Evolution of the Western Amazon Lowland Relief: impact of Andean foreland dynamics

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ABSTRACT

The congruency in the depositional origin and age of the uppermost sedimentary strata forming non-flooded rainforest ground (*terra firme*) in the western and central Amazon lowlands is a much debated subject. Here we conclude from the study of remote sensing imagery that active Andean foreland dynamics have played a major role in the evolution of the Plio-Pleistocene fluvial landscape in the western Amazon. Foreland dynamics have resulted in a *terra firme* composed of late Tertiary alluvium and younger alluvial terraces and plains. In Peru, thermoluminescence and ^{14}C dating show local aggradation of this younger alluvium between 180 and 30 ka. The documented high age heterogeneity of the *terra firme* has implications for considerations of the biogeography of the Amazon forest.

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INTRODUCTION

The topmost sedimentary deposits forming the present non-flooded rainforest ground (*terra firme*, Sioli, 1984) in the western and central Amazon basin have been widely reported as a relatively thin (10–40 m thick) surficial, horizontal, sandy lithostratigraphic unit (Oppenheim, 1946; Kummel, 1948; Almeida, 1974; Projeto RADAMBRASIL, 1977; ONERN, 1977, 1984; Khobzi *et al.*, 1980; Eden *et al.*, 1982; DNPM, 1984; Campbell and Frailey, 1984; Campbell *et al.*, 1985; Frailey *et al.*, 1988). The extensive documentation of the surficial lithostratigraphic uniformity of the *terra firme* has created an illusion of the presence of a widespread 'surficial mantle' in the Amazon (Campbell and Frailey, 1984; Frailey *et al.*, 1988). This view has given rise to several controversial hypotheses on the genesis of these beds, the first being Agassiz's erroneous proposal that they are glacigenous (Agassiz, 1865).

The sedimentary history of the beds forming the *terra firme* has been very important for studies on the biogeography of the Amazon basin. In many cases (Haffer, 1985; Haffer and Fitzpatrick, 1985) the biogeographical tradition still relies on the assumption that in large areas of the lower and central Amazon (east of the Iquitos arch, Fig. 1), the *terra firme* deposits result from sedimentation in a large inland 'Belterra lake' during the high Calabrian (early Pleistocene) sea-level (Sombroek, 1966). Thus biogeographers have regarded the Quaternary history of the lowland Amazon as geodynamically relatively stable, especially in the central Brazilian Amazon, which has long acted as a model for the palaeogeography of the whole basin. The 'Belterra lake'-hypothesis was originally based on clay sediments found up to 180 m above sea level in the eastern Amazon. The lake was supposed to have covered the major part of the lowland Amazon basin below this elevation. More recently the existence of 'Belterra lake' has little support (Irion, 1984a).

Catastrophic Holocene flashflooding has also been proposed for the origin of the *terra firme* deposits in the southwestern Amazon (Campbell and Frailey, 1984; Campbell *et al.*, 1985). Based on the same deposits a more recent suggestion is that the *terra firme* is derived from sedimentation in a late Pleistocene–Holocene delta-lake environment, initiated after 36,000 yr BP and with the latest lacustrine phases occurring as recently as at 2800 yr BP (Frailey *et al.*, 1988). This 'Lago Amazonas' would have covered approximately the same area in central Amazon as its predecessor 'Belterra lake'. Clearly, with such large discrepancies in the geohistory of the Amazon, there is no sound basis on which to make meaningful deductions about the factors behind Amazon biogeography.

