ATLANTIC ZONE PROGRAMME

Report No. 74
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HOLOCENE, ARC-VOLCANISM CONTROLLED, EPISODIC SEDIMENTATION IN THE ATLANTIC LOWLAND OF COSTA RICA

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WAGENINGEN - AUW

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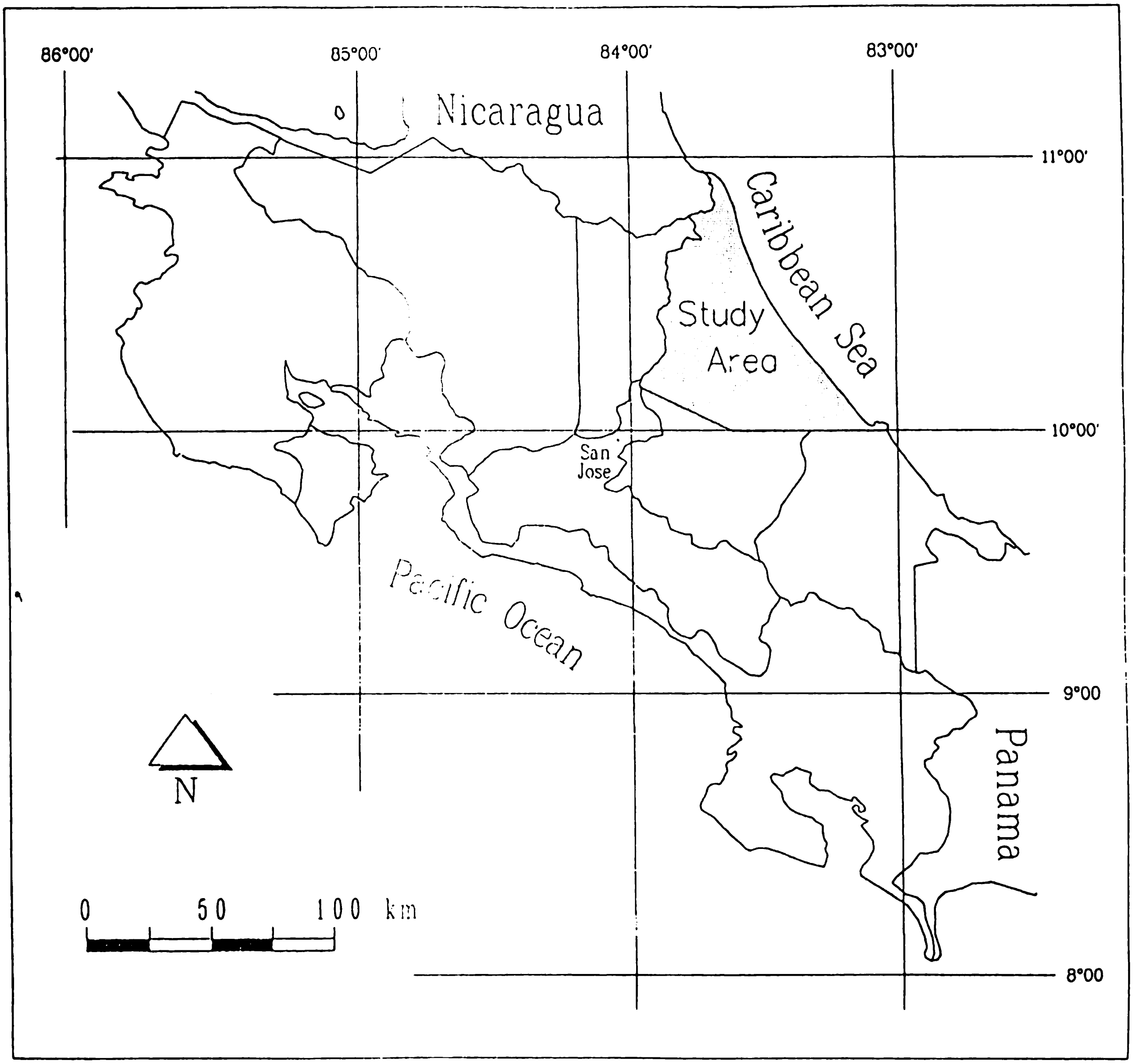
GANADERIA DE COSTA RICA - MAG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PREFACE

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 the research I have done in Costa Rica during a six months field work, from June until December 1991.

I would like to thank the following persons who made it possible to do this research. First of all the supervisors: André Nieuwenhuyse, Professor Salle Kroonenberg, Professor Nico van Breemen and Professor Olaf Schuiling.

I also want to thank señor Leandro, the owner of the 'Hacienda Río Cascadas' for his help during the field work at the 'Yucatica farm', and all the others in Costa Rica and at the Yucatica farm who made the time I spent there a great one.

Finally I want to thank Poppe de Boer for his useful comments during the writing of the report, and the W.S.O. (Stichting Wetenschappelijke Studiereizen naar Ontwikkelingslanden) for the financial support.

June 1993

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1. Introduction

Alluvial systems in foredeep basins such as the Atlantic Zone of Costa Rica (see fig. 2.2: Tortuguero Trough) are among the most dynamical fluvial environments on Earth. Due to high sediment supply from uplifting active volcanic mountain ranges on the one hand, and active basin subsidence on the other hand, thousands of meters of sediments can accumulate in relatively short time spans (in the order of tens of millions of years).

In the footslopes of the volcanic mountain front most characteristic fluvial environments are braided rivers and alluvial fans. Sedimentation of mainly coarse-grained materials ranges from deposition by braided stream flows to dumping by sediment gravity flows such as lahars and pyroclastic flows. Deposition in this environment is highly episodic, in the form of sudden floods after heavy rains in the mountain area, earthquake triggered landslides or volcanic eruptions.

Farther away from the mountain front meandering or anastomosing rivers prevail and the sediment discharge tends to be more steady. Deposition from sediment gravity flow is of minor importance and sediments are commonly finer grained.

A sort of transitional environment exists between the highly dynamic fluvial environment close to the mountain front and the more quiet fluvial environment at greater distance from the mountain front. In this transitional environment sediment supply is still episodic and mainly stems from braided river streams. For lahars and pyroclastic flows, distance is probably too large to reach this parts. It is suggested, however, that some large sand bodies in these regions are deposited from highly concentrated sandy sediment flows (Nieuwenhuyse and Hartman, 1991).

A detailed sedimentological study was carried out in order to get more insight into the mechanisms of transport and deposition of sediments in such a transitional region. The studied area is located about 30 km north of the volcanic range in the Atlantic lowland of Costa Rica (see fig. 2.4). The study is mainly concerned with deposits of laterally extending sand sheets. It was tried to establish the influence of allochtonously controlled processes as volcanic eruptions on the sedimentation pattern.

This research may contribute to a better understanding of sedimentological processes in alluvial systems bordering an active volcanic mountain area in the humid tropics, since relatively little is known about the depositional processes in such humid regions.

2. Geological setting

Costa Rica forms part of the southern part of the central American isthmus, which emerged from the collision between the Cocos and Caribbean plates (see fig. 2.1).

An island arc had developed in which, from the SW to the NE, a trench-slope, an outer-arc, a fore-arc, an arc, and a back-arc can be distinguished (see fig 2.2).

A fault system (see fig 2.2, Trans-Isthmus Fault System) divides the Costarican part of the back-arc area into two structurally different regions: The Baja Talamanca Trough in the south and the Tortuguero Trough and the Nicaragua graben in the north. The Tortuguero Trough is the undeformed northern complement of the Talamanca Trough; extensive coastal swamps indicate that the basin is still subsiding (Seyfried et al., 1991).

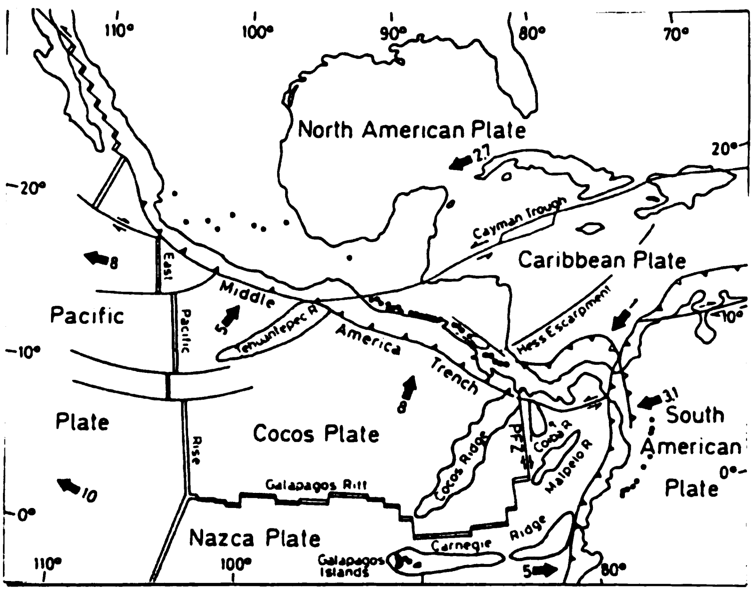


Fig. 2.1. Tectonic setting of Central America. Black arrows indicate drift directions; numbers represent absolute movements in cm/ yr; black dots are active volcanoes (Seyfried, 1991).

Since the Late Cretaceous, in the Tortuguero Trough or Limón Basin a (almost 8 km) thick shallowing upward sedimentary sequence (see fig. 2. 3) has been laid down more or less continuously (Seyfried et al., 1991). The final transition from marine to terrestrial deposits started in the Mid-Miocene (Calvo and Bolz, 1987); in places marine ingressions are recorded until Early Pliocene. The Quaternary in the Limón basin already comprises about 500 m in the Río San Juan depo-

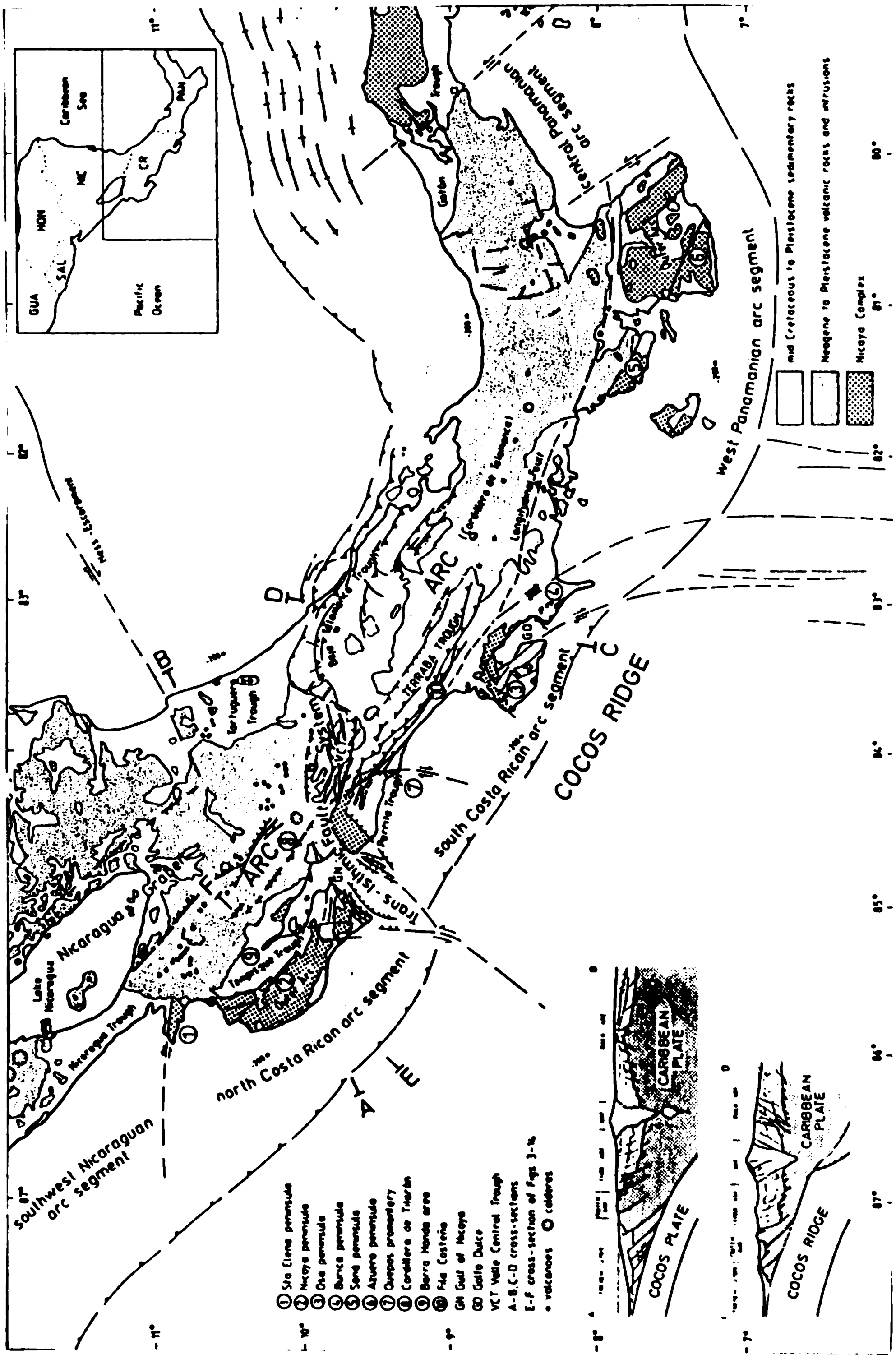


Fig. 2.2. Structural map of southern Central America, showing major tectonic elements, main tectonostratigraphic units and large sedimentary basins (Seyfried, 1991).

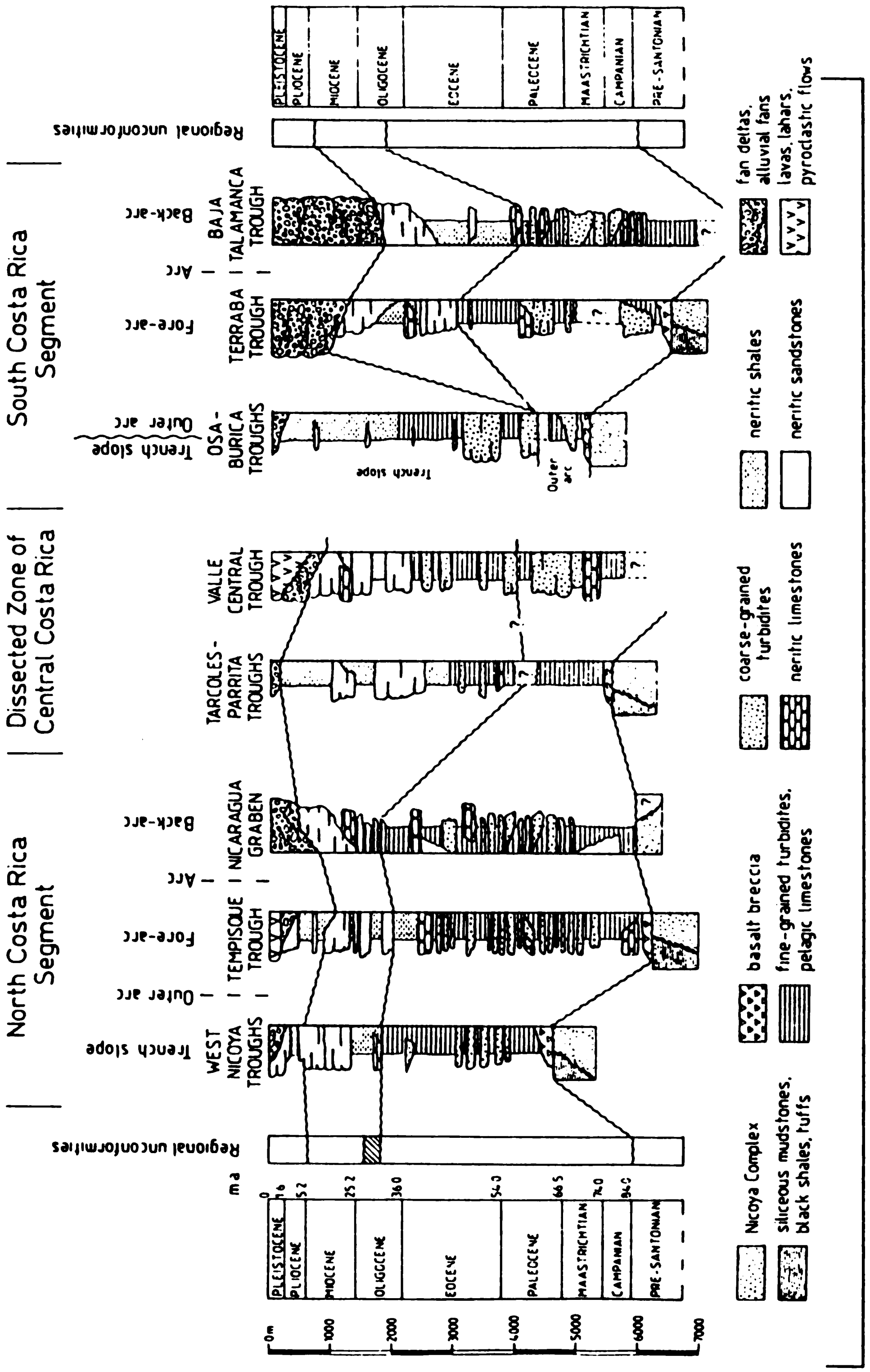


Fig. 2.3. Generalized stratigraphic sections along and across the Costa Rican part of the south Central American isthmus. For location, compare with Fig. 2.2. (Seyfried, 1991).

centre, implying average subsidence rates of at least 0.25 mm/y during the last 2 Ma (Kroonenberg, 1992).

The most recent fill of the Limón basin consists of Quarternary fluviovolcanic deposits derived from the stratovolcanoes of the Central Cordillera (Johnsson, 1990). Active or recently active volcanoes, e.g. the Turrialba, Irazú (see fig. 2.4) and Poás produce large quantities of loose debris and may trigger volcanic mudflows. The last eruptive cycle of the Irazú took place in 1963-1965, that of the Turrialba in 1866. The Poás is still active. Also seismic activity gives rise to massive landslides and non-volcanic mudflows, as was the case in the recent (April 22, 1991) 7.4 earthquake in the Atlantic Zone.

Going from the Central Cordillera towards the Caribbean sea, four main land units can be distinguished (after Wielemaker and Oosterom, 1990): (1) the slopes of the volcanoes themselves, consisting of lava streams and pyroclastic deposits; (2) the foot-slopes, consisting of alluvial fan and pyroclastic debris flows mainly; (3) the fluvial volcanic plain, consisting of deposits of meandering rivers and distal parts of pyroclastic flows; (4) the coastal barrier zone.

The Yucatica area, described in this paper is located at the inactive alluvial plain of the Toro Amarillo-Tortuguero river system, a few kilometers south-west of the confluence of the river Tortuguero with the river Guápiles (after Van Seeters, 1992) (see fig. 4.2). Distance to the nearest volcano, the Turrialba, is about 37 km. This volcano and its eruption units are described below.

