.
[e] All texture and particle size estimations according to USDA classification (Gee & Bauder, 1986).
[f] Not measured.
[g] RT2-5.4 and RChM-1.6 were taken in a soil profile.
[h] No reaction.

Calculation of the potential calcite content of a perfectly mixed RChA deposit (see discussion section 4.5)

Composition[a]	fraction of total	*	$CaCO_3$ (wt%)	=	Potential $CaCO_3$ content
Andesites, bas.like	0.164		0		0
Compl.alt.hydroth.	0.024		1.3		0.031
Compl.alt.hydroth.	0.035		0		0
Sl.alt.hydr.volc.	0.213		2.1		0.45
Sl.alt.hydr.volc.	0.139		0		0
Granites	0.038		0		0
Sand/silt/claystone	0.234-0.221		7.0		1.64-1.55
Sand/silt/claystone	0.011		0		0
Limestone[b]	0.013-0.026		56.7		0.74-1.47
Breccias, conglom.	0.077		0.4		0.031
Breccias, conglom.	0.024		0		0
Not determined	0.007		1.0		0.007
Not determined	0.021		0		0
	1.00				3-3.5

[a] Petrographical composition (see table 4.2).

[b] Estimation of limestone percentage: 5-10% of total sand-/silt-/clay-/limestone (= 25.8%) = 1.3-2.6%.