All previous concepts of the origin of the surficial beds follow the 'layer-cake' concept, according to which homogeneous deposits were formed in a uniform environment. Little attention has been paid to the possible diachronism of the deposits. The Amazon basin has a long fluvial history (Klammer, 1984; Irion, 1984b; Räsänen *et al.*, 1987) and despite their lithostratigraphic similarity the surficial sequences may differ substantially in age. This supposition is supported by studies invoking Quaternary fluvial origins for some of the central Amazon non-flooded *terra firme*, formed when the sea levels were higher than they are during the present interglacial (Klammer, 1984; Irion, 1984b). In the western Amazon (west of the Iquitos arch, Fig. 1), though, the landscape is mostly unaffected by Quaternary eustatic sea-level fluctuations. In Ecuador, in the Andean forelands, the surficial beds have been attributed to fluvial deposition following late-Pliocene Andean tectonism (Baldock, 1985). In Peru, some of the beds are postulated to be products of more re-

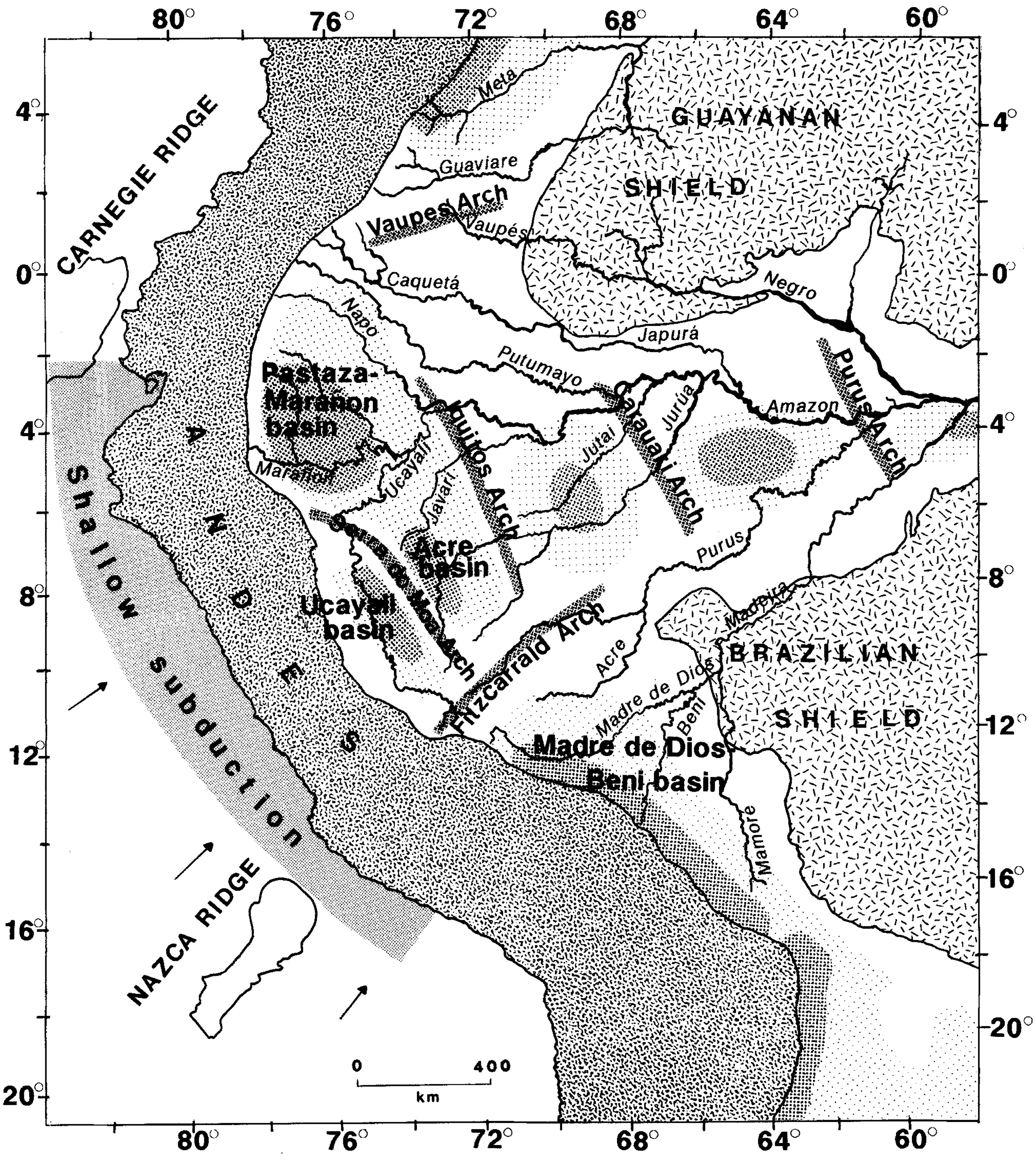

Fig. 1. *Major continental and submarine structures in northwestern South America (Unesco, 1975; Jordan* et al.*, 1983; Cunha, 1988). The locations of the structural highs, the Andean retroarc and the pericratonic and intracratonic basins are shown in the Amazon sedimentary basin. Dotting depicts the relative thickness of their Tertiary–Quaternary deposits. The flat subducting segment of the Nazca plate is thrown, and the oceanic ridges are depicted according to their 3000 m bathymetric contours.*

cent Pleistocene fluvial sedimentation under the influence of Sub-Andean tectonics (Räsänen *et al.*, 1987). In southeastern Colombia (Hoorn, 1988), northwestern Brazil (Almeida, 1974) and northern Peru (Räsänen *et al.*, in prep.), the alluvium forming the major *terra firme* has an eastern provenance. In Colombia, these sediments have a proposed Oligo-Miocene age, and only the Quaternary *terra firme* terraces have obtained their material from the Andes (Hoorn, 1988).

Thus it seems clear that over an area of continental size such as the western and central Amazon, which has affinities with the Andes and the cratonic shields, different parts of the surficial deposits forming the *terra firme* have aggraded diachronously. Sedimentation has been controlled by Mio-Pleistocene uplift and deformation of the Andes and their foreland and also by eustatic sea-level changes in the central Amazon. Although foreland deformation covers only a restricted area of the western Amazon, it affects the headwaters of the Amazon drainage system, and hence Andean dynamics have strongly modified both the palaeohydrological conditions and surface erosional patterns in the Amazon lowlands. For this reason, the *terra firme* forest beds are considerably more heterogeneous in origin and age than biogeographers have previously assumed.