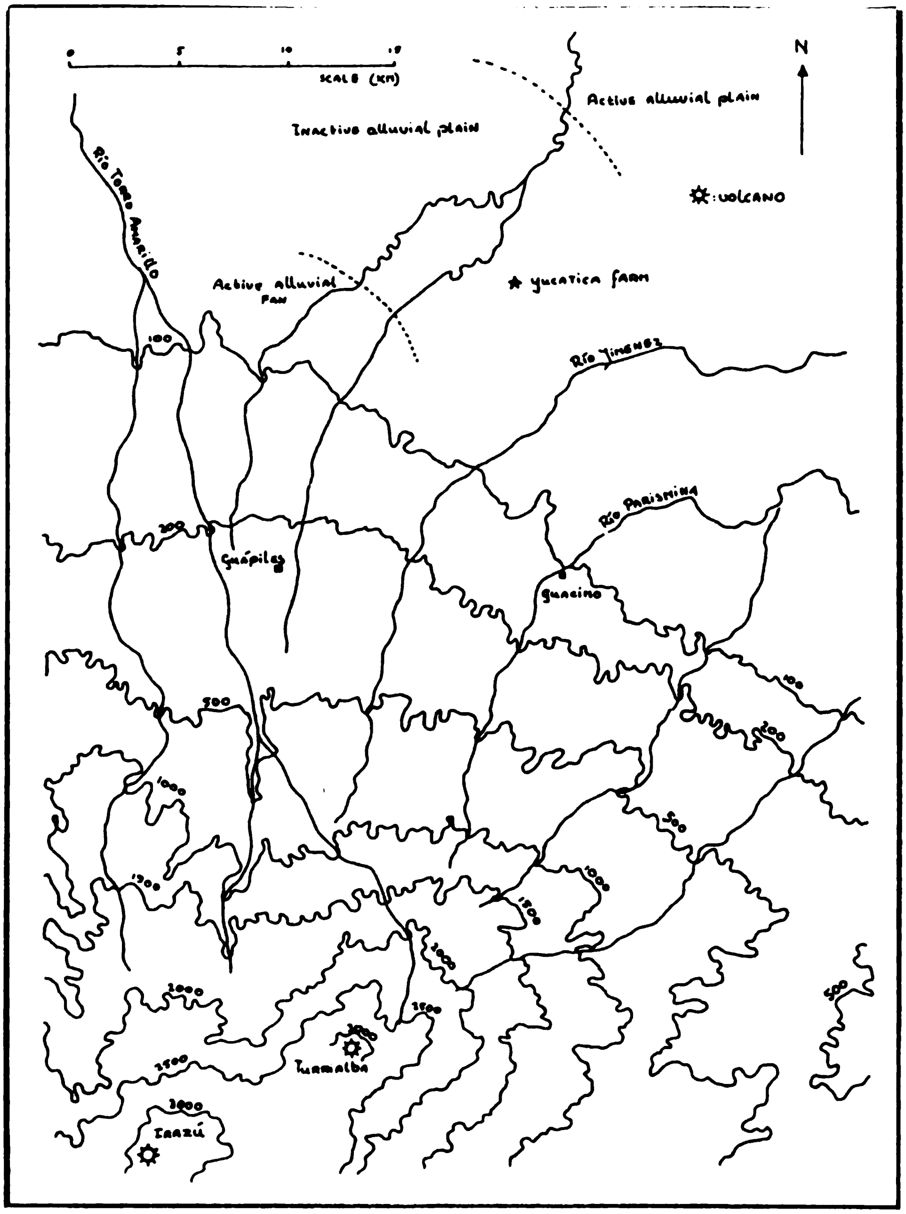


Fig. 2.4.a Location of the Yucatica area, about 30 km north of the volcanos Turrialba and Irazú.

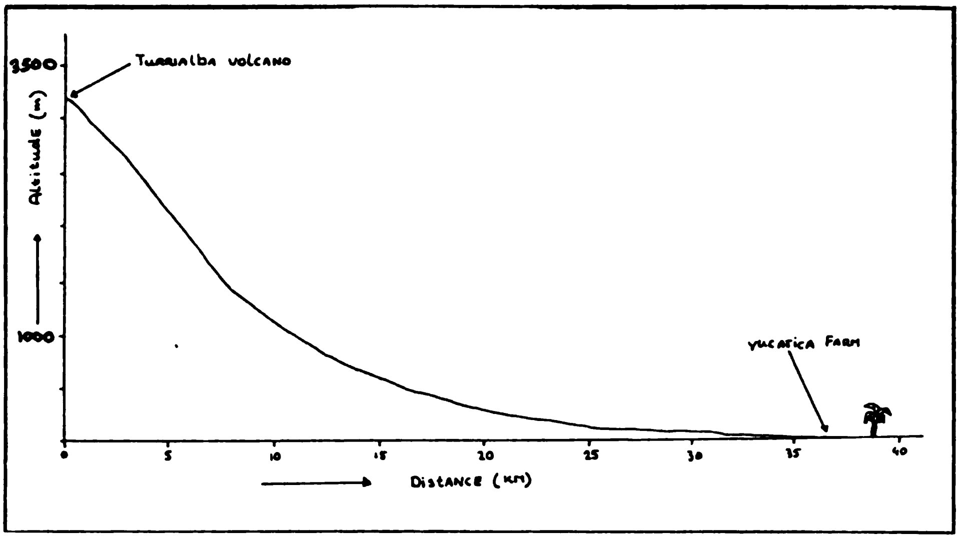


Fig 2.4.b Cross section from the top of the Turrialba downslope to the Yucatica area.

Chronology of the Turrialba eruptions

(After Reagan, 1987)

During the last 2000 years the Turrialba volcano had erupted violently four times, the last eruption happened in 1866. The currently active edifice began erupting more than 8250 years BP. At least 16 eruptions are recorded in the crater and the summit region of this edifice. The eruptions are described below, from the oldest to the youngest, in the context of 13 stratigraphical units.

Unit 13:

-minimum age: 8250 years;

-basalts, andesites and dacites, lahars and lava-flows;

-emplaced in at least 5 eruptions during a time period of substantial duration.

Unit 12:

-andesite lava flows and blocky pyroclastic deposits;

-one eruption.

Unit 11:
-minimum age: 8250 years;
-andesite lava flows;
-extruded during two eruptions.

Unit 10:
-basaltic andesite lava flows and flow breccias.

Unit 9:
-andesite to dacite lava flows.

Unit 8:
-andesitic pyroclastic breccias, pyroclastic surge and air-fall deposits;
-interbedded lake beds were probably deposited from a crater lake that formed during or after the eruption of unit 8.

Unit 7:
-andesite lava flows;
-discharged during one eruption.

Unit 6:
-pyroclastic breccias.

A period of quiescence and erosion of unknown duration followed the eruption of unit 6. Headword stream erosion and small debris avalanches took away 0.5-1 km^3 of the rainy, northeast side of Turrialba. The eroded material was brought primarily by lahar down to the Rio Elia and Rio Guacimo valleys, and deposited on the coastal plane north of Turrialba.

Unit 5:

-andesitic pumice, fallout, pyroclastic flow and surge deposits;

-Radiocarbon ages of airfall and pyroclastic flow deposits range from 2330 to 1860 years, pumice erupted approximately 2000 yrs BP.;

-Volume of the airfall deposits are approximately 0.075 km^3, pyroclastic flow and surge volumes were roughly 0.01-0.03 km^3. Total volume of pyroclastic materials were about 0.1 km^3. (0.05 km3 dense rock equivalent) Unit 5 is the largest volume pyroclastic unit preserved at Turrialba;

-Fallout deposits were transported downwind to the west.

Quiet period of roughly 1000 to 1500 years predated eruption of unit 4.

Unit 4:

-andesitic pumice, fallout, pyroclastic flow and surge deposits;

-volume is less than 0.02 km3 (=dense rock equivalent).

Unit 3:

-massive andesitic lava flows;

-traveling up to 19 km north of the volcano;

-volume of about 3 km3.

Time between eruption of unit 4 and unit 2 is about 300 to 700 years.

Unit 2:

-andesitic fallout and surge deposits;

-volume is less than 0.02 km^3 (=dense rock equivalent).

Unit 1:

-erupted from 1864 to 1866;

-andesitic pumice, fallout, pyroclastic flow and surge deposits;

-ash fell on Costa Ricas Central Valley. The distribution of tephra suggests that much of the area within 5 km of the volcano was destroyed by the eruption. Surge deposits devastated the entire summit area out to a distance of up to 5-6 km or more. Small volume lahars flowed down the Rio Aquiares and probably other valleys.

3. Climate

The Northern Atlantic Zone including the Limón Basin is a humid tropical rainforest area, with precipitation ranging between 3000 and 6000 mm/yr, and a mean annual temperature of 25 to 26°C. Prolonged high intensity rain storms (temporales) frequently occur (Vahrson et al., 1990), and may cause flooding, land-slides, and other water damage. During such heavy down pours, rain intensity may exceed 2 mm/min (Nieuwenhuyse and Jong van Lier, 1988). 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 less higher 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.

Hooghiemstra (1992) has studied the paleoclimatology in the Cordillera Talamanca. He concluded that during the Late Glacial to Holocene transition (10,000 yr BP) the mean annual temperature increased with ca. 8°C, and that the modern climatological conditions were already present at the beginning of the Holocene.

4. Pyroclastic and fluvial deposits

In the previous chapter it was pointed out that the Yucatica area is located in a back-arc basin, bordering an active magmatic arc. Within such subsiding back-arc basins of a magmatic arc great volumes of volcaniclastic materials accumulate (Mathisen and Vondra, 1983). The basins can accommodate a large variety of sedimentary environments such as fluvial-deltaic shorelines (see fig 4.1), shallow marine shelves, turbidite and grain-flow-covered marine slopes, submarine fans, etc.

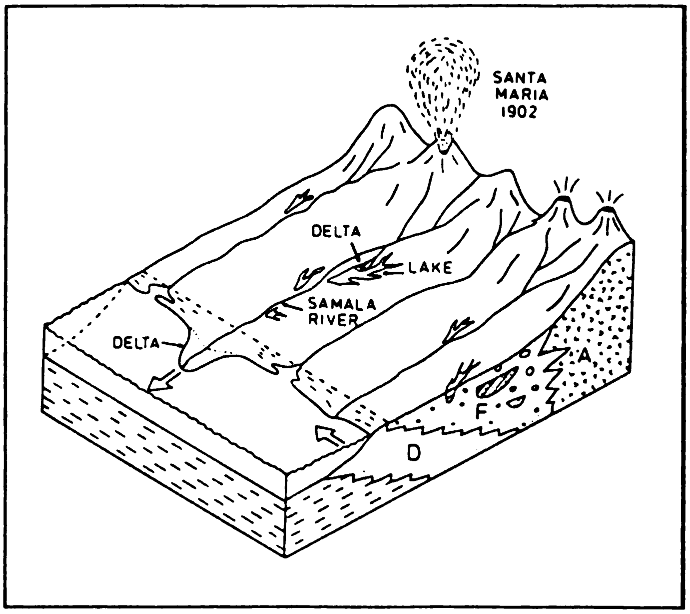


Fig. 4.1. Fluvial-deltaic system after 1902 eruption of Santa Maria volcano, Guatemala. Inferred facies resulting from long term progradation along entire length of coastal plain. A: Arc-derived lava flows, pyroclastic flows, lahars and fallout ash; F: braided stream, deltaic and lacustrine facies environments consisting of volcaniclastic rocks and sediments; D: Littoral and strand-line volcanic sands composed largely of coalesced deltas (Kuenzi et al., 1979).

Recent sediments in the Yucatica area are derived from pyroclastic deposits and are probably deposited in a high-energy fluvial depositional setting. Therefore in the next chapters attention is paid to the different types of pyroclastic deposits, depositional patterns and transport mechanisms in fluvio-volcanic environments. It has to be clear that descriptions of fluvio-volcanic deposits can be made from both volcanological and sedimentological points of view. Both use a different nomenclature, which is sometimes confusing. The following text is compiled mainly from Fisher (1984), Walker (1984), Boggs (1987), and Einsele (1991).

4.1 Pyroclastic rocks.

Pyroclastic rocks are composed of fragments that originate from volcanic eruptions. Eruptions giving rise to pyroclastic fragments may be grouped into two general categories:

1) those caused by expansion of gases initially contained within the magma (pyroclastic (magmatic) eruptions);

2) those caused by vaporization of external water in contact with hot magma or lava (hydroclastic eruptions).

The initial driving force of rising magma columns is buoyancy and, at low pressures, internal gas expansion in explosive eruptions. The magma however may come into contact with water as it ascends and be blown to bits by expansion of steam. Thus, magmatic and hydroclastic processes may overlap. Whatever causes an eruption, fragments are either 1) abruptly transported through the air and fall back to the surface to become fallout deposits, or else 2) become pyroclastic flow deposits from flows along the ground surface.

Major kinds of subaerial deposits that originate from pyroclastic eruptions are fallout deposits, the deposits from pyroclastic surges, pyroclastic flows and lahars (see fig. 4.2). Subaerial deposits that originate from hydroclastic eruptions include fallout deposits, surges and lahars. (see fig. 4.3). The different types of deposits are described below.

4.1.1 Pyroclastic fallout

Fallout deposits come to rest after transport by initial trajectory (large fragments), or after scattering by wind from turbulent eruption clouds. Fallout deposits may also form from fine-grained particles that move turbulently upward from the

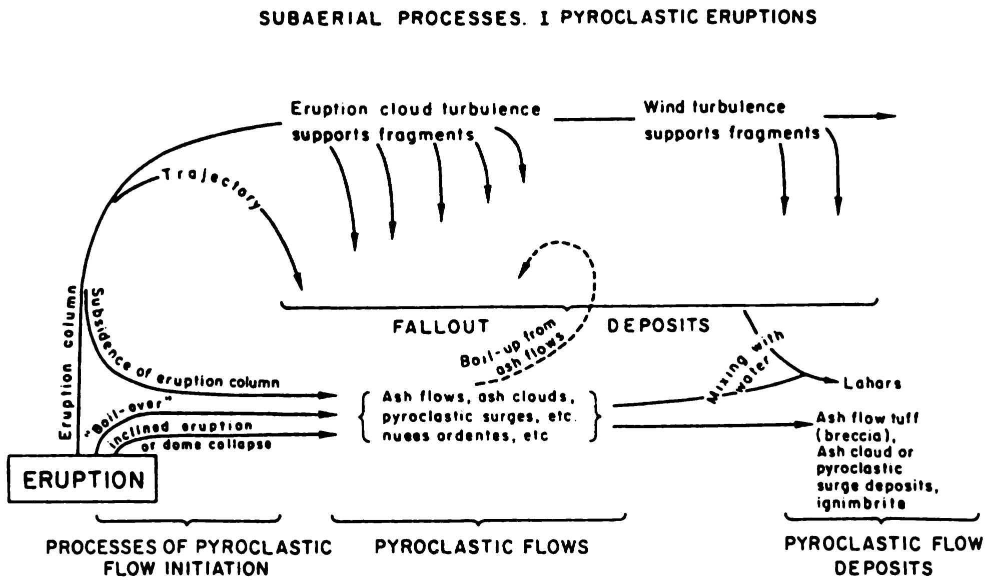


Fig. 4.2. Processes by which subaerial pyroclastic flow and fallout deposits originate (Fisher, 1984).

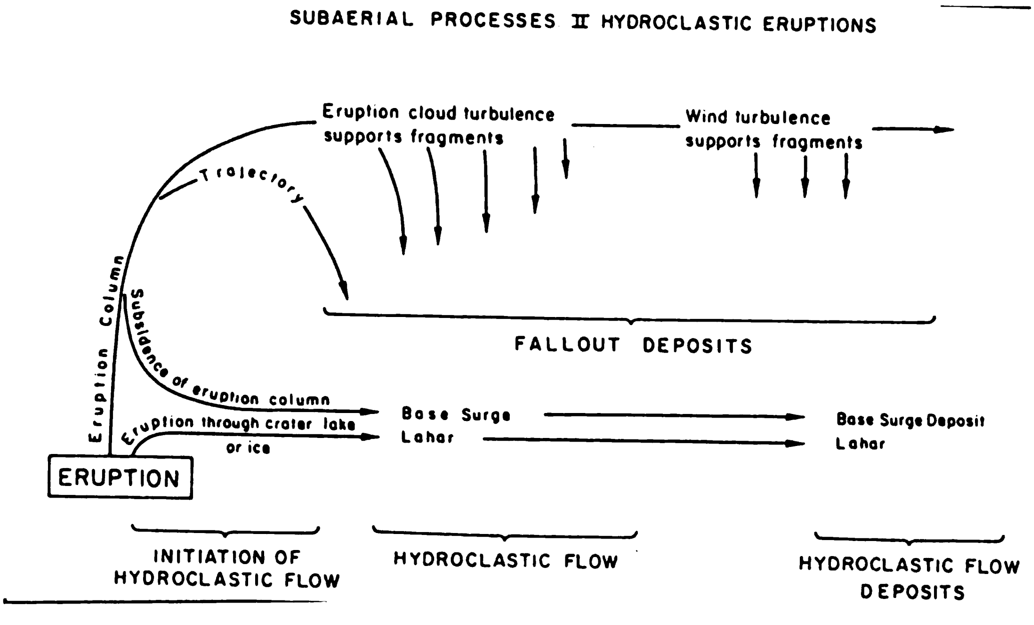


Fig. 4.3. Processes by which subaerial hydroclastic flow and fallout deposits originate (Fisher, 1984).

tops of pyroclastic flows. Grain-size of particles within these deposits is highly variable depending upon the type of volcanism and the distance to the source, commonly ranging from 2-4 mm close to the source to 0.12-1.0 mm at greater distance.

4.1.2 Pyroclastic flow

Pyroclastic flows are volcanically produced hot, gaseous, particulate density currents. They originate from collapsing eruption columns, by the low-pressure 'boiling-over' of vents, and by the laterally directed eruptions frequently associated with domes and dome collapse.

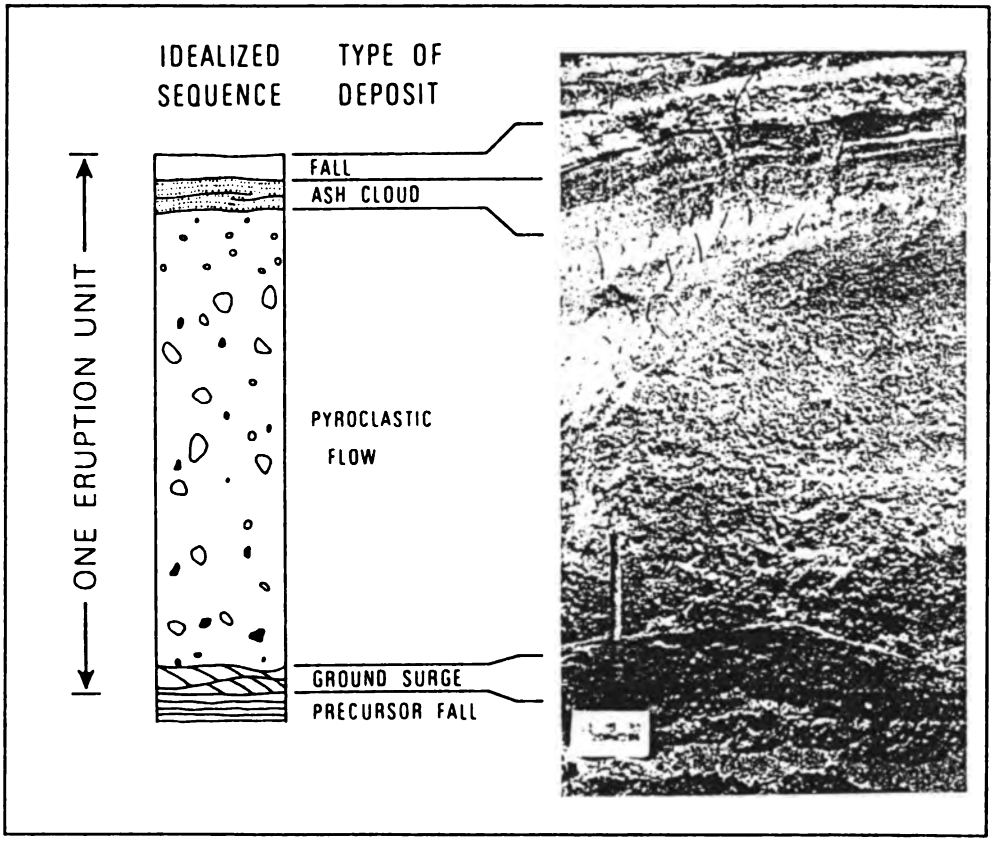


Fig. 4.4. Idealized depositional sequence of one eruption unit, with an example from Mount Pelée, Martinique (after Walker, 1984).

Pyroclastic flow deposits can be divided into 1) flow deposits and 2) surge deposits.

Flows (see fig. 4.4) are defined as hot, high-concentration mixtures where the fluid is gas. The deposits are poorly sorted, massive or reversely graded. These features characterize laminar flows. They are also found in lahars (see 4.1.3) where the interstitial fluid is water rather than gas. Surges are turbulent density currents (ignimbrites), and can from a sedimentological point of view be considered as a tubidity current (Walker, 1984). The deposits are thin-bedded (in the order of centimeters) and commonly laminated and cross-bedded.

4.1.3 Lahars

Lahars are subaerial or subaqueous debris-flow deposits composed of poorly sorted volcanic fragments which range in size from clay to boulders.

Lahars make up a large volume of the volcaniclastic pile around volcanoes. Their characteristics are those of sedimentary debris-flow deposits resulting from laminar transport driven by gravity (see fig.4.5). The deposits are massive or reversed-graded, with sharp, non-erosive basal contacts. Since they are controlled by gravity, they commonly fill large or small valleys.

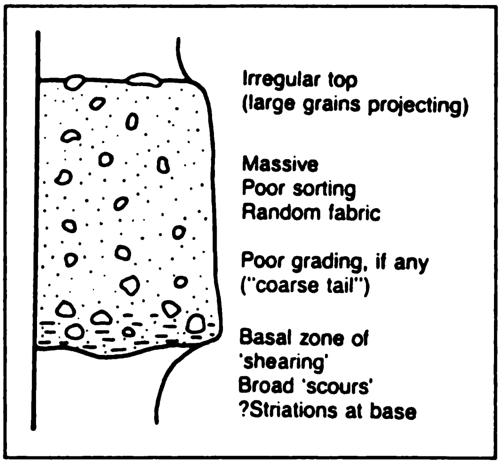


Fig. 4.5. Sedimentary structures in a debris flow (after Boggs, 1987).

Two ways in which lahars can form are 1) directly by eruptions through crater lakes, or 2) from hot pyroclastic flows that mix with snow or water on the flanks of volcanoes. They may also originate from post-depositional failure of water-soaked pyroclastic and fragmented lava flow debris on steep slopes.

4.2 Volcanic facies

Vessel and Davies (1981) were among the first to describe nonmarine facies associations of an active volcanic region based upon a depositional facies model approach. They have divided nonmarine volcanic deposits of active, pyroclastic flow-producing volcanoes in the fore-arc area of Guatemala into four facies (see fig. 4.6):
1) vent facies, consisting of interbedded lavas, coarse and fine-grained fallout tephra and breccias caused by erosion of the steep volcano flanks, 2) proximal facies, consisting of breccias deposited from pyroclastic flows and eroded debris within valleys on the volcano flanks, and fall-out tephra, 3) medial facies, consisting of alluvial fans at the base of the volcano, composed of lahars, fluvial debris and tephra beds, 4) distal facies, consisting of fluvial deposits of braided streams, interbedded with thin fallout ash beds. Similar facies are to be expected in non-marine back-arc regions. Proximal, medial and distal facies are relative terms used with reference to the distance to the source. Absolute distance cannot be defined. A large and highly explosive volcano, for example, will distribute coarse-grained and fine-grained debris to greater distances than a less energetic source.

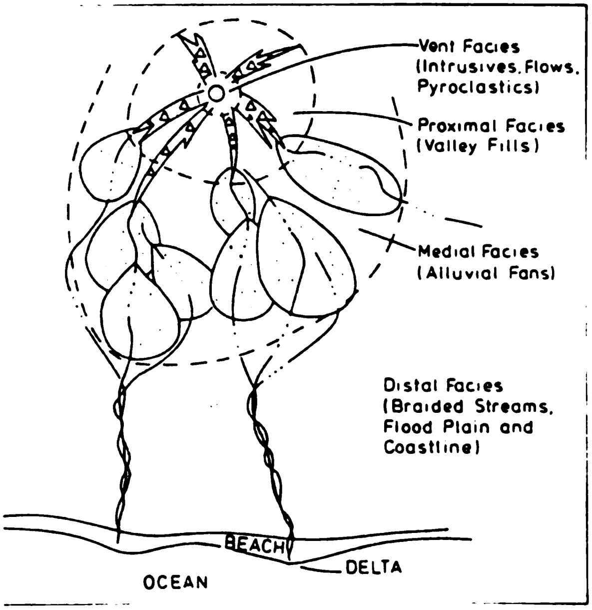


Fig. 4.6. Sedimentary facies of modern volcaniclastic debris on an active volcano. Unornamented areas are older rocks of similar kinds (after Vessel and Davies, 1981).

4.3 Fluvial systems

Fluvial deposits encompass a wide spectrum of sediments generated by the activities of rivers, streams, and associated sediment-gravity flow processes.

Most fluvial deposits can be assigned to one of three broad environmental settings: alluvial fan, braided river, and meandering river (see fig. 4.7). These fluvial environments are interrelated and overlapping.

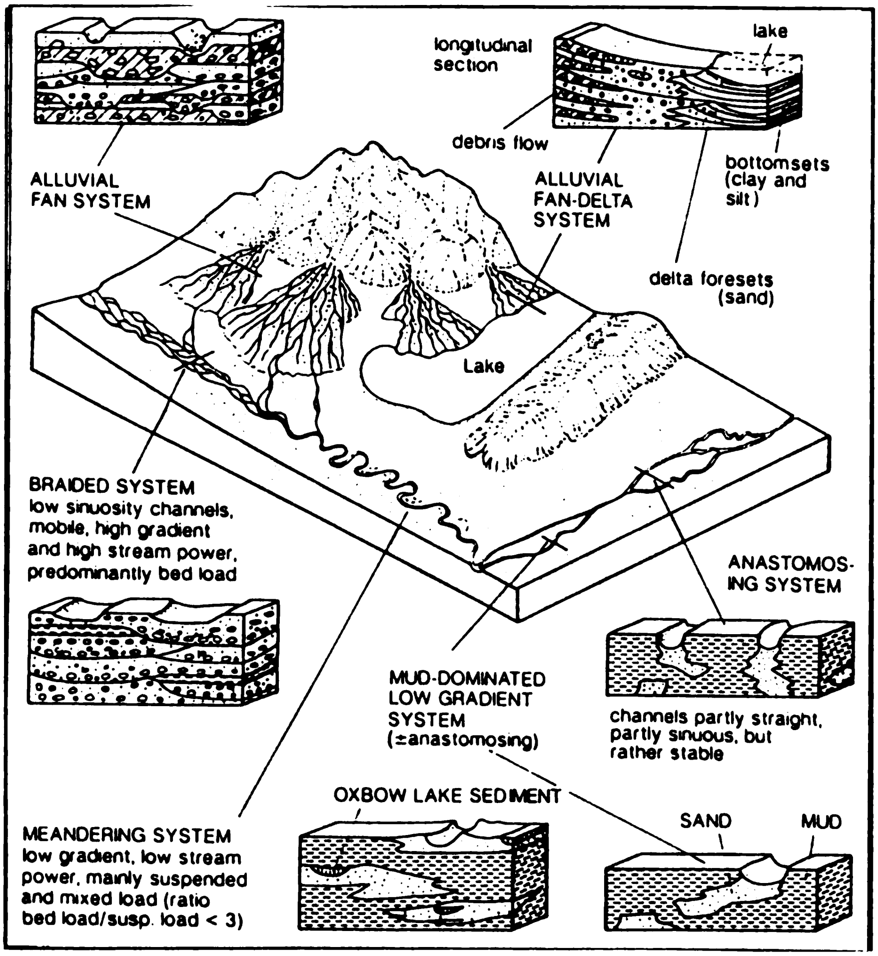


Fig. 4.7. Principal types of fluvial systems and generalized characteristicsof their cross sections (after Einsele, 1992).

4.3.1 Alluvial fans.

Alluvial fans are cone-shaped piles of sediment formed at the foot of highlands where streams, confined by (narrow) valleys emerge into adjacent lowland. A series of overlapping alluvial fans generates a clastic wedge (see fig. 4.8). Sedimentation on alluvial fans begins where the streams leave their confined valleys and loose some of their transport efficiency. Basically, alluvial fans are composed of two types of sediment: stream deposits and sediment gravity flow deposits. Current-transported sediments commonly predominate. They are

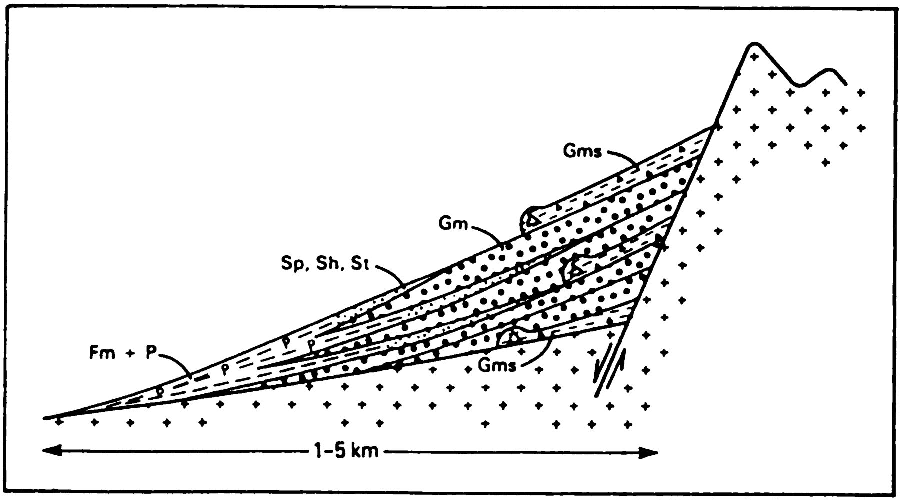


Fig. 4.8. Diagrammatic cross-section of an alluvial fan, showing proximal-distal facies variation. See tabel 4.2. for explanation of facies codes (after Walker, 1984).

deposited either from water flow in the channel system or, after extreme rain storms, from sheet-floods inundating large parts of the alluvial fan. Sometimes gravel is concentrated locally to form sieve deposits (coarse gravel and boulders devoid of finer-grained matrix). From time to time, large debris flows with a muddy-sandy matrix reach the proximal and mid-fan area and bury part of the pre-existing, radiating channel system. In humid regions, alluvial fans are dominated by stream processes with marked seasonal variations in run-off. The mid- and lower-fan areas are vegetated and therefore less susceptible to reworking. They are cut by a limited number of active narrow channels. The sedimentary processes in such fans, particularly those in humid, tropical regions, are only poorly known. Down-slope, alluvial fans grade into other alluvial deposits, mostly those of a braided river system.

4.3.2 Braided river systems

Braided rivers are distinguished from meandering rivers by their lower sinuosity. They are characterized also by many channels separated by bars or small islands (see fig. 4.9).

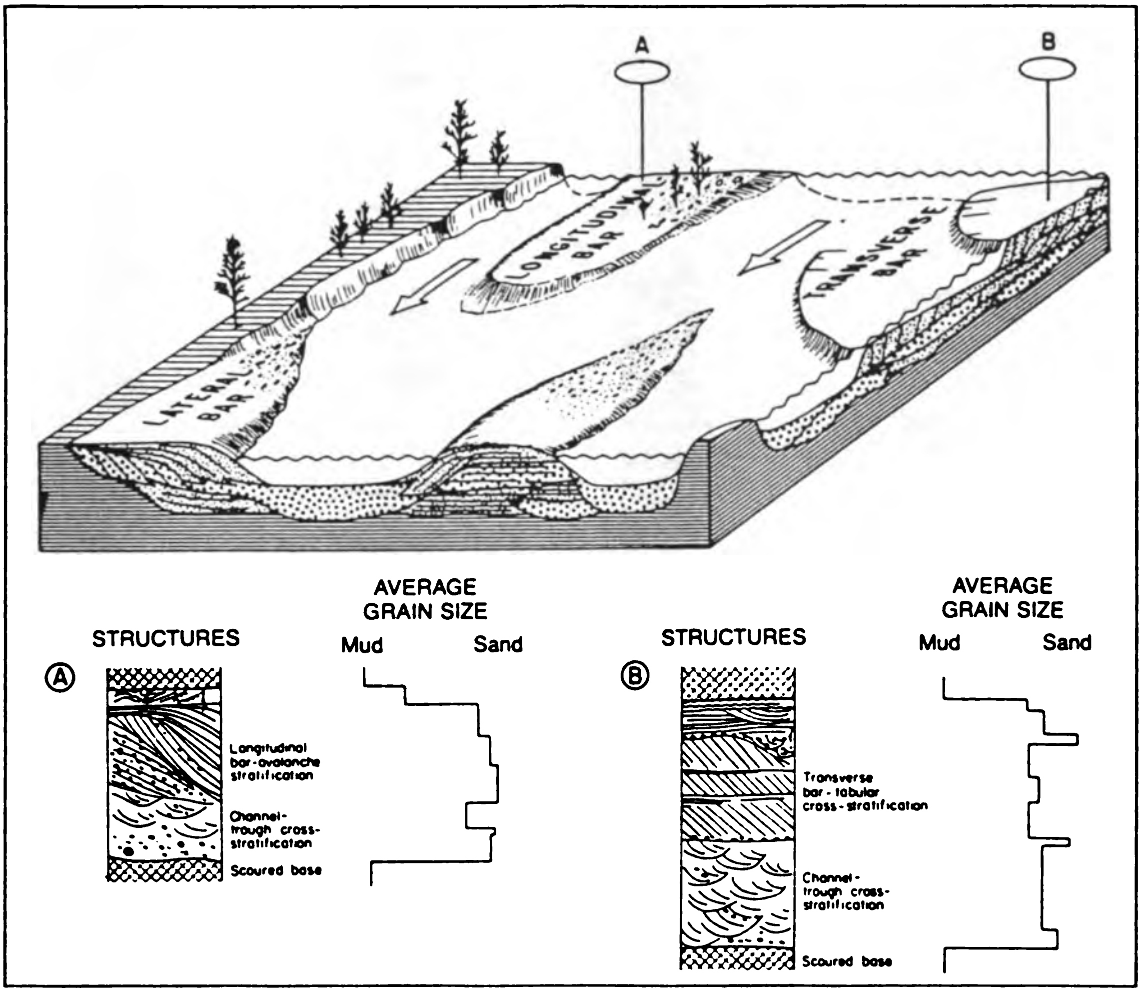


Fig. 4.9. Structure of bars in braided rivers. Sequence A is dominated by migration of a gravelly longitudinal bar. Sequence B records deposition of successive transverse bar cross-bed sets upon a braid-channel fill (after Galloway, 1983).

Braided rivers are best developed in distal parts of alluvial fans, on outwash plains, and in the mountainous reaches of river systems. Braiding apparently takes place because of rapid large fluctuations in river discharge, abundance of coarse sediments, and easily erobable, noncohesive banks (Cant, 1982).

Miall (1977) proposed four vertical profile models of braided river systems that can develop under different conditions of bedload and discharge (see fig. 4.10). The Scott-type model consists mainly of roughly horizontally bedded gravels and minor sand wedges; this model

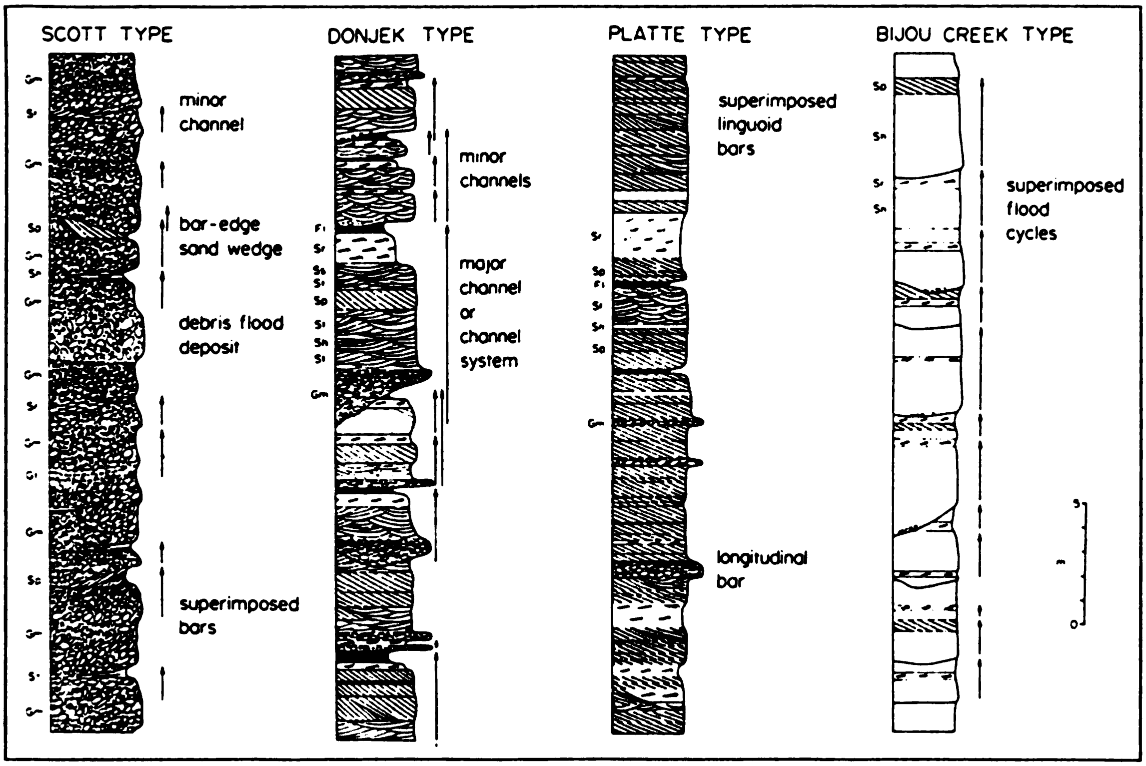


Fig. 4.10. General stratigraphic models for sandy braided streams. See table 4.2. for description of individual facies (after Miall, 1977).

shows poorly developed cycles and reflects deposition in gravelly proximal streams during high river discharge. The Donjec-type model consists of fining-upward cycles of variable scale that reflect deposition in braided rivers with mixed bedloads of sand and gravel, where sedimentation may occur at different levels within channels or where channel aggradation runs parallel to channel shifting. Sandy braided rivers with more steady discharge are dominated by linguoid and transverse bars that generate largely cross-bedded, sandy deposits of the Platte-type that do not have very distinctive cycles, although some fining upward sequences may be identified. Braided streams with markedly variable discharge, owing to periodic flooding and relatively little topographic differentiation between channels and bars, generate deposits of the Bijou Creek type (Cant, 1982), which are characterized by superimposed flood deposits that accumulate during waning current. In table 4.1 two more models of braided streams are proposed: The South Saskatchewan-type, which represents a mainly sandy braided river deposit of the middle reaches, and the Slims-type, which represents a silt and mud-dominated distal braided stream deposit.