Our evidence supporting this view is based on analyses of side-scanning radar (SLAR) images of Peru and Brazil and Landsat Planimetric Maps and on site-specific Landsat Thematic Mapper (TM) imageries of the Peruvian area. Ground-truth stratigraphic data with thermoluminescence (TL) and ^{14}C age determinations were collected to date the beds of *terra firme* in the Peruvian Amazon.

SHALLOW SUBDUCTION MAINTAINS DYNAMIC FORELAND BASINS

The western Amazon lowland (< 500 m a.s.l.) is structurally composed of at least four large retroarch intraforeland basins, delineated by emerging structural highs (arches, Fig. 1). The evolution of the Andean foreland is controlled by W–E compressive forces originating from the convergence of the Nazca suboceanic plate under the continental South American plate and giving rise to the Andean orogeny slowly developing eastwards. Along the Andean strike, the deformed Sub-Andean foreland belt is widest in the western Amazon in Peru, where the tectonic stress is released in a thin-skinned thrust and fold belt with reverse and thrust faults dipping westwards.

The shallow subducting segment of the Nazca plate (Jordan *et al.*, 1983) has caused the present tectonic situation in the Peruvian foreland (Fig. 1). The flat subduction is considered to have been initiated only 10 to 5 Ma (Isacks, 1988, Barberi *et al.*, 1988) due to subduction of the Nazca aseismic ridge (Fig. 1). The initiation has been dated by the cessation of volcanism of the Andes along this segment and by the reconstructed subduction geometry of the Nazca ridge (Pilger, 1984). This change in subduction geometry is among the most recent along the Cordilleran trench, and the low dip of the Benioff zone evidently effectively directs the compressional forces to the foreland crust (Suarez *et al.*, 1983). The present high relative rate of subduction, up to 11 cm yr^{-1} at the trench (Minster *et al.*, 1974), further promotes deformation (Jordan *et al.*, 1983). The foreland shortening is estimated to have been recently in the range of 1–2 mm yr^{-1} (Suarez *et al.*, 1983). Deformation is further evidenced by modern upper plate seismicity in the foreland, with the highest activity along the Cordilleras (Jordan *et al.*, 1983; Suarez *et al.*, 1983; Cisternas *et al.*, 1988).