Table 4.1. Main characteristics of selected braided river systems (After Miall, 1985).

Subenvironment, general description	Percentage of gravel (%)	Prevailing lithofacies and internal structure	Minor lithofacies[a]	Name of type (Miall 1985)
Proximal braided river deposits (including lower alluvial fans), gravel-dominated	>50	Massive gravel	Gp, Gt Sp, St Sr, Fl Fm	Scott
Braided river deposits (middle reaches), rich in gravel	10-70	Planar and trough cross-bedded gravel and sand, massive gravel	Sh, Sr Fl, Fm	Donjek
Mainly sandy		Trough and planar cross-bedded sand	Sh, Sr Sl, Gm Fl, Fm	South Saskatchewan
Distal braided river deposits, sand-dominated	< 10 Mainly sand	Trough and planar cross-bedded sand[b]	Sh, Sr Gm, Fl Fm	Platte
Silt and mud-dominated	Silt and mud	Massive and fine laminated silt, mud and sand	St	Slims
Sandy river plains subject to flash floods	Mainly sand	Horizontal and low angle cross-bedded sands	Sp Sr	Bijou creek

4.3.3 Meandering river systems

In contrast to the network of channels that characterizes braided rivers, meandering rivers tend to be confined within a single major channel, characterized by cohesive banks that are difficult to erode. Meandering rivers also differ from braided rivers by their much greater sinuosity, lower gradients, and finer sediment load (see fig. 4.11). Many meandering rivers are simply downstream continuations of braided rivers, formed as stream slope and coarseness of bedload decrease and large-scale fluctuations in discharge become less marked. The meandering river deposits will not be discussed more extensively since the Yucatica deposits are supposed to be formed in a relatively dynamic braided river environment.

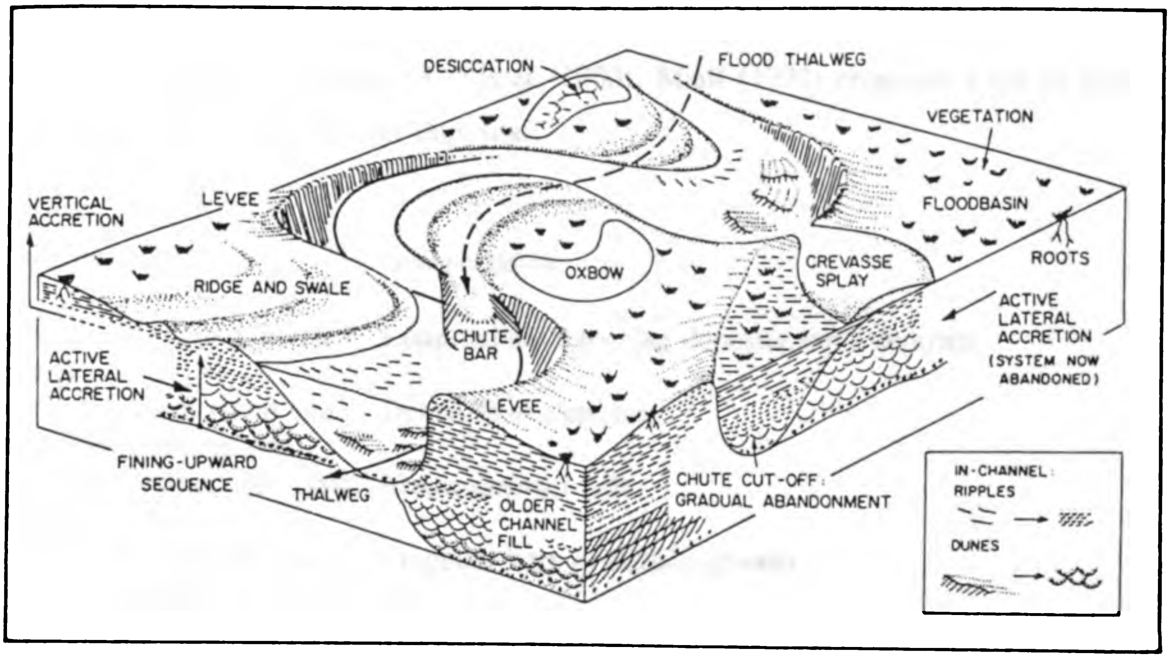


Fig. 4.11. The morphological elementsof a meandering river system (after Walker, 1984).

4.4 Lithofacies types in braided river deposits

A lithofacies is the sum of the lithological characteristics exhibited by a sedimentary deposit in a particular sedimentary environment (Visser, 1980). Maill (1977) proposed a list of lithofacies types identified in braided river deposits:

Code	Description	Interpretation
Gm	Massive or crudely bedded gravel	Longitudinal bars, lag deposits,sieve deposits
Gms	Massive matrix (sand and mud) supported gravel	Debris flow deposits
Gt	Trough cross-bedded, clast supported gravel	Minor channel fills
Gp	Planar cross-bedded gravel and/or matrix-supported gravel	Linguoid bars or deltaic growth
St	Trough cross-stratified sand	Dunes, lower flow regime
Sp	Planar cross-stratified sand	Linguoid bars, lower flow regime
Sh	Horizontally stratified sand	Planar bed flow, upper flow regime
Sr	Ripple marks and small-scale cross-stratification	Ripples, lower flow regime
Sm	massive sand a)	Very rapid deposition from suspension or from highly concentrated sandy sediment dispersions
Fl	Laminated or cross-laminated fine sand, silt or mud	Overbank or waning flood deposits
Fm	Massive, fine sandy mud or mud	Overbank or drape deposits
P	Pedogenic features	Soil formation

Table 4.2 Lithofacies codes

a) Massive (structureless) bedding.

The term massive bedding is used to describe beds that appear to be homogeneous and to lack internal structures. Reported occurrences of massive beds include both graded bed-units in turbidites, which may lack internal structures other than size grading, and certain thick, nongraded sandstones (Boggs, 1987). Certain massive beds may be a secondary feature produced by extensive bioturbation by organisms, although bioturbation commonly produces recognizable mottled structures. Liquefaction of sediment by seismic shocking or other mechanisms shortly after deposition has also been suggested as a means of destroying original stratification. Otherwise it is assumed that lack of stratification is a primary feature that results when traction transport is absent and sediments are deposited very rapidly from suspension or from highly concentrated sediment dispersions from sediment gravity flows. The sediment is presumably dumped very rapidly without subsequent reworking and forms a more or less homogeneous mass. DeCelles (1991) interpreted 'massive, very coarse sandstone with floating pebbles' as sandy mudflows.

4.5 Stream flows and sediment gravity flows.

Fluvio-volcanic deposits result form both stream flows and sediment gravity flows. Examples of stream deposits are pebbly fluvial lag-deposits and stratified fluvial sands. Debris flows, including lahars, are examples of sediment gravity deposits. In order to distinguish both types of deposits upon field criteria, more has to be known about their transport mechanism and the way in which the sediment is deposited.

Water is the only fluid important in sediment transport. Water can display variable properties as a fluid medium if it contains substantial concentrations of sediment. Because these fluid properties affect the way fluids flow and transport sediment, it is important to understand the behavior of various types of fluid flows. Depending upon the extent to which dynamic viscosity changes with shear or strain rate, three types of fluids can be distinguished:

1) Newtonian fluids have no strength and do not undergo a change in viscosity as the shear rate increases. Thus, ordinary water, which does not change viscosity as it is stirred or agitated, is a Newtonian fluid.

2) Non-Newtonian fluids have no strength, but show variable viscosity with change in shear or strain rate. Water containing dispersions of sand in concentrations greater than about 30 percent by volume -or even lower concentrations of cohesive clay- behaves as a non-Newtonian fluid. Therefore, highly water saturated, non-compacted mud display non-Newtonian behavior. Such mud may flow very sluggish at low velocities, but display much less viscous flow at higher velocities.

3) Some extremely concentrated dispersions of sediment may behave as plastic substances, which have an initial strength that must be overcome before yield occurs. If the plastic material behaves as a substance with constant viscosity after the yield strength is exceeded, it is called a Bingham plastic. Debris flows in which large boulders are supported in a matrix of interstitial fluid and fine sediment are examples of natural substances that behave as Bingham plastics.

4.5.1 Deposits of stream flows

During stream-flow transport, sediments are simply carried along with and by the fluid. Large and small particles are carried in the water by turbulence and traction processes; as velocity decreases, progressively smaller fragments settle from the water. Sediments deposited from normal water flow are characterized by layers or beds of various thickness, scarcity of vertical grain-size grading, grain-size sorting from poor to excellent depending upon depositional conditions, and the presence of a variety of sedimentary structures. Sediments deposited from traction currents are commonly characterized by sedimentary structures such as cross-beds, ripple marks, and pebble imbrication. Sediments deposited from suspension lack these flow structures and are characterized by fine lamination instead.

4.5.2 Deposits of sediment gravity flows.

Sediment can also be transported independently of fluid motion by the affect of gravity acting directly on the sediment. In this type of transport, fluids may play a role in reducing the internal friction and in supporting grains, but they are not primarily responsible for down slope movement of the sediment. Movement of sediment under the influence of gravity creates the flow, and when flow stops, the sediment load is deposited. Sediment gravity flows that occur in subaerial environments include pyroclastic flows and surges resulting from volcanic eruptions, and both volcanic and non-volcanic debris flows and mudflows.

In debris flows, which behave as a Bingham plastic, the water and solids form an intimate mixture that flow with laminar motion. As velocity decreases, the entire flow stops abruptly, after which water separates from the granular material by percolation or evaporation. On steep slopes , velocities may be rapid enough (internal stress high enough) to keep the

Table 4.3. Comparison of coarse-grained deposits with lahars (after Fisher, 1984).

	Lahars	Till (excluding water-laid till)	Unwelded ignimbrite	Fluvial deposits
Large fragments (>2 mm)	May have boulders weighing many tons	May have boulders weighing many tons	Extremely large boulders absent	Extremely large boulders rare
Sorting	Poor. May contain abundant clay-size material	Poor. May contain abundant clay-size material	Poor. Clay-size material rare or absent	Poor to good. Clay-size material sparse
Grading	Commonly reverse. May be normal or absent	Commonly absent	Commonly absent, but may be normal or reverse	Commonly normal
Bedding and thickness	Commonly very thick with vague internal bedding	Very thick. Bedding poor or absent	Commonly very thick with vague internal layering	Thin with channels and cross beds. Shingled gravels
Composition	Commonly 100% volcanic. May be pyroclastic or mixed with epiclastic materials. May contain bread crust bombs	Commonly heterolithologic with admixtures from many sources. Plutonic, metamorphic and sedimentary clasts commonly more abundant than pyroclasts	Pyroclastic. May contain abundant bread crust bombs	Material usually 100% epiclastic except in areas of active volcanism
Rounding of large fragments	Commonly angular to subangular	Commonly faceted subangular to subrounded. May be faceted with striations and chatter marks	Commonly subangular	Commonly subrounded to rounded
Carbonaceous matter	Uncharred to charred	Uncharred	Charred	Uncharred if present
Pumice	Common in some lahars	Not present except on active volcanoes	Common	Not present except in areas of active volcanism
Distribution	In valleys spreading onto flat piedmont surfaces	Plains and valleys. May mantle all surfaces. Moraines with steep fronts	Lower parts of valleys and flat piedmont surfaces	Confined to valleys
Lower surfaces	Commonly not erosional	Erosional. Commonly rests on striated bedrock	Commonly not erosional	Erosional

entire mass in motion, but as the slope decreases, internal shear stress falls below the critical yield stress , so that the mass freezes. Debris flow deposits are thick, poorly sorted units that lack internal layering. They typically consist of chaotic mixtures of particles that may range in size from clay to boulders. The large particles commonly show no preferred orientation. They are generally poorly graded. Debris flows may fill water-cut channels but they cannot cut channels themselves.

In pyroclastic flows such as ignimbrites, the fluid is gas rather than water. However, deposits of laharic debris flows and deposits of pyroclastic flows are very hard to distinguish (see table 4.3).

5. Methods

The studied area forms part of the Yucatica farm. In order to drain the area, several drainage channels have been dug. These channels form an unique opportunity to study the geology of the upper two to four metres of the ground. Especially the stratigraphical relations could be observed very well over hundreds of metres.

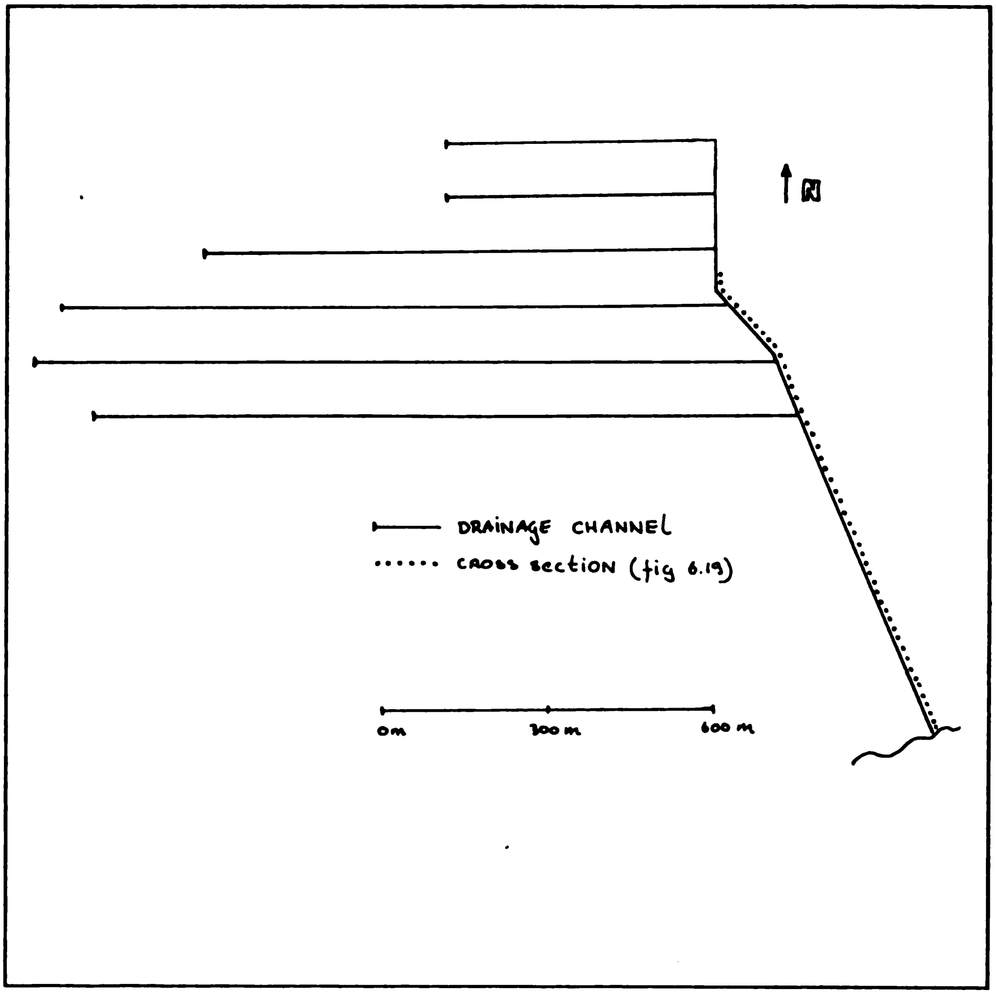


Fig. 5.1. Drainage channels at the Yucatica farm.

First a detailed description of a cross-section was made in an about 1 km long channel-wall. The different sediments were described and their stratigraphical relations were determined. The sediments were divided into different lithofacies types according to their texture and sedimentary structures. After studying the stratigraphical relations, the sediments were grouped into sedimentary units and subunits. Thickness of the units and subunits were measured in the cross-sectional channel and other channels. At several locations samples of organic materials were taken for carbon-14 datings. A sedimentological interpretation of the units was made, as well as a model sequence for the sediments in the Yucatica area.

Soils were also studied in the Yucatica area. Different soil-types were distinguished, and related to their drainage characteristics. The soil-types were described (FAO-system) and mapped (see appendix).

6. Descriptions and interpretations

6.1 Cross section

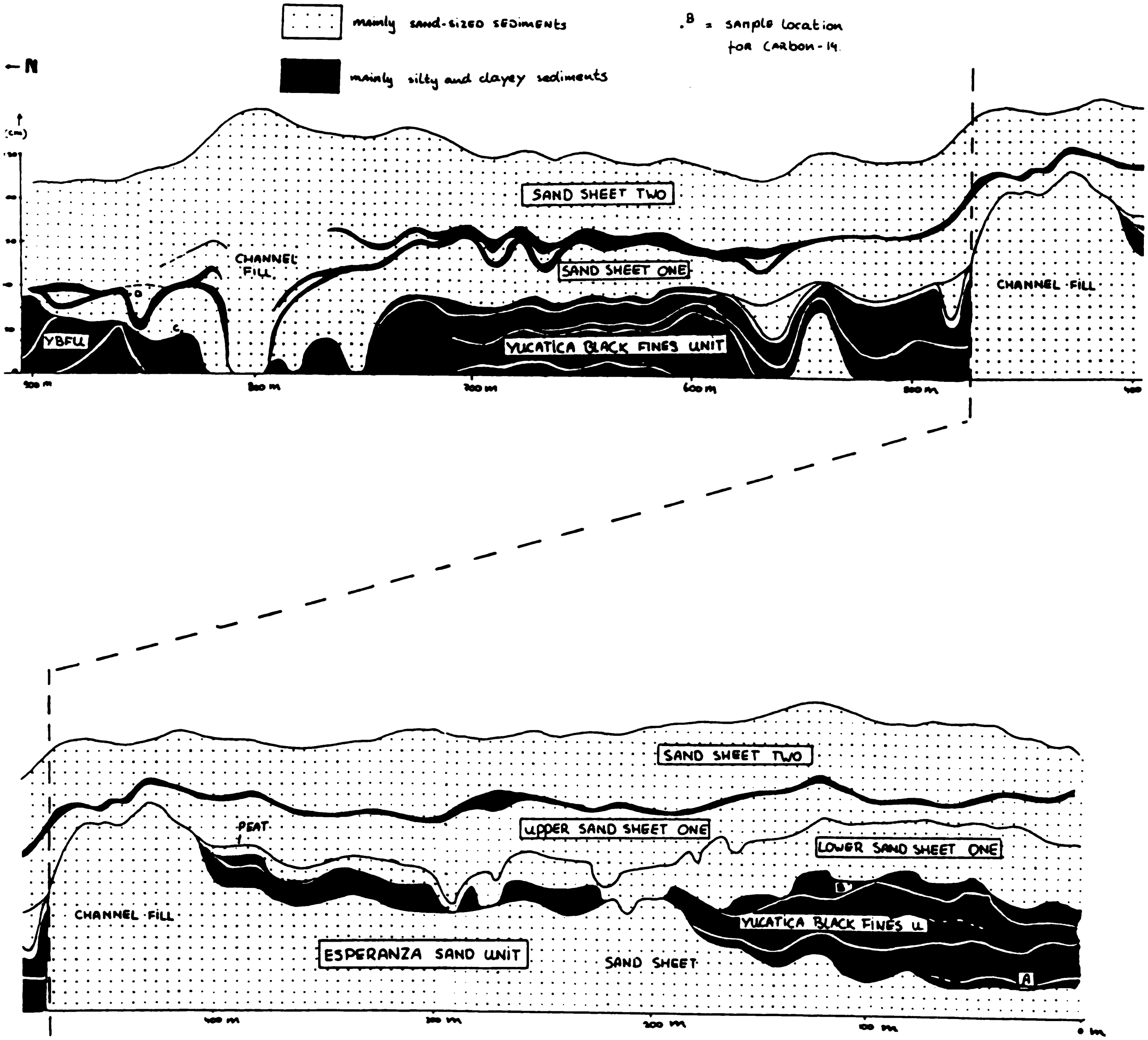


Fig. 6.19. Cross section that was made in a 900 m long channel. See fig. 5.1 for exact location.