THE *TERRA FIRME* DEPOSITS

General stratigraphy

In the Pastaza-Marañon, Ucayali, Madre de Dios-Beni and Acre intraforeland basins the surficial sandy beds of *terra firme* are reported at erosional banks, the majority of which are carved into terraces along present-day rivers. They are frequently reported to rest unconformably on older Quaternary and Tertiary deposits as various structural or surficial formations: the 'Terciario Superior Amazonico' and 'superficia de arcila' composed of 'Trinidad Beds' in Colombia (Khobzi *et al.*, 1980; Eden *et al.*, 1982), the Içá or Sanozama Formations forming the 'Planalto rebaixado da Amazonia' in Brazil (Almekia, 1974; Projeto RADAMBRASIL, 1977; DNPM, 1984) the 'Monte and Sierra Realms' in Bolivia (Campbell *et al.*, 1985) and the Madre de Dios (Oppenheim, 1946), Iñapari, Pagorene, Iquitos (Onern, 1977, 1984; Campbell and Frailey, 1984) or Ucayali (Kummel, 1948) Formations in Peru. The unconformities exhibit abrupt changes in degree of consolidation and weathering and, at the marginal parts of the foreland basins, even in the dip of the strata (Oppenheim, 1975; Frailey, 1986). Unconformities are more parallel in the central parts of the basins, where differences in facies, degree of weathering and consolidation are usually less marked (Fig. 2).

In places, 0.2–2 m-thick conglomerates occur above the basal unconformity, with large-scale trough crossbedding in the intercalated sands. These conglomerates are frequently strongly cemented by iron oxides. The conglomerates are the source beds for the majority of the Plio-Pleistocene vertebrate fossils and fossilized wood found in the area (Simpson and Paula Couto, 1981). Frequently documented in the western Amazon, the conglomerates seem to phase out eastwards towards the central Amazon (Silva, 1988). The fauna in the conglomerates seem to be somewhat younger (Simpson and Paula Couto, 1981) than the fauna found in the Oligo-Pliocene Pebas Formation (Williams 1949) that is frequently reported to underly the surficial formations in the western Amazon.

The uppermost parts of the 10–40 m-thick beds (above the basal conglomerates) constitute a sequence with varying numbers of fluvial cycles (multistoried aggradational cycles) often composed of more sandy material than below the basal unconformities (Fig. 2). The individual upward-fining fluvial cycles are predominantly composed of channel lag (coarse sand, gravel), pointbar (fine to medium sand) and overbank facies (silty-clayey) with occasional, weakly developed palaeosols.

Deposition of the alluvium

The original aggradational surface of the surficial beds has been preserved in the central parts of the Madre de Dios–Beni and Ucayali basins in Peru. Here

Fig. 2. *Stratigraphy of surficial alluvial beds in a terrace deposit with a multistoried sequence of upward fining fluvial cycles (a) exposed in a roughly 15 m-high erosional bank along the Madre de Dios (12°15′50″ S, 70°48′25″ W). The lower part of the bank is covered by colluvium (b). The basal unconformity (c) to older more consolidated and flat-lying fine-grained deposits (d) is parallel, and the basal conglomerate is poorly developed. The fluvial cycles of the surficial sandy beds were originally inclined (e).*

the *terra firme* relief also reveals abandoned channels, indicating that the material was deposited by the laterally mobile channels of meandering rivers (IFG, 1984). In the Madre de Dios–Beni basin, terraces have developed asymmetrically along the northeastern side of the Madre de Dios (Räsänen *et al.*, 1987), whereas the southwestern side of the river shows younger Pleistocene and Holocene aggradational surfaces partly formed by the transversal rivers draining the Andes (IFG, 1984; DeCelles and Hertel, 1989). These geomorphological features show that the river system migrates laterally to the southwest becoming increasingly parallel to the Andean strike owing to active faulting along the Sub-Andean thrust zone (Fig. 4) (Räsänen *et al.*, 1987).