6.2 Carbon-14 datings

sample		age (years)	dated material
Yucatica BSFZ 2	A	2500 ± 80 BP	nut
Yucatica BSFZ 1	B	3020 ± 80 BP	branche
Yucatica SF 2	C	2340 ± 60 BP	branches
Yucatica SF 1	D	2165 ± 30 BP	branches

Fig. 6.1 shows the exact sample locations. Sample A was taken from the basis of the Yucatica Black Fines Unit and represents the maximum age of the Backswamp Unit, which is 2500 ± 80 years. Sample B was taken from the upper part from the Yucatica Black Fines Unit and reveals a maximum age of 3020 ± 80 years. This can not be the actual age of the Yucatica Black Fines Unit since it can be not older than the basis of the same deposit. Most likely sample B is from a reworked branche. It could have been stored in a bog, and after some centuries reworked and redeposited as part of the Yucatica Black Fines Unit.

Sample C was taken at the basis of the Sand Sheet One and reveals a maximum age of 2340 ± 60 years. Sample D represents the maximum age of Sand Sheet Two which is 2165 ± 30 years.

6.3 Esperanza Sand Unit

Description:

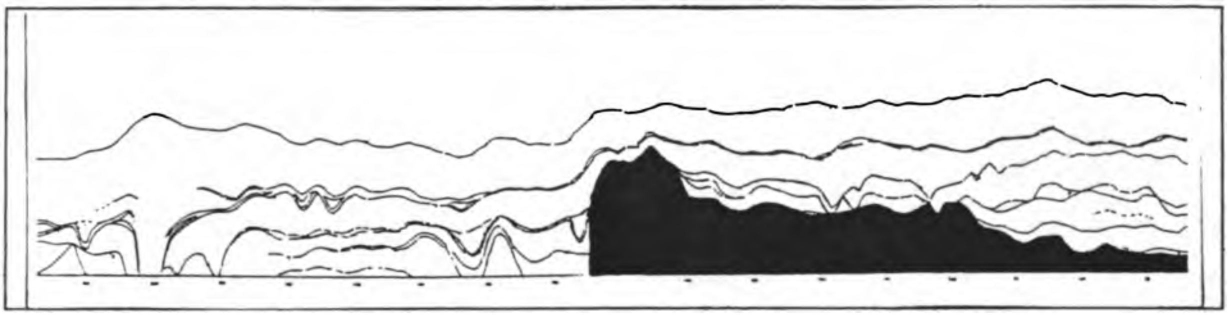


Fig. 6.2. In black, location of the Esperanza Sand Unit in cross section.

The Esperanza Sand Unit (see fig. 6.2, for details see fig. 6.19), which is at least 2500 years old, only occurs in the southern part of the cross-section and underlies the Yucatica Black Fines Unit and the Yucatica Sand Sheet Unit. The Esperanza Sand Unit forms a sandy body containing a channel fill which laterally towards the south grades into a massive sandsheet (see fig. 6.19).

The sand sheet is more than 400 m wide. It is not certain if this is the actual width perpendicular to the paleo-flow direction, since the flow direction could not be determined. Thickness of the sheet is at least 32 to 100 cm. The deposit has been strongly weathered and consists of fine to medium, unstratified sand. Dominant facies is Sm (see facies codes, table 4.2).

The channel fill (see fig. 6.3 and 6.4) is about 70 m wide and at least 200 cm thick. Texture is fine to very coarse sand. Few rounded volcanic pebbles, with diameters up to 6 cm, are found above erosive boundaries. The sediments are planar- and cross-stratified. Dominant facies are Sp and St.

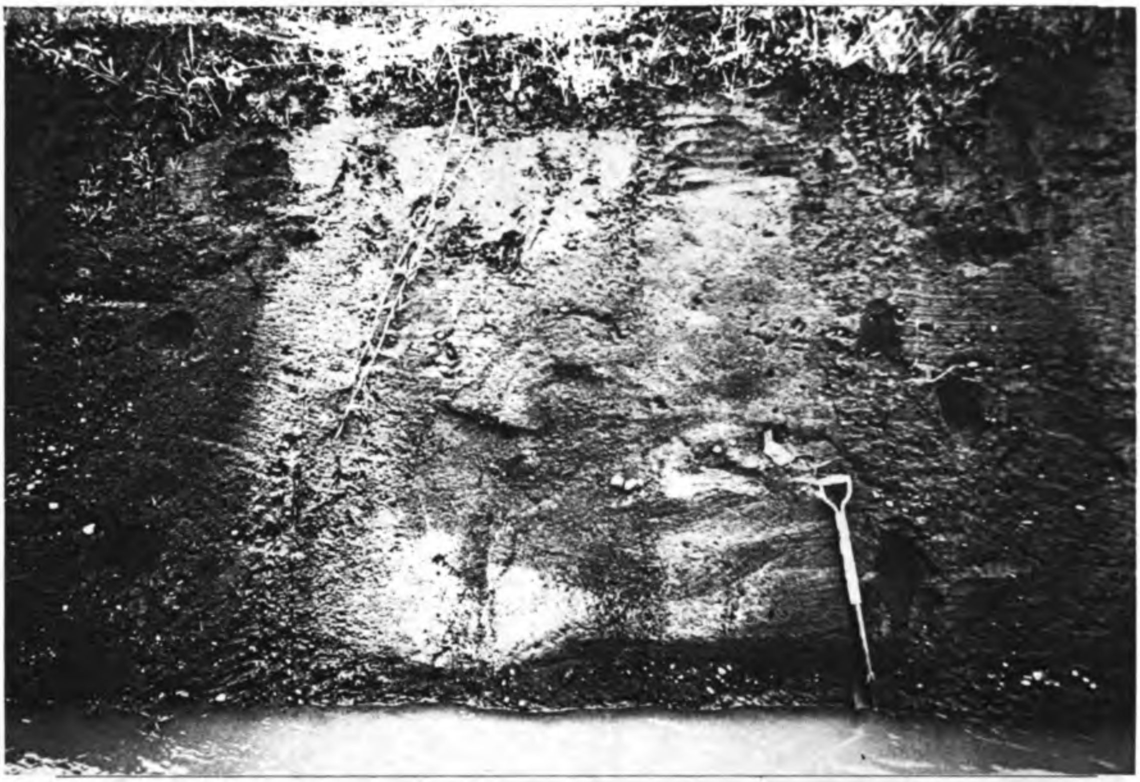


Fig 6.3. Paleosol in the top of the Esperanza Sand Unit. A = Black coloured top horizon, B = orange mottled horizon, ESU = Esperanza Sand Unit.

In the top of the Esperanza Sand Unit a soil occurs (see fig.6.3), consisting of a black tixotropic top horizon and an orange mottled horizon beneath it. Thickness of the dark horizon ranges from about 40 cm in the channel fill to less than 15 cm at the most southern part of the sand sheet. Towards the south the Esperanza Sand Unit lies at greater depth below the current surface.

Interpretation:

The Esperanza Sand Unit is interpreted as a braided river deposit, in which a more than 2 m thick and at least 70 m wide channel fill occurs. Major parts of it were deposited by migration of dunes and linguoid bars under lower flow conditions. The buried megaripple (in fig

6.4) indicates a period of high sediment supply.

Fig 6.4. Sedimentary structures in the channel fill of the Esperanza Sand Unit. M = burried mega-ripple, St = trough cross stratification, Sp = planar cross stratification.

The in-channel deposits laterally grade (with increasing distance away from the channel) into an unstratified sandsheet with a width of maximally 400 m. Interpretation of the massiveness of this sheet is difficult because of it has been strongly weathered. Thus, it is not clear if the non-stratification is primary sedimentary or the result of weathering. It is most likely that the sand sheet was formed during floodings and periods of much sandy sediment supply.

At last the stream choked its bedding and consequently abandonned it (see fig. 6.5). Soil formation started and lasted until the Esperanza Sand Unit became covered with fresh sediments (see fig. 6.9). Considering the thickness of the paleosol, the channel fill was the last

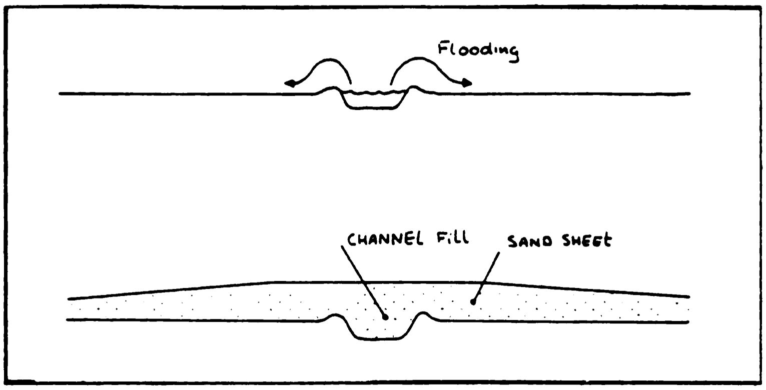


Fig. 6.5. During floodings a sand sheet was formed and the stream bed was choked.

part that became covered by sediments. In comparison with modern soils formed under the same conditions in volcaniclastic material, the paleosol with the 40 cm thick dark tophorizon, could have been formed in at least 2000 years. This is a rough estimation.

6.4 The Yucatica Black Fines Unit

Description

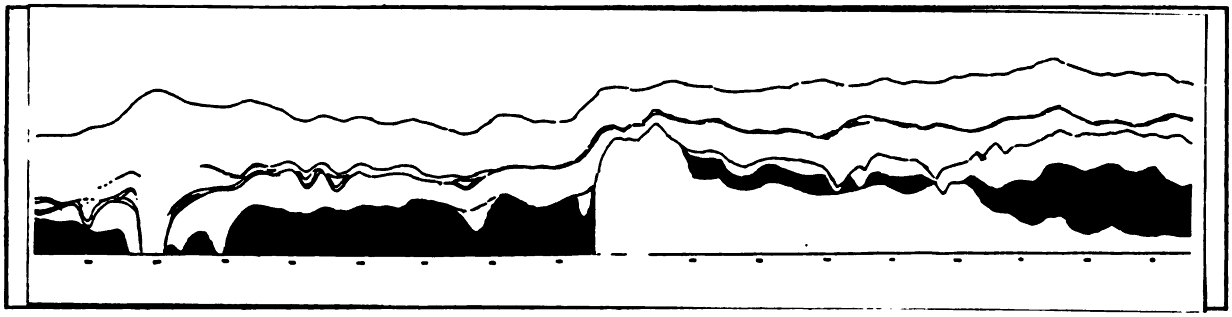


Fig. 6.6. In black, location of the Yucatica Black Fines Unit in cross section.

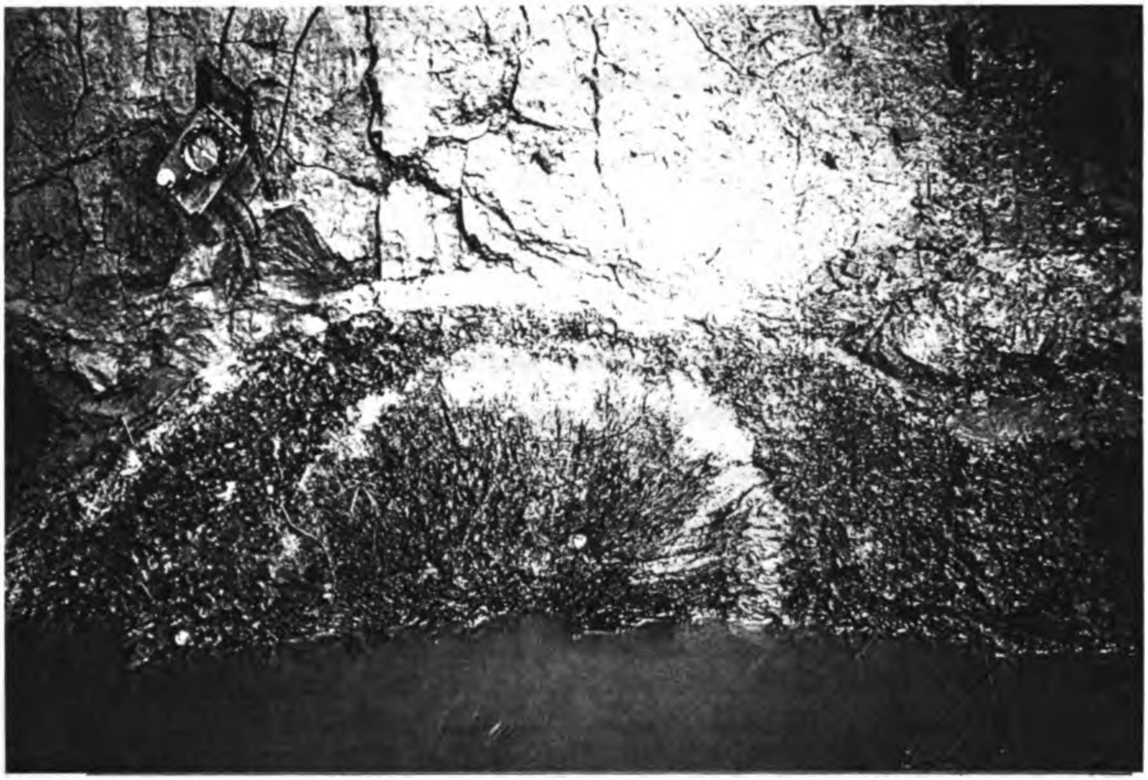


Fig. 6.7. Tree trunk in the Yucatica Black Fines Unit.

The Yucatica Black Fines Unit partly overlies the Esperanza Sand Unit and is up to 90 cm thick (see fig. 6.6, for details see fig. 6.19). The unit is at most 2500 ± 80 years old and itwas deposited in less than 160 years. North of the Esperanza Sand Unit in the cross-section the Yucatica Black Fines Unit is located beside the Esperanza Sand Unit, contacting it with an erosive boundary. The Yucatica Black Fines Unit consists of a sequence of very finely laminated clayey, silty and fine-sandy layers. It also contains some fine to medium sandy lenses with small scale cross-stratification. The lenses are about 40 m wide and up to 40 cm thick. The top of the unit contain loadcasts (see fig. 6.8). Dominant facies is Fl, and minor facies Sr.

The Unit is mainly dark-coloured because of its high content of organic material; large tree trunks (see fig. 6.7 and 6.12), tree roots, leafs, branches, seeds and peats. It also contains a

30 m wide and about 25 cm thick peat-layer. North of the Esperanza Sand Unit channel fill a 5 cm thick paleosol (characterized by mature clay and black mottling) has formed in the top of the unit.

Interpretation

The Yucatica Black Fines Unit mainly contains waning flood and overbank deposits. Sand lenses represent small streams that probably were filled with sand during flooding. Thus, textures and sedimentary structures represent a relatively quiet environment (see fig. 6.9). The peat layer, branches, leafs, tree trunks, roots, etc, suggest that the area was covered with abundant vegetation.

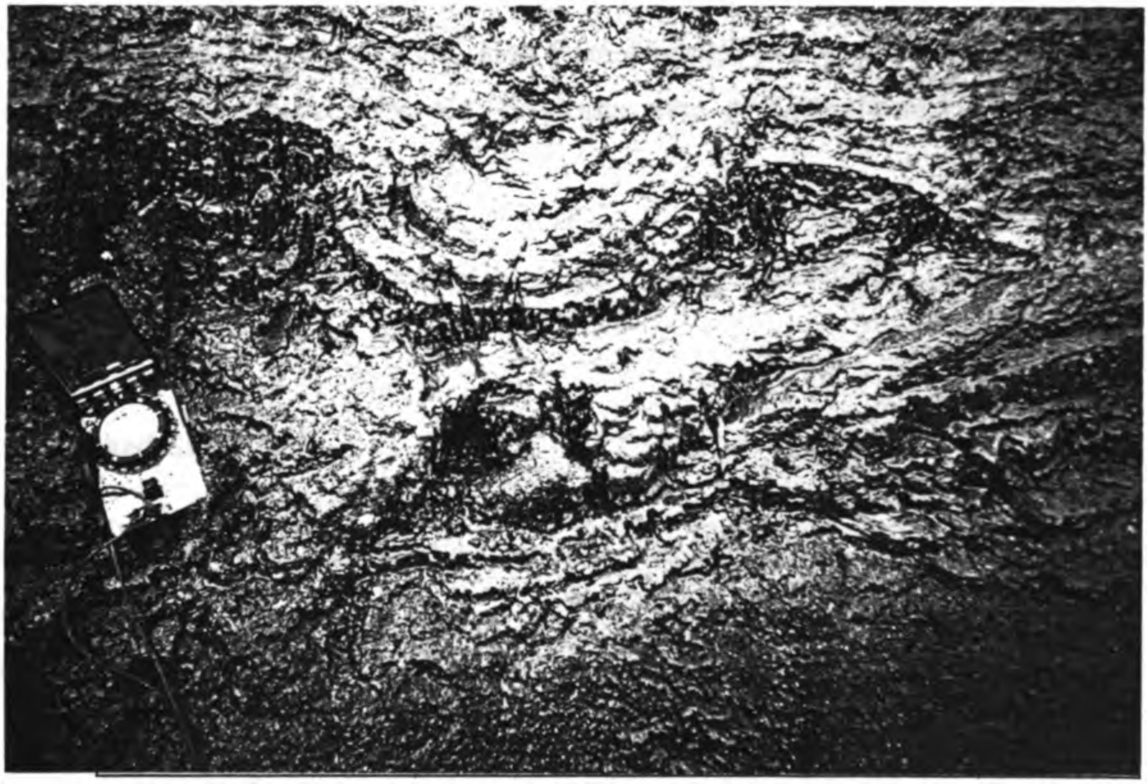


Fig. 6.8. Loadcasts. SSO = Sand Sheet One, YBFU = Yucatica Black Fines Unit.