Both the lower and higher terraces along the river show the above stratigraphy (Fig. 2). We suggest that the surficial sequence (with basal conglomerates and overlying fluvial cycles) on the Madre de Dios is due to slow lateral depocentre migration, and we interpret the basal conglomerates as having deposited during major stages of incision. As the present-day Madre de Dios is incised and deposit resembling conglomerates, incision may have occurred during interglacials. The overlying fluvial cycles in the terraces were deposited when the river system was more aggrading (certain phases of glaciations?). From the way the basin is deformed, the Madre de Dios river system was more ready to relocate its course southwestwards during maximum aggradation. As the river can be incised more than once, the cycle is repeated and the river system may migrate laterally.

The extensively documented surficial formations (with or without basal conglomerates) at the foreland, which partly derive from similar terrace systems should be considered as lithostratigraphic units each with its own diachronic depositional history. In contrast to the 'layer-cake' concept (Sombroek, 1966; Campbell and Frailey, 1984; Frailey *et al.*, 1988), these formations of Western Amazonia do not have documented lateral continuity and cannot be correlated across the foreland either lithostratigraphically or temporally. Older sediments are exposed along the emerged areas (Fitzcarrald, Serra do Moa and Vaupés arches) (ONERN, 1977; Hoorn, 1988) owing to gradual offlap (regressive overlap) of the strata. These sediments were deposited in rather similar fluvial environments, and lithostratigraphically they resemble the younger *terra firme* sediments in the central parts of the foreland basins. Their deposition was also controlled by foreland subsidence.

We thus conclude that there is no single surficial 'alluvial mantle' in the Amazon as was assumed by the flash-flood, 'Belterra lake' or 'Lago Amazonas' depositional models for the Amazon *terra firme*. We suggest that more or less gradual, regressive, late-Cenozoic time-transgressive deposition took place