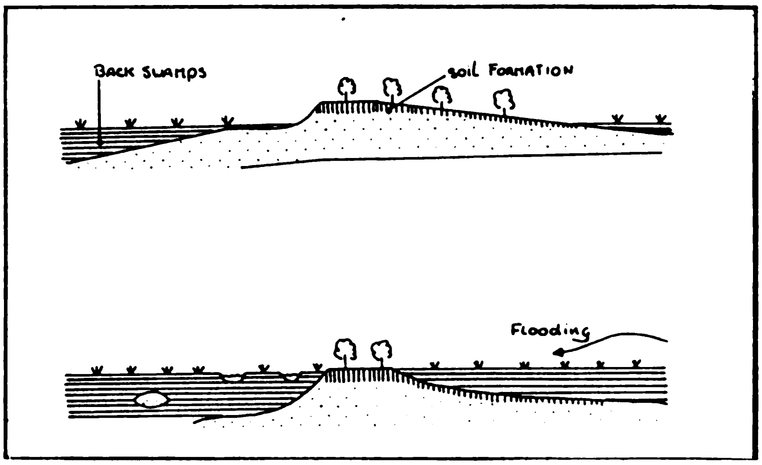


Fig 6.9. Deposition of the Yucatica Black Fines Unit

The Yucatica Black Fines Unit is likely to have been deposited in a swampy environment in which organic matter could be preserved. Loadcasts were probably formed due to post-depositional seismic activity.

In better drained parts or the topographical highs thin soils had developed, for example the thin soil described above.

6.5 Yucatica Sand Sheet Unit

The Yucatica Sand Sheet Unit contains three Subunits: Two sand sheets and a clayey layer.

6.5.1 Sand Sheet One

Description:

Sand Sheet One (see fig. 6.10, for details see fig. 6.19) is composed of an upper and a lower sand sheet, and some sand lenses. The upper sand sheet overlies two sand lenses in the

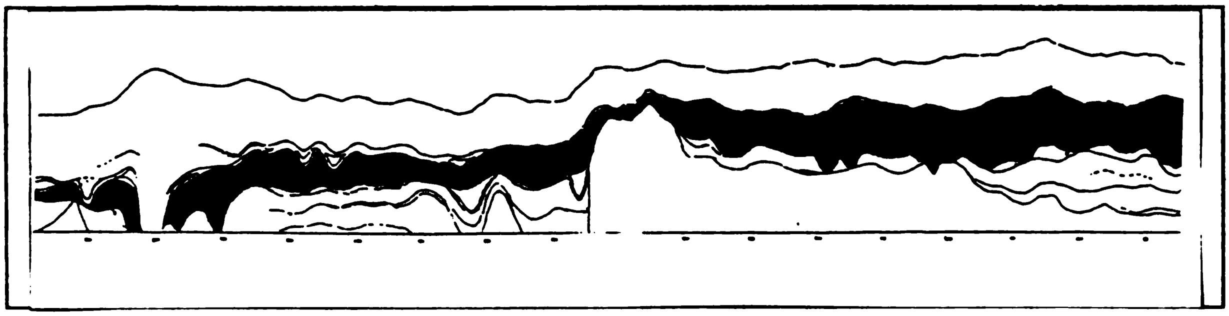


Fig. 6.10. In black, location of Sand Sheet One in the cross-section.

northern part of the crossectional area. In the southern part, lateral away from the the channel fill of Yucatica Sand Sheet Unit (see fig. 6.19), the upper sand sheet overlies the lower sand sheet. Sand Sheet One is at least 2340 ± 60 years old.

The lower sand sheet is 20 to 75 cm thick, and overlies the Yucatica Black Fines Unit. The fine to very coarse sand texture is poorly to moderately sorted and non-rounded. Scour fills at the base of the sand sheet are pebbly. The sand is mainly horizontally stratified (Sh) and trough cross-stratified (St). The sheet contains much reworked branches and leafs. It has an erosive boundary with the Yucatica Black Fines Unit and the Esperanza Sand Unit.

Laterally nearby the channel fill of the Yucatica Sand Sheet Unit in the northern part of the cross-section, the lower sand sheet is absent. There, sand lenses occur of about 30 m wide and up to 80 cm thick. The lenses consist of cross-stratified, moderately sorted, fine to very coarse sand, and contain reworked organic matter.

The upper sand sheet is a continuous, more than 800 m wide (perpendicular to the paleoflow direction) and between 20 and 100 cm thick sheet. It overlies all sediments of the Yucatica Black Fines Unit and the lower sand sheet. It has a poorly to well sorted, fine to very coarse sandy texture. Scour fills at the base of the sheet are pebbly. The sheet is predominantly trough cross-stratified (St) (see fig. 6.11) or unstratified (Sm), but also planar cross-stratification (Sp) and horizontal stratification (Sh) occur.

The upper sand sheet is the lateral continuation of a channel in the northern cross-section. Nearby this channel the upper sand sheet conformably overlies the Yucatica Black Fines Unit (see fig. 6.12). Laterally away from the channel the sheet has an erosional boundary with the underlying lower sand sheet.

Interpretation:

The lower sand sheet is a braided river deposits from which major parts were deposited from planar bed flow in the upper flow regime and from migration of dunes under lower flow conditions. The absence of scours or pedogenic features within the sheet and the presence of much reworked organic matter indicates that rate of deposition was high in a high energy environment.

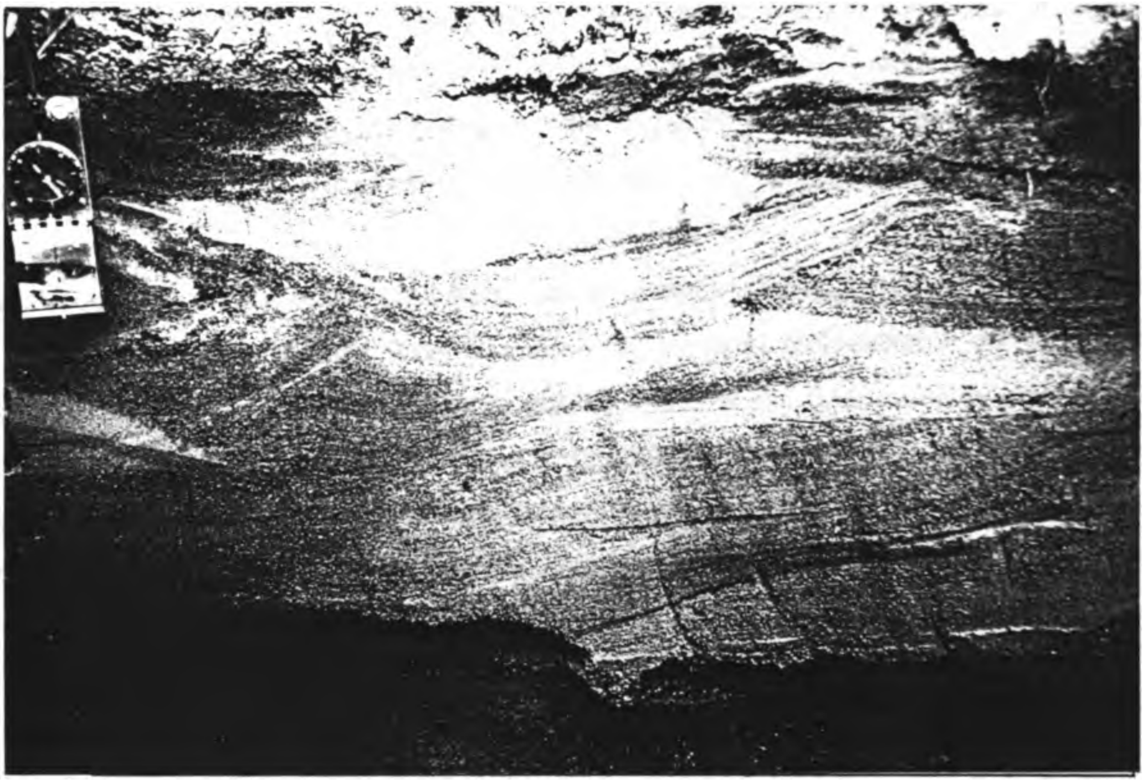


Fig. 6.11. Trough cross stratification in the Upper Sand Sheet One.

The sand lenses closer to the channel fill of the Yucatica Sand Sheet Unit have been deposited under lower flow conditions by migration of dunes. The lenses represent small channel fills. These fills can stratigraphically be correlated to the lower sand sheet, because both deposits formed after deposition of the Yucatica Black Fines Unit and before deposition of the upper sand sheet. During deposition of the channel fills, the northern part of the cross-section was topograghically higher (thin paleosol in top of the Yucatica Black Fines Unit) than the southern part. In the southern part a braided stream developed while in the northen part of the cross-section only small channels were filled (see fig. 6.13).

The upper sand sheet (see fig. 6.13) is interpreted as a braided river deposit of which major parts were deposited both under 1) 'normal' lower flow conditions, by migration of dunes (cross-stratification) and 2) hyperconcentrated sediment flow conditions (massive sands) (see chapter 7.1). The cross-stratification which mainly occurs in the southern cross-section, seems to be associated with scours and erosive boundaries within and at the bottom of the sheet. In the northern part hyperconcentrated sediment flow deposits dominate. These deposits are probably associated with non-erosional contacts with underlying sediments.

The lateral continuity of the upper sandsheet, which amounts more than 900 m perpendicular to flow direction, suggests that the sheet was deposited by rapid sedimentation during one or perhaps a few floods. In the southern part of the cross-section the flow probably had a more braided river character while in the northern crossectional area the flow had a more hyperconcentrated sediment flow character. One of the feeder channel was probably the main channel of the Yucatica Sand Sheet Unit (see fig. 6.19). Deposition took place in a high-energy environment. Stream power was probably big enough to unroot trees (unrooted tree, see fig. 6.12).

Fig. 6.12. Remnants of an unrooted tree in the Yucatica Black Fines Unit. SSO = Sand Sheet One, YBFU = Yucatica Black Fines Unit.

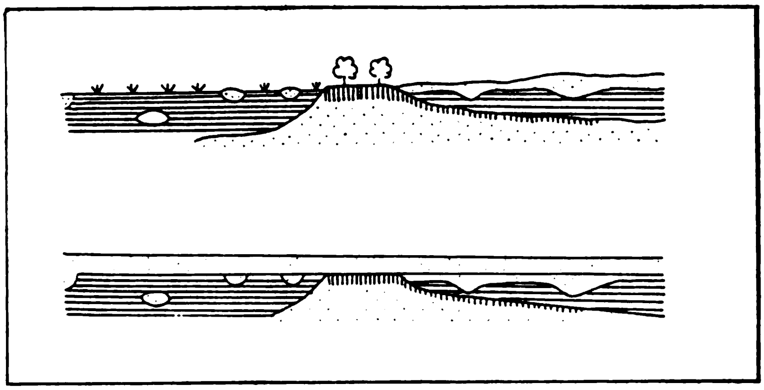


Fig. 6.13. a) Deposition of the Upper Sand Sheet One and, b) deposition of the Lower Sand Sheet One.

6.5.2 White Fines Deposit

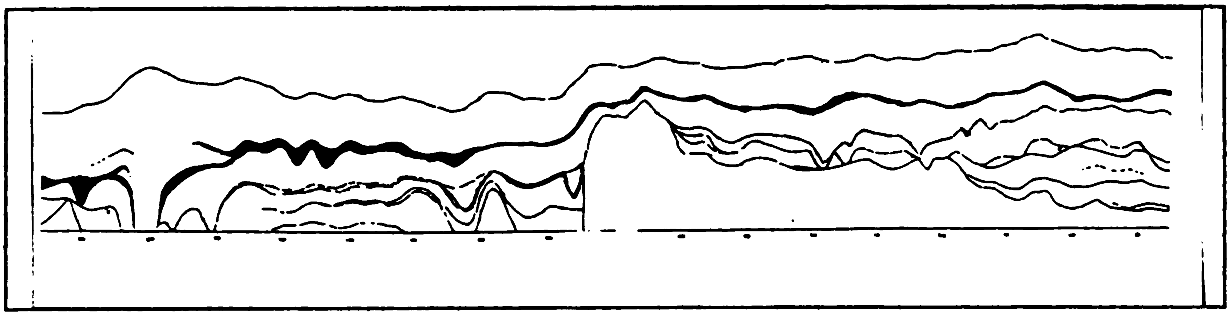


Fig. 6.14. In black, location of the White Fines Deposit.

Description

The White Fines Deposit (see fig. 6.14, for more details see fig. 6.19) is a very fine-grained layer, between 10 and 30 cm thick, which separates the Sand Sheet One and the underlying Sand Sheet One. It is at least 2165 ± 30 years old. Deposition of the Sand Sheet One and the White Fines Deposit took place in less than 175 years. Because of the characteristical white colour of it, the White Fines Deposit is a markable layer that can be recognized in the whole

Description

The Sand Sheet Two (see fig. 6.16 and fig. 6.17, for more details see fig. 6.19) is an at least 50 cm thick sand sheet that covers the whole Yucatica area (more than 1,5 km^3). It is at most 2165 ± 30 years old.

One main channel can be recognized consisting of a more than 250 cm thick and more than 20 m wide sand body, with a paleo-flow direction toward the north-east. The channel laterally grades into a sand sheet that extends for more than 800 m towards the south-east and more than 800 m towards the north-west. Thickness of the sheet ranges from 50 to 200 cm.

The in-channel deposits consist of fine to very coarse sand and contain few small pebbles. In the lower part of the channel the deposits are horizontally stratified (Sh) and planar cross-stratified (Sp), and the pebbles are concentrated at erosive boundaries. Higher in the in-channel sequence massive sands (Sm), containing few floating pebbles, dominate. Within this in-channel deposit five units can be distinguished, three of them having an erosional base. The channel deposits have an erosional contact with the Yucatica Black Fines Unit and the Sand Sheet One.

The sand sheet, which is a lateral continuation of the channel, consists of poorly to well sorted, fine to coarse sand, and contains few pebbles. Downstream and laterally away from the main channel texture is slightly finer. Major parts are unstratified (Sm) and normally graded. Some trough stratification (St) occurs. The sheet conformably overlies the White Fines Deposit.

The three dimensional shape of the Sand Sheet Two deposit shows a north-eastern paleo-flow direction (see fig. 6.17). Downstream the main-channel width decreases from about 110 m to 20 m. Thickness of the sand sheet decreases both downstream and laterally away from the main channel. The deposit seems to have a lobe form in which the channel structures show a slightly distribuary pattern and faint out.

Yucatica area. The White Fines Deposit has a clayey to silty texture and contains few fine-sand lenses of about 10 m wide. The sediment is predominantly horizontally laminated. Dominant Facies is Fl (Sr in sandlenses). It contains little organic material (less than 1%) like branches and leafs. When the sediment dries it gets its characteristical light grey colour.

Interpretation

The fine texture, the fine lamination and the facies association (Fl and Sr) indicate that the White Fines Deposit is an overbank deposit. It was deposited during flooding of a nearby flowing stream (see fig 6.15), probably the Yucatica Sand Sheet Unit channel fill (see fig. 6.19). The sandlenses are probably crevasse splays, deposited under lower flow conditions (Sr). Because of its relatively small contents of organic matter, the White Fines Deposit easily oxidizes and becomes white coloured.

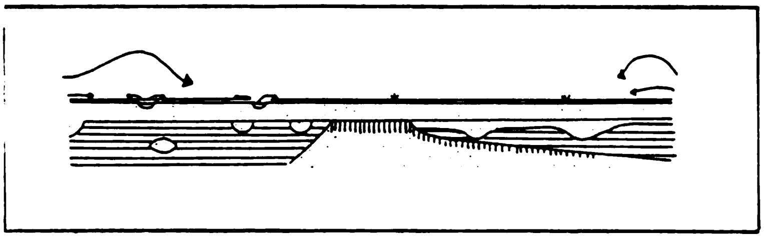


Fig. 6.15. Deposition of the White Fines Deposit.

6.5.3 Sand Sheet Two

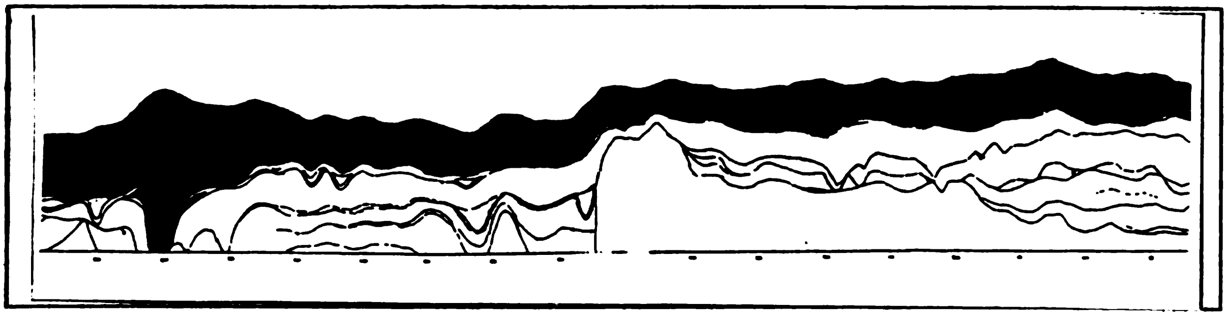


Fig. 16.6 In black, location of Sand Sheet Two.

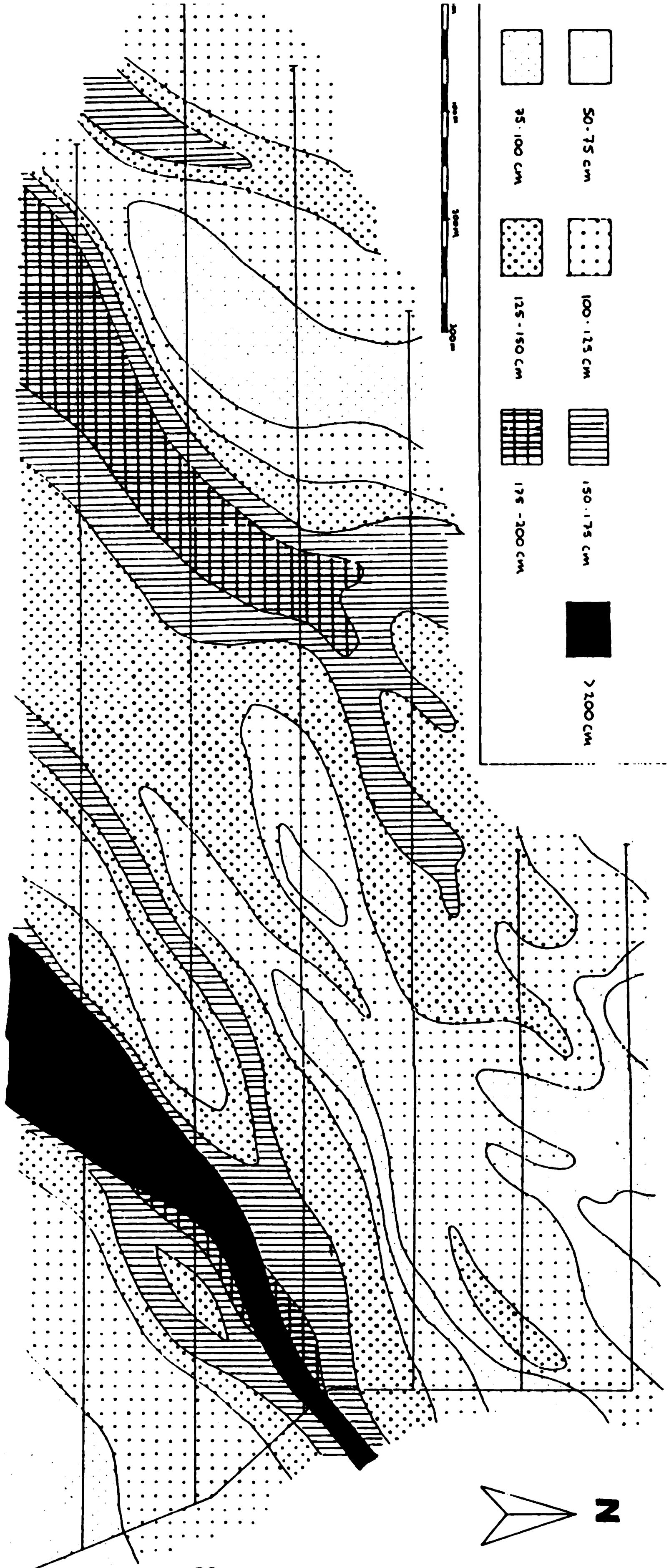


Fig. 6.17. Thickness of Sand Sheet Two

A well developed soil had formed in the top of the Sand Sheet Two (see appendix).

Interpretation:

The lateral continuity and massiveness of the sand sheet suggests that the main part of the sheet was deposited by a highly concentrated sediment flow (chapter 7.1). The flow entered the studied area from the south-west and probably spreaded out over the area while rapidly depositing its sandy sediment load. Some downstream and lateral sorting happened. Erosion of the underlying sediments did not happen, except for the banks besides the main channel. Before the highly concentrated sediment flow reached the area the main channel already existed, in which normal fluvial sediments had been deposited by migration of liguiod bars and by planar bed flow.

The flow probably followed the existing the paleo-topography. The flow didnot cut channels itself. Thus, thickness of the sheet is determined by the paleo-topography and the lateral distance toward the main channel and distance toward the source area. During the flow event an amount of 1,250,000 m^3 sediment was deposited in the studied area (average thickness = 125 cm, surface area = 1.0 km^3). During deposition the area became choked with sand and the Yucatica area was abandonned (see fig 6.18).

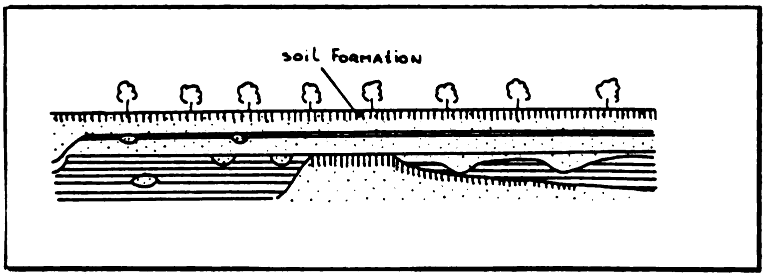


Fig. 6.18. After deposition of Sand Sheet Two, soil formation starts.

7. Discussion and conclusions

7.1 Mechanisms of transport and deposition

Point of discussion is the mechanism of transport and deposition of the massive sandy deposits, occurring in the Esperanza Sand Unit and the Yucatica Sand Sheet Unit. Most of the stratified sands were deposited under normal fluvial conditions as in-channel deposits or flood deposits by migration of linguiod bars and dunes and by planar bed flow, under both lower and upper flow conditions.

The following discussion of the massive sands, which were probably not deposited under normal fluvial conditions, will be mainly confined to the Sand Sheet Two, since this deposit has best been studied. The non-stratified sands contain fine to very coarse sand, are moderately to poorly sorted, non-graded and normal-graded, and contain a few small floating pebbles. The lower surfaces are commonly not erosional. The massive sands form the major part of the continuous sand sheets in the Yucatica Sand Sheet Unit and probably also in the Esperanza Sand Unit, but they can laterally change into more stratified parts such as the channel fill in the Sand Sheet Two, dominated by more fluvial deposits. The Sand Sheet Two is lobe shaped, thickness of the sheet decreases downstream and laterally away from the main channel. Grainsize slightly decreases downstream. According to its continuity and the absence of erosional boundaries within the deposit, the Sand Sheet Two is supposed to be deposited in mainly one flow event.

Transport of the Sand Sheet Two sediments towards the Yucatica area may have happened in several ways (see chapter 4.5): 1) In a normal Newtonian water-flow, in which the sediments are simply carried along with and by the fluid 2) In a non-Newtonian sediment concentrated water flow, which acts as a sort of gravity flow. 3) In a debris flow, that is an extremely concentrated dispersion of sediment, behaving like a Bingam plastic. 4) In a hyperconcentrated flow in which the fluid is rather a hot gas (i.e. a pyroclastic flow).

The non-stratification indicates that the sediments were dumped very rapidly, without subsequent reworking from a highly concentrated sediment dispersion. The lobe shape and the non-erosional boundaries at the lower surfaces also suggest deposition from a sediment gravity flow. The Sand Sheet Two also has fluvial characteristics: Erosional surfaces and fluvial strata in channel-fills, laterally grading into non-stratified sands, the absence of large boulders and the relatively good sorting (mainly sand-sized material). The mixed character of a sediment gravity flow and a fluvial deposit supports the idea that the the transport medium is rather water that a hot gas.

Thus, the Sand Sheet Two is most likely to have been transported and deposited as a concentrated sandy sediment dispersion or sediment gravity flow containing water. It has some fluvial characteristics. The flow is a mixture between a real debris- or mud-flow and a normal sediment carrying stream flow. In the hinterland, the source material probably started flowing under the influence of gravity, after mixing with water. When flow velocity increased, viscosity of the sediment flow decreased. After flowing downslope, the flow entered the flat Yucatica area and flow velocity decreased. The flow viscosity again became higher, so that the main parts of the flow freezed and were deposited rapidly as a homogenous mass, without much reworking.

The absence of boulders and the dominance of sandy material can have been resulted from the nature of the source, which would have been mainly sandy, and the absence of reworking processes of coarse-grained sediments during transport.

The massive parts of Sand Sheet One and the Esperanza Sand Unit probably also result from this same kind of concentrated sandy sediment dispersion flows.

7.2 Sedimentation related to volcanism.

The Yucatica area is located 37 km north at the foot of the Turrialba volcano (see fig. 2.4). Sedimentation in this area is supposed to be related to eruptions of the Turrialba volcano, that have produced large amounts of volcaniclastic materials. Chapter 2 shows the chronology of the Turrialba eruptions during the last 8,000 years.

Fig. 7.1 shows a model sequence for the Yucatica deposits. The sequence is dominated by massive and stratified sands with some interbedded finer grained layers. The model consists of two major cyclic sequences, both containing a well developed soil in their top. The upper part of the sequence is subdivided in two more cyclic sequences.

The cyclicity within the Yucatica sequence is the result of frequent changes of high sediment input and periods of low sediment input. During periods of high sediment input both massive and stratified sand sheets are deposited, both by stream flows and highly concentrated sediment flows. During periods of low sediment input soils are formed and backswamp sediments are deposited.

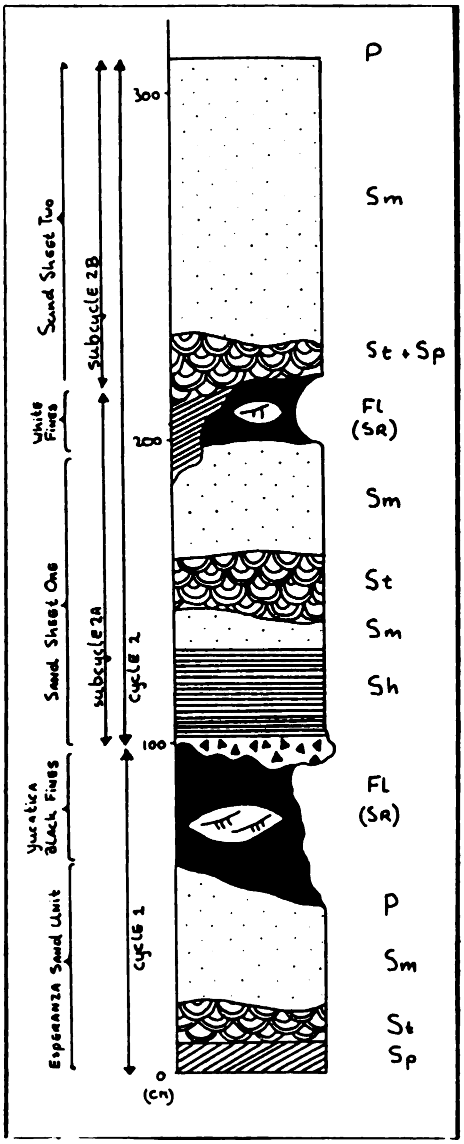


Fig. 7.1. Model sequence of the Yucatica deposits.

The irregular sediment input can be explained by 1) episodic sediment supply from the hinterland and 2) lateral facies movement of a river system over the alluvial fan and plain. Climatic influence can be neglected in the Yucatica area since climate has not changed the last 10,000 years.

In the second case, periods of relatively high sedimentation rates coïncide with the presence of an active river system. After some time, often due to avulsione, the active river system switches to another part on the alluvial fan or plain. The former active part becomes an inactive part of the alluvial system, and is characterized by low sedimentation rates.

In the case of episodic sediment supply from the hinterland, periods of high sedimentation rates are related to the volcanic and tectonically activity in the hinterland. Sedimentation in the Yucatica area seems to be influenced by volcanism and tectonical activity in the Cordillera Central. During episodes of volcanic activity large amounts of volcaniclastic sediments were deposited in the Atlantic lowland. A recent example of this proces is the volcaniclastic sand deposit in the Atlantic Zone, described by Nieuwenhuyse and Hartman (1991). After volcanic activity of the volcan Irazú from 1963 to 1965 followed by heavy rain showers in 1970, the Chirripó river choked its bedding with sandy sediments and changed its course. During this event a sandy body was deposited with an extension of 35 km, an average width of 50 m and at some places more than 200 cm thickness. This equals an amount of about 3.5 million m^3 sediment. The sedimentary structures in this deposit are cross- and horizontal-stratification, parts of the body are unstratified.

In the Yucatica area, two major periods of high sediment input are recognized. The first is represented by deposition of the Esperanza Sand Unit and probably occurred more than 4500 years BP. This period was followed by a period of low sediment input, which is marked by the paleosol in the Esperanza Sand Unit and the Yucatica Black Fines Unit sediments. This quiet period lasted at least until 2500 BP, and at most until 2340 BP. The Yucatica Sand Sheet Unit represents the second period of high sediment input and started maximal 2340 years BP. Within this period of high sediment input, a short period of quiescence has been recognized. It is represented by the White Fines Deposit and happened at least 2165 years BP. After the second period of high sediment input a period of quiescence followed that lasted until now. It is marked by the soil in the top of the Yucatica Sand Sheet Unit.

In fig. 7.2 the Yucatica sequence is stratigraphically correlated with the Turrialba eruptions. Deposition of the Yucatica Sand Sheet Unit can be related to the eruption unit 5 (see chapter

2) of the Turrialba. During this eruption about 0.075 km³ airfall and about 0.01-0.03 km³ pyroclastic flows and surges were deposited. Unit 5 is the largest volume pyroclastic deposits preserved at Turrialba. The voluminous fallout deposits probably supplied the sand sized source material of the Yucatica Sand Sheet Unit.

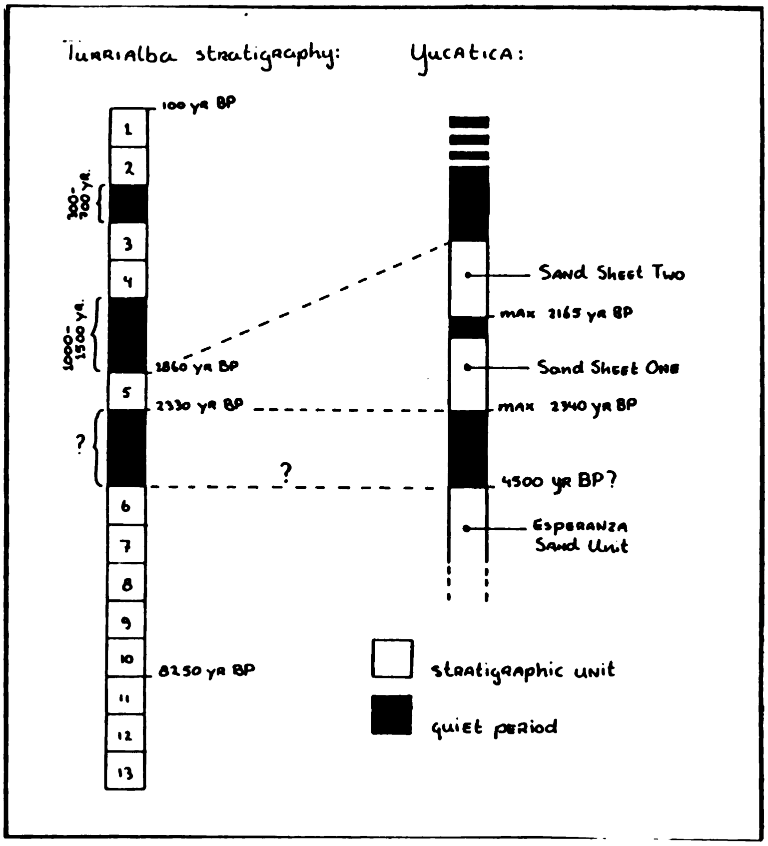


Fig. 7.2. Stratigaphical correlation of the Yucatica sequence with the Turrialba eruption units.

The period of soil formation, following the deposition of the Yucatica Sand Sheet Unit, seems to have resulted of a lateral facies movement on the alluvial plain, due to avulsion. Since that time the Turrialba has erupted several times, but no sediments were deposited in the Yucatica area. The period of soil formation that predated deposition of Yucatica Sand Sheet Unit can be correlated to the quiet period of the Turrialba, before unit 5 erupted. Deposition of the Esperanza Sand Unit probably consists of pyroclastic rocks derived from one of the earlier eruption units 6 to 13.

The Irazú volcano (see fig. 2.4) may also have influenced the sedimentation processes in the Yucatica area. However, influence was probably minor, since the vent lies further away.

7.3 A reconstruction of the Yucatica Sand Sheet Unit deposition.

2330 Years BP, following a quiet period, the Turrialba volcano became active. During eruptions large amounts of andesitic pyroclastic rocks were thrown out. Pumice, airfall, pyroclastic flows and surges were deposited on the slopes of the volcano and in nearby valleys.

Torrent rains that frequently occur in the Atlantic Zone (see chapter 3) and often accompany volcanic eruptions, caused mixing of water with the loose fallout deposits, which were stored on the slope of the volcano. This resulted in transport of the volcaniclastic materials into the Atlantic lowland. Transport mechanisms ranged from braided river streams to highly concentrated sediment flows and laharic debris flows. It is also possible that this sediment flows stemmed from hot pyroclastic flows mixed with water during eruptions.

Just before the Turrialba started erupting, the alluvial plain of the Atlantic lowland, about 30 km north and downslope of the volcano, was covered with tropical rain forest. In the Yucatica area backswamps had developed and in the drier parts soils had formed. During the following period of volcanic activity braided streams and highly concentrated sediment flows reached the Yucatica area (see fig. 7.3), while debris flows were deposited upstream. The braided streams commonly reworked upstream sediments and organic materials stored in swampy environments. Highly concentrated sediment flows did not erode and rework older deposits. While entering the Yucatica area probably part of the vegetation was destroyed. At least three floods or flows reached the area, but probably more. At most 2165 years BP, a voluminous, highly concentrated sediment flow deposited 1,250,000 m^3 sandy sediments and choked the area. A period of non-deposition and soil formation followed. Deposition probably continued in other parts of the alluvial plain. Deposition of the Yucatica Sand Sheet unit took place in a relatively short timespan, less than about 200 years.

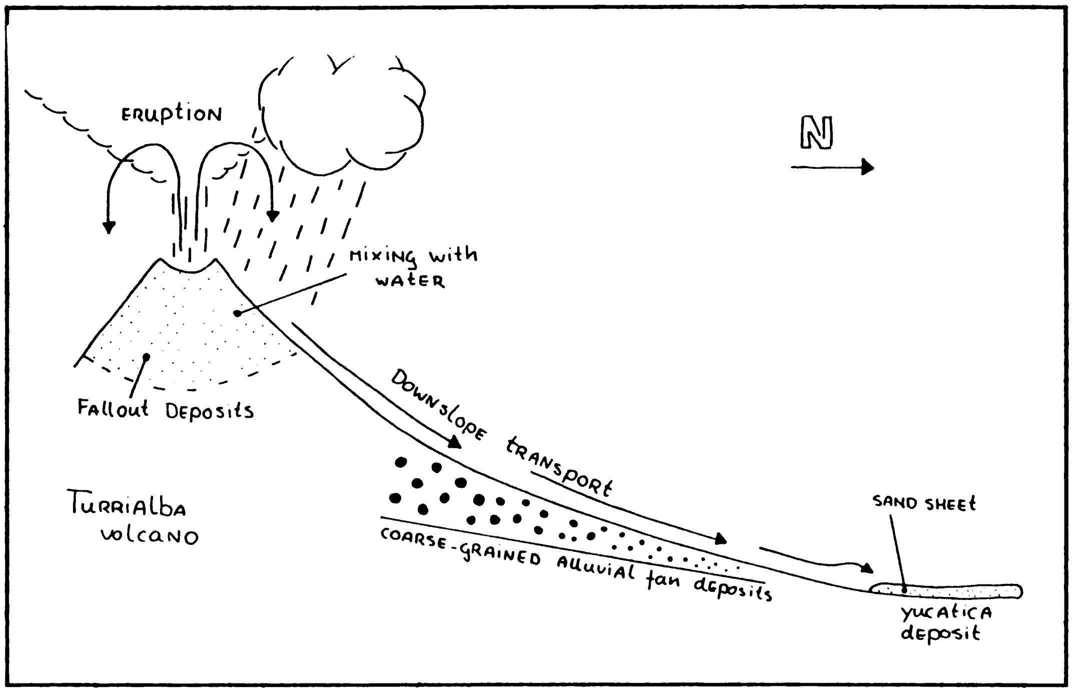


Fig. 7.3. Reconstruction of the Yucatica Sand Sheet Unit deposition.

7.4 The Yucatica sequence; an example of distal braided river deposition in a volcanic region.

A model sequence (see fig. 7.4) of the Yucatica model (of fig. 7.1) was made. This model sequence can be compared with existing models for braided river sequences (see chapter 4.3.2). According to grainsize of the fluvial sediments, the Yucatica model comes closest to the Platte and Bijou creek type, respectively a sand dominated, distal braided river deposit and a sandy river plain deposit subject to flash floods. The Bijou creek type has better developed cyclic sequences, like the Yucatica model. Lithofacies type Sm (massive sand), that frequently occurs in the Yucatica model is not present in the braided river types, but they may be related to the horizontal bedding of the Bijou creek type, since both types result from episodic flood deposits.