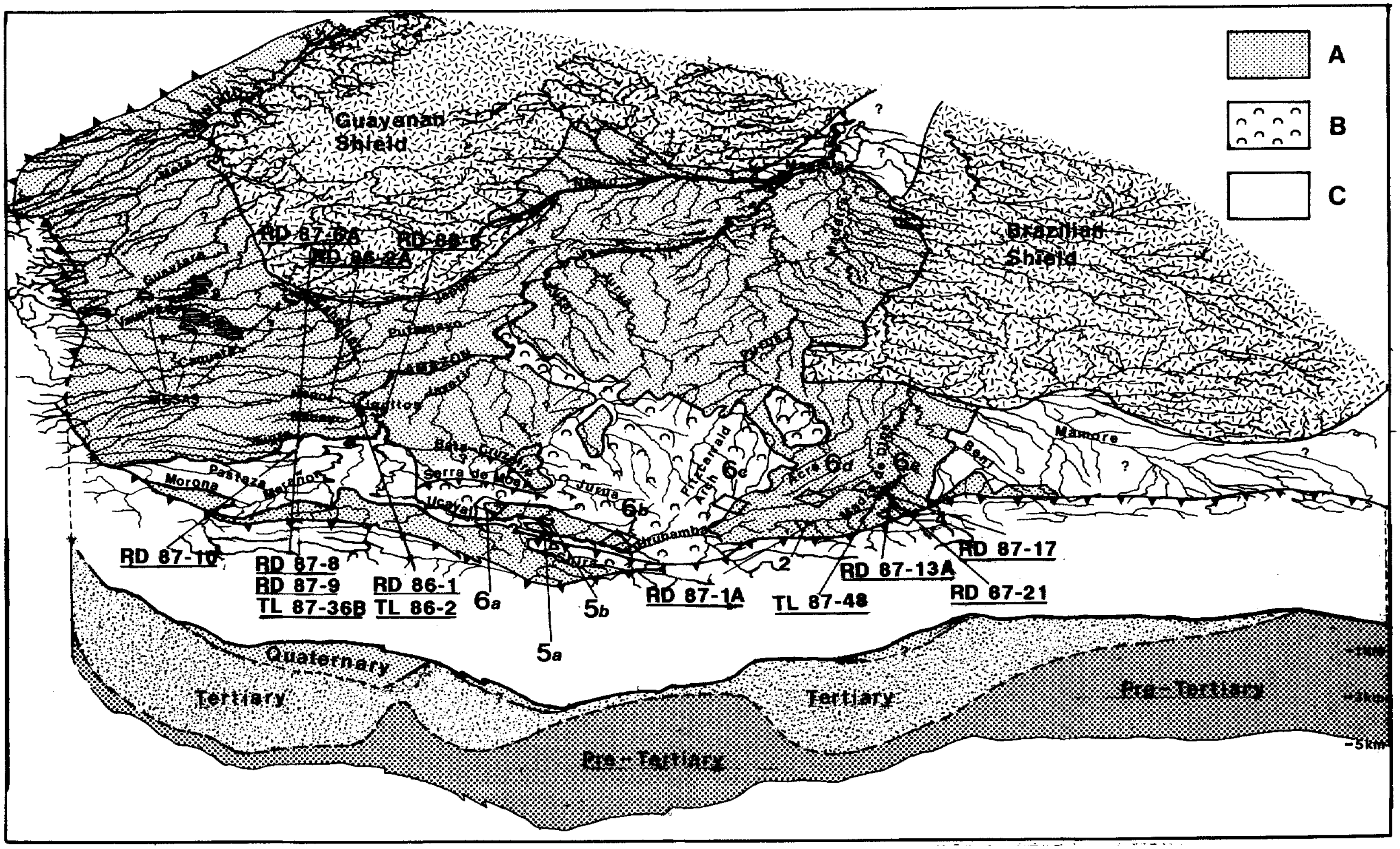

Fig. 3. *Block diagram looking towards the western and central Amazon lowlands over the Andes from the south-west. The figure shows, in a highly generalized manner, the different states of landscape evolution immediately east of the considerably elevated part of the Sub-Andean fold and thrust belt. (A) The areas where the originally planar deposurface of flat-lying* terra firme *alluvium is locally well-preserved. For Peru, the coverage is based on our field and laboratory investigations; for the other areas several sources have been used Brazil (Projeto RADAMBRASIL, 1976, 1977), Bolivia (Campbell* et al., *1985) Colombia (Khobzi,* et al., *1980). The more sporadic presence of* terra firme *alluvium in the shield areas and in the lower Amazon east of Manaus is not depicted. A question mark (?) indicates lack of data. (B) Strongly dissected area where the original deposurfaces have been eroded and the older alluvium is exposed. (C) Large modern to subrecent aggradational plains in the Pastaza–Marañon and Ucayali floodbasins and in the Pastaza fan between the Morona and Tigre rivers. The higher mesas at the Vaupés arch are also shown. 2, 4, 5a,b, 6a–e are the sites of the figures. The RD and TL code numbers indicate the sites of the respective* ^{14}*C and TL samples. The frontal generalized stratigraphical sequence with vertical exaggeration roughly depicts the deep stratigraphy of the Pastaza-Marañon, Ucayali and Madre de Dios–Beni basins and is projected to one plane (Unesco, 1975, Guizado, 1986).*

away from the most actively emerging arch areas during partitioning of the intraforeland. The effects of climatic oscillations are superimposed on the tectonic control of sedimentation and full diachrony of the alluvial deposits thus may not exist. Remnants of deposurfaces cover the Serra do Moa uplift and the Fitzcarrald and Vaupés arches and are pre-uplift evidence of the latest aggradation in these areas (Fig. 3) (Koch, 1959; Instituto Geologico del Peru, 1975; Khobzi *et al.*, 1980; Frailey *et al.*, 1988). In the intensively dissected areas greater uplift has exposed strata ores deeply buried. Irrespective of whether or not the original deposurface is preserved, we here refer to the various surficial formations as *terra firme* alluvium.