The Yucatica model sequence represents a distal braided river deposit nearby a volcanic active cordillera in a wet tropical environment. The sequence forms part of the distal volcanic facies type (Vessel and Davie, 1981).

7.1) was made.

Characteristic are the cyclic sequences produced by episodic input of sandy stream flows and concentrated sediment flows, which are related to periods of active volcanism in the hinterland and heavy rain showers. During episodes of much sediment input, sedimentation rates are high. Stream flows generate cross-bedded (St and Sp) and horizontally bedded (Sh) sands, the concentrated sediment flows generate massive sand deposits (Sm). An episode of high sedimentation rates is often terminated with a non-stratified sand deposit, choking the former stream beds. Due to its distal character the sequence contains little gravel.

Periods of low input of sediments are marked by pedogenic features (P) and/or depostion of laminated fines (Fl). During more quiet periods the sandy sediments are rapidly overgrown by tropical rain forest and due to the strong weathering conditions soils are developed rapidly in top of the sediments. In this environment probably quiet meandering river systems dominate and backswamps are formed.

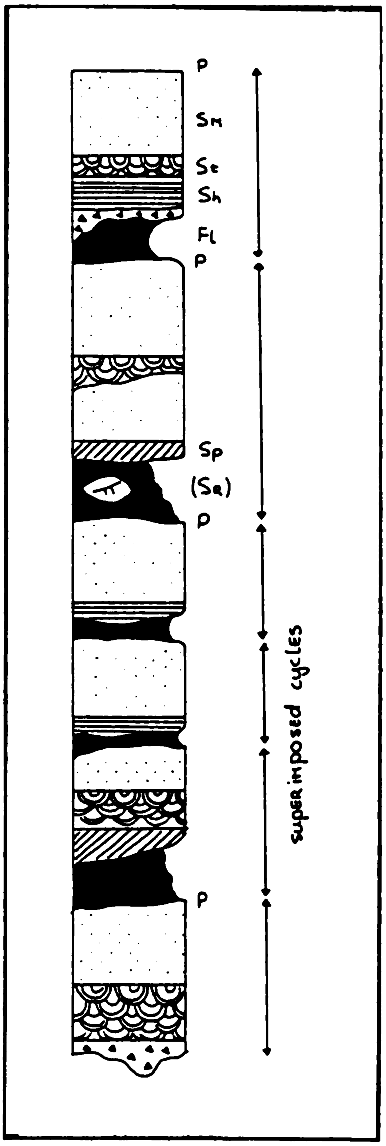


Fig. 7.4. A model-sequence for distal braided river deposits in a humid volcanic region.

Appendix A: Fold-out table with lithofacies codes

Code	Description	Interpretation
Gm	Massive or crudely bedded gravel	Longitudinal bars, lag deposits,sieve deposits
Gms	Massive matrix (sand and mud) supported gravel	Debris flow deposits
Gt	Trough cross-bedded, clast supported gravel	Minor channel fills
Gp	Planar cross-bedded gravel and/or matrix-supported gravel	Linguoid bars or deltaic growth
St	Trough cross-stratified sand	Dunes, lower flow regime
Sp	Planar cross-stratified sand	Linguoid bars, lower flow regime
Sh	Horizontally stratified sand	Planar bed flow, upper flow regime
Sr	Ripple marks and small-scale cross-stratification	Ripples, lower flow regime
Sm	massive sand a)	Very rapid deposition from suspension or from highly concentrated sandy sediment dispersions
Fl	Laminated or cross-laminated fine sand, silt or mud	Overbank or waning flood deposits
Fm	Massive, fine sandy mud or mud	Overbank or drape deposits
P	Pedogenic features	Soil formation

Appendix B: Soil descriptions

Five soil types have been distinguished, ranging from well drained (soil A) to poorly drained (soil E):

Soil A

Information on the site sampled

Profile number: 10.3
soil name: A
date of examination: 09-10-91
author: Frank van Ruitenbeek
location: see soil map
landform: summit, undulating, top of river bed
slope: flat
vegetation/landuse: agriculture, yuca
climate: humid tropics

General information on the soil

parent material: coarse sand
drainage: well drained
moisture conditions in the soil: moist throughout profile
human influence: deforestation

Brief general description of the profile

The A-soil is the best drianed soil in the studied area, it has a dark yellowish brown B-horizon and is formed on top of the channel fill of Sand Sheet Two.

Description of individual soil horizons

A 0-8cm: very dark grayish brown (10YR3/2) when moist; clay loam; moderate fine and medium subangular blocky; friable; non-sticky, slightly plastic; common fine and medium pores; frequent fine roots; smooth and clear to:

AB 8-17cm: brown/dark brown(10YR4/3) when moist; clay loam; weak fine and medium subangular blocky; very friable; non- sticky, non-plastic; common medium pores; few fine roots; wavy and gradual to;

B1 17-33cm: dark yellowish brown(10YR3/4) when moist; loam; very weak medium angulare blocky; very friable; non-sticky, non-plastic; many fine and medium pores; few fine roots; diffuse and wavy to:

B2 33-51cm: dark yellowish brown(10YR3/5) when moist; sandy loam; very weak medium angular blocky; ver friable; non-sticky, non-plastic; many fine and medium pores; difuse and wavy to:

BC 51-68cm: very dark grayish brown(2.5YR3/2) when moist; loamy sand; massif; firm; common medium pores; diffuse and wavy to:

C 68-120cm: very dark grayish brown(2.5YR3/2) when moist; gravelly coarse sand; loose.

B-SOIL

Information on the site sampled

profile number: 10.2
soil name: B
date of examination: 09-10-91
author: Frank van Ruitenbeek
location: see sil map
landform: slope, undulating, nearby top of sandsheet
slope: gently sloping
vegetation/landuse: agriculture and forest
climate: humid tropics

General information on the soil

parent material: fine and medium sand
drainage: well drained
moisture conditions in the soil: moist throughout profile
depth groundwater table: >2.5m.
human influence: deforestation

Briel general description of the profile

Well drained soil which has a dark yellowish brown B-horizon, at 80 cm depth the soil has brown mottles

Description of the individual soil horizons

A 0-16cm: very dark grayish brown(10YR3/2) when moist; silty clay loam; strong very fine and fine subangular blocky; fiable; slightly sticky, slihgtly platsic; many fine and medium pores; frequent very coarse to coarse roots; smooth and clear to:

B1 16-35cm: dark yellowish brown(10YR3/4) when moist; clay loam; weak fine to coarse angular blocky; very friable;non-sticky, non-plastic; many fine and medium pores; few medium roots; wavy and gradual to:

B2 35-51cm: dark yellowish brown(10YR4/4) when moist; clay loam; very weak fine to coarse angular blocky; friable; non-sticky, non-plastic; many fine and medium pores; few medium roots; gradual and wavy to:

BC1 50-81cm: brown/dark brown(10YR4/3) when moist; few, medium, faint, diffuse reddish mottles; loam; massif; very firm; common medium pores; gradual and wavy to:

BC2 80-106cm: brown(10YR5/3) and brown/darkbrown(10YR4/3) mottled when moist; sandy loam; firm; few, small, hard, red concrations; few fine pores; clear and smooth to:

C 106-120: grayish brown(10YR5/2) when moist; clay loam; very friable.

Soil C

Information on the site sampled

profile number: 11.1
soil name: C
date of examination: 10-10-91
author: Frank van Ruitenbeek
location: see soil map
landform: slope, undulating, between depression and top in sandsheet
slope: gently sloping
vegetation/landuse: agriculture and forest
climate: humid tropics

General information on the soil

parent material: fine sand
drainage: moderately well drained
moisture conditions in the soil: moist throughout the profile
depth groundwater table: >2.5m
human influence: deforestation

Brief general description of the profile

The soil has a dark brown B-horizon, is moderately well drained.

Description of the individual soil horizons

A 0-13cm: very dark grayish brown(10YR3/2) when moist; silty clay loam; strong very fine and fine subangular blocky; friable; non-sticky, slightly plastic; many fine and medium pores; frequent fine and medium pores; smooth and clear to:

B 13-29cm: dark brown(10YR3/3) when moist; clay loam; weak fine angular blocky; slightly friable; non-sticky, non-plastic; many fine and medium pores; few medium roots; smooth and diffuse to:

BC1 29-47cm: brown/dark brown(10YR3/4) when moist; loam; massif; friable; non-sticky, non-plastic; common fine and medium pores; wavy and gradual to:

BC2 47-66cm: brown/dark brown(10YR3/4) when moist; common medium, distinct, clear, orange mottles; sandy loam; massif; firm; common medium pores; wavy and diffuse to:

CB1 66-103cm: brown(10YR5/3) when moist; many coarse, distinct, clear, orange brown mottles; loamy sand; massif; firm; clear and wavy to;

CB2 103-120cm: brown(10YR5/3) when moist; many coarse, distinct, clear orange brown mottles; clay loam; massif; friable; few small, hard, irregular, red nodules.

Soil D

Information on the site sampled

profile number: 10.1
soil name: D
date of examination: 09-10-91
author of description: Frank van Ruitenbeek
location: see soil map
landform: slope, undulating, between top and depression in sandsheet
slope: gently sloping
vegetation/landuse: agriculture and forest
climate: humid tropics

General information on the soil

parent material: fine sand
drainage: moderatetly well/imperfectly drained
moisture conditions in the soil: moist throughout profile
depth groundwater table: > 2.5m
human influence: deforestation

Brief general description of the profile

The soil has a dark grayish brown B-horizon, is moderatly well/imperfectly drained and contains orange mottles at shallow depth.

Description of the individual soil horizons

A 0-14cm: very dark grayish brown(10YR3/2) when moist; silty clay loam; moderate medium and coarse granular; friable; slightly sticky, slightly plastic, many very fine and fine pores; frequent fine and medium roots; clear and smooth to:

B 14-32cm: dark grayish brown(10YR4/2) when moist; loam; very weak very fine and fine angular blocky; very fiable; non-sticky, non-plastic; common fine pores; gradual and wavy to:

BC 32-44cm: dark brown(10YR3/3) when moist; common coarse, faint, diffuse, orange/brown mottles; sandy loam; massif; firm; common fine and medium pores; gradual and wavy to:

CB1 44-58cm: grayish brown(10YR5/2) dark yellowish brown (10YR4/4) mottled when moist; sandy loam; massif; firm; few fine roots; gradual and smooth to:

CB2 58-100cm: grayish brown(10YR5/5) dark reddish brown(5YR3/4) mottled when moist; loam; massif; firm; very few, small, hard, red nodules; clear and smooth to:

C 100-120cm: grayish brown(10YR5/2) when moist; clay loam; massif; friable.

E-SOIL

Information on the site sampled

profile number: 14.1
soil name: E
date of examination: 12-10-91
author of description: Frank van Ruitenbeek
location: see soil map
landform: plain, flat, depression in sandsheet
slope: flat
vegetation/landuse: agriculture and forest
climate: humid tropics

General information on the soil

parent material: fine sand, at 100cm depth silty clay layer
drainage: imperfectly drained
moisture conditions in the soil: moist throughout the profile
depth groundwater table: >2.5m
human influence: deforestation

Brief general description of the profile

The soil is the poorliest drained one in the studied area, has a dark grayish brown B-horizon and many orange mottles starting at 34cm depht

Description of individual soil horizons

A 0-10cm:	very dark grayish brown(10YR3/2) when moist: clay loam; strong fine and medium subangular blocky; friable; non-sticky, non-plastic; common fine and medium pores; frequent fine and medium roots; clear and wavy to:
B 10-25cm:	dark grayish brown(10YR4/2) when moist; few fine, distinct, clear, orange mottles; loam; moderate fine angular and subangular blocky; friable; non-sticky, slightly plastic; many fine and medium pores; frequent fine roots; clear and wavy to:
CB1 25-34cm:	brown(10YR5/3) dark brown(7.5YR3/4) mottled when moist; fine sandy loam; massif; friable; many very fine and fine pores; gradual and wavy to:

C2 34-67cm: brown(10YR5/3) when moist; many coarse, prominent, clear orange mottles; medium sand; massif; very friable; common fine pores; abrupt and smooth to:

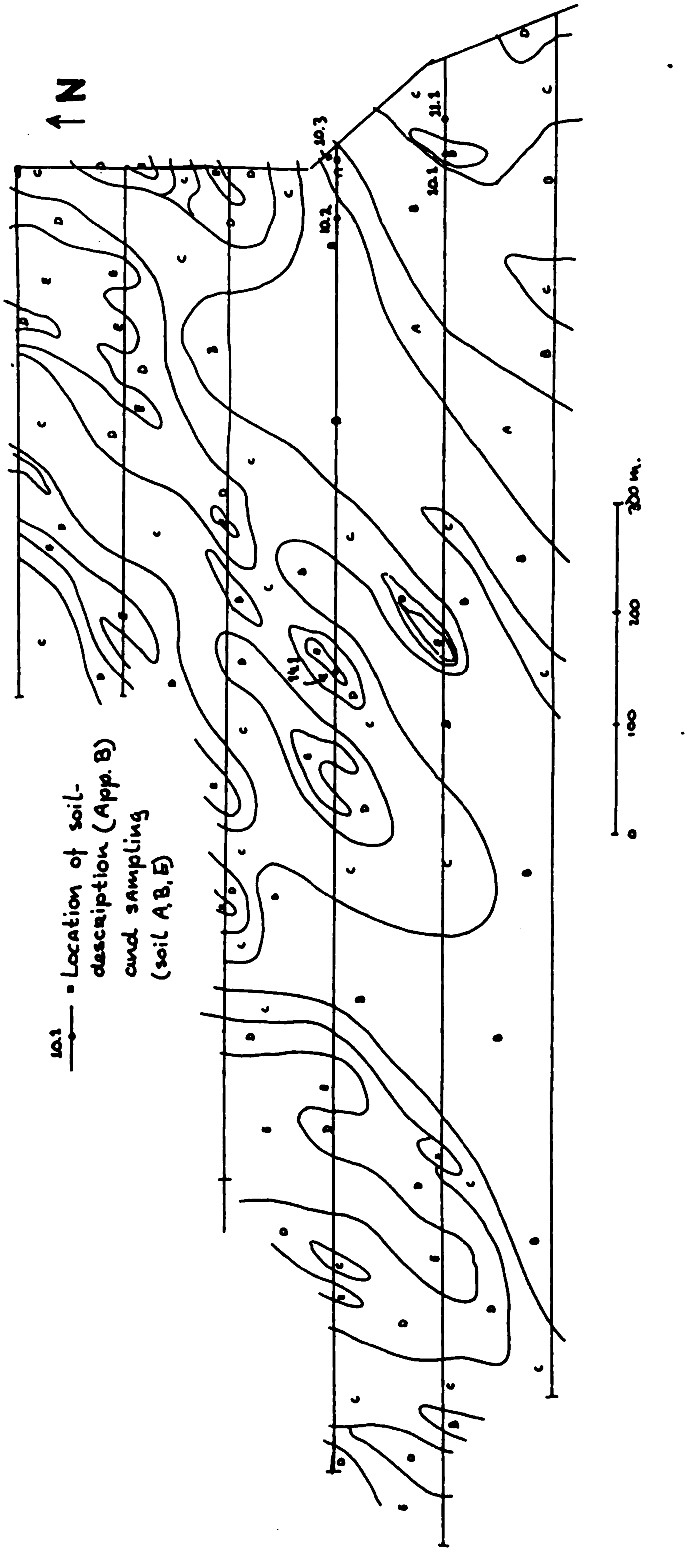
C3 67-69cm: pinkish gray(10YR6/2) when moist; siltloam; massif; friable; abrupt and smooth to:

C4 69-85cm: brown(10YR5/3) when moist; many coarse, prominent, clear orange mottles; fine sand; massif; friable; abrupt and wavy to:

C5 68-101cm: dark gray(10YR4/1) when moist; sandy loam; massif; friable; abrupt and wavy to:

C6 101-120cm: dark gray (10YR4/1) when moist; clay loam; massif; friable.

Appendix C: Soil map



A: Soil A; B: Soil B; C: Soil C; D: Soil D; E: Soil E

Appendix D: Soil analysis

Soil A:

Depth (cm)	O.M. (Wgt %)	pH-H_2O (1:2.5)	pH-NaF
0-8	8.6	6.3	10.6
8-17	6.4	6.1	10.9
17-33	3.8	6.2	11.0
33-51	2.4	6.3	11.1
51-68	0.5	6.0	10.5
68-120	0.5	6.0	9.4

	Ca - meq/	Mg 100g	K soil -	Na	CEC	Acidity
0-8	20.2	3.0	0.6	0.1	45.5	0.3
8-17	8.0	1.6	1.2	0.2	50.3	0.2
17-33	7.3	1.6	0.9	0.2	50.3	0.1
33-51	4.7	1.4	0.8	0.2	41.0	0.2
51-68	2.7	1.1	0.2	0.1	15.1	0.1
68-120	3.3	1.1	0.1	0.1	22.0	0.2

	Al (o)	Al (p)	Fe (o)	Fe (p)	Fe (d)
0-8	2.2		0.9		
8-17	2.2		1.0		
17-33	2.8		1.1		
33-51	3.0		1.2		
51-68	1.5		0.7		
68-120	0.7		0.7		

Soil B:

Depth (cm)	O.M. (Wgt %)	pH-H_2O (1:2.5)	pH-NaF
0-16	9.4	5.3	11.2
16-35	5.9	5.7	11.2
35-51	2.1	5.9	11.0
51-80	0.8	6.1	10.8
80-106	0.5	6.4	10.0

	Ca - meq/	Mg 100g	K soil -	Na	CEC	Acidity
0-16	3.9	1.1	0.3	0.3	46.8	0.2
16-35	5.0	1.9	0.2	0.2	46.5	0.2
35-51	3.8	0.7	0.2	0.2	39.4	0.1
51-80	4.4	0.8	0.2	0.1	31.4	0.2
80-106	3.4	3.3	0.3	0.4	38.0	0.1

	Al (o)	Al (p)	Fe (o)	Fe (p)	Fe (d)
0-16	2.2	0.8	0.8	0.7	1.8
16-35	2.7	0.7	1.0	0.6	2.1
35-51	2.2	0.3	0.9	0.2	2.0
51-80	1.8	0.2	0.6	0.0	1.6
80-106	0.3	0.1	0.6	0.0	2.0

Soil E:

Depth (cm)	O.M. (Wgt %)	pH-H_2O (1:2.5)	pH-NaF
0-12	8.6	5.6	9.9
12-28	1.6	6.0	9.7
28-42	0.5	6.2	9.2
42-65	0.5	6.4	9.0

	Ca - meq/	Mg 100g	K soil -	Na	CEC	Acidity
0-12	4.9	3.3	0.4	0.3	49.0	0.2
12-28	4.2	4.5	0.2	0.4	37.1	0.1
28-42	3.0	3.6	0.4	0.3	21.1	0.1
42-65	3.0	3.5	0.3	0.2	50.3	0.1

	Al (o)	Al (p)	Fe (o)	Fe (p)	Fe (d)
0-12	0.6	0.4	0.5	0.4	1.5
12-28	0.4	0.1	0.6	0.1	1.4
28-42	0.1	0.1	0.9	0.1	2.3
42-65	0.0	0.0	0.3	0.0	1.3