TL AND ^{14}C METHODS DATE LATE PLEISTOCENE *TERRA FIRME* DEPOSITION

To achieve data on the age heterogeneity of Western Amazon *terra firme,* we applied TL and ^{14}C methods to date some terrace levels (sites as in Fig. 2) covering extensive parts of the nonflooded relief in Peru and representing the latest depositional phases of the *terra firme* alluvium. TL was used for the first time to date *terra firme* deposits of the Amazon basin, thus enabling the age determinations to be extended further back into the Pleistocene.

In northeastern Peru, infinite ^{14}C ages (RD 86-1, 86-2A, 86-6, 87-10, Table 1 and Fig. 3) were obtained from organic material lying in the uppermost parts of the Pebas Formation (inferred Mio-Pliocene brackish-lacustrine origin, Williams, 1949; Hoorn, 1988) and at the contact with (or under) the *terra firme* alluvium. In southeastern Peru, in a section along the River Tambopata, a tree trunk well in the middle of a 40 m-thick *terra firme* alluvium with a well-preserved original deposurface also gave an infinite age (RD 87-13). Our ^{14}C results thus indicate that most of the deposits forming the *terra firme* levels are outside of the range of the ^{14}C dating method.

A clearly definable 13-15 m-high terrace level (similar and close to the site in Fig. 2) which has asymmetrically developed along the northeastern side of the Madre de Dios at Titipisco, yielded both a finite ^{14}C age (39,300 yr BP) and an infinite age (> 40,000 yr BP) (RD 87-1A,B). At other sites along the lower Madre de Dios (RD 87-17) and Tambopata (Campbell and Romero, 1989) (Fig. 3), wood collected from basal conglomerate deposits, which may belong to the initial depositional phases of this terrace, also gave finite dates of around 36,600 yr BP. However, results with a finite (32,000 yr BP) and an infinite (> 40,000 yr BP) age were obtained from a simple trunk from another basal conglomerate deposit (RD 87-21) nearby (Table 1). Since all dated wood has been collected from groundwater saturated sediments, and may be contaminated by younger carbon, wood of infinite age may give ages between 32,000 and 39,300 yr BP (Irion, G., pers. comm.). These controversial results seem to imply that even this clearly defineable low terrace can only be determined with certainty to be > 30,000 yr BP old.

The models according to which *terra firme* originated from late Pleistocene–Holocene flashfloods or delta-lake 'Lago Amazonas' deposition are based on ^{14}C data, some of which were collected from the same rivers and basal conglomerate deposits as ours. Five of the dates were infinite when only two gave dates around 36,000 BP (Campbell and Romero, 1989). The dates are as uncertain as ours and thus even the central conclusion that *terra firme* deposited after 36,000 yr BP is open to question.

To date the fluvial sediments forming *terra firme* levels, TL samples were collected at two localities expected to yield infinite ^{14}C ages. The first site dated was at Laberinto, on the Madre de Dios, southeastern Peru. Here an erosional bank is carved into deposits forming a flat *terra firme* 40 m above the low water datum of the river. Similar deposurface is well developed over large areas in the Madre de Dios-Beni basin (Figs 3 and 6e). A sample (TL-87-48) was taken from the lower part of the section, some 8 m above the river, from the lower homogeneous channel sediments of a fluvial cycle. Dating revealed deposition at around 176 ka. Although we consider these sediments to be among the youngest *terra firme* deposits in the area, they are still much older than the flashflood or 'Lago Amazonas' delta-lake depositional models would imply. This TL result indicates major changes in the level of sedimentation during the late Pleistocene.

The second site for TL dating was on the northern side of the River Solimões, 20 km downstream from Iquitos at Santa Teresa, northeastern Peru (Fig. 3 and Table 1). A sample (TL-86-2) was collected from an erosional bank carved into a 15-m-high dissected hill of unknown original aggradational level. The material at 5 m above the contact between the Pebas Formation and the overlying *terra firme* alluvium was brownish sand, with palaeocurrent from west, intercalated by layers of horizontally bedded clay 10–15 cm thick. The dates for the two mineral fractions are in good agreement, placing the age of deposition at around 100 ka (Table 1). Thus it may represent the age of the youngest part of the similarly dissected *terra firme* on the northern side of the Solimões channel.

Distinct fluvial terraces of *terra firme* are common throughout the lowland area (Koch, 1959; Projeto RADAMBRASIL, 1977; Khobzi *et al.*, 1980; Räsänen *et al.*, 1987; Cunha, 1988). They may be climatically associated with cyclic glaciations in the Andes but owing to the limited number of absolute dates available their exact provenance is still poorly known. The TL dates from the two sites indicate early glacial times. However, these data are still sparse and TL dates may also be subject to uncertainties, which makes a detailed attempt to interconnect the depositional ages and the known climatical oscillations premature. However, the ^{14}C ages of a few low terraces along the River Ucayali in Peru seem to cluster at around 13 ka (Dumont, 1989), at times of increased discharge during the last deglaciation, which started at around 13.5 and peaked at around 9.6 ka (Showers and Bevis, 1988).

Evidence also exists for the strong influence tectonics has had on the origin of many asymmetric lowland terrace systems (Räsänen *et al.*, 1987; Cunha, 1988; Dumont, 1989). In the immediate Sub-Andean zone along the upper course of the Tambopata, a well-developed three-stage terrace system is incised into an emerging anticlinal structure in the Sub-Andean thrust zone (Fig. 4). This indicates that tectonic movements played an important role in the origin and preservation of the late-

Table 1. Dates for surficial formations in Peruvian lowland Amazon. The ^{14}C samples were all of wood except sample RD 86-2A which consisted of compressed remnants of peat in detritus gyttja. As the wooden samples were in a state of decay, which made the recovery of cellulose difficult, samples were subject to acid-alkaline-acid pretreatment. To diminish the influence of any contaminants, the innermost core of each stump was used for dating. Special attention was paid to the ^{14}C measurements of samples RD87-1, 87-17 and 87-21. To check for any contamination, parallel samples were submitted to accelerator dating at the University of Uppsala, Sweden. Samples Ua-1213, Ua-1214 and Ua-1215 were redated by accelerator techniques. Pretreatment in 2M NaOH for 6-8 h and 2M HCl for 1 h (with additional NaOH treatment when necessary) was performed. The dated sites are shown in Fig. 3.

The TL samples were collected using an enclosed tube sampler that fed the samples directly into black plastic bags. The datings were performed using potassium feldspar (FK), except for sample TL 86-2, for which the plagioclase (FN) fraction was also used. For the laboratory technique used see Jungner *et al.*, (1989). The dates given were not corrected for long-term fading. With the value of 711 kyr for the mean life of Scandinavian feldspars (Mejdahl, 1989), corrections of about 10 kyr and 40 kyr should be added to the age given in the table for samples TL 86-2 and TL 87-48, respectively. The date for TL 87-48 is based on an exponential growth curve, and the natural TL level comprises about 65% of the level reached when a radiation dose of 3000 Gyr was given to the feldspar sample after a thorough artificial UV bleach.

Radiocarbon dates

Object dated	Lab. no.	Field no.	Site	Coordinates (long.W,lat.S.)		Facies for material	Dated material	$\partial^{13}C$	Age yr BP
Deposits under the surficial beds	Hel-2388	RD 86-1	Santa Teresa	73°07'10"	3°34'05"	brackish/fluvial	wood	-26.0	>42000
	Hel-2389	RD 86-2A	Bellavista	73°30'20"	2°53'45"	contact, brackish/fluvial	peat	-27.0	>43000
	Hel-2390	RD 86-6	Tamchiyacu	73°08'20"	4°02'05"	contact, brackish/fluvial	charred wood	-26.0	>42000
	Hel-2585	RD 87-10	Corrientes	75°14'45"	3°44'35"	fluviolacustrine	wood	-26.2	>44000
Surficial beds	Hel-2473	RD 87-13A	Tambopata	69°09'20"	12°39'40"	overbank sediment	wood	-29.0	>42000
Clearly definable terrace	Hel-2584	RD 87-1A	Titipisco	70°45'45"	12°17'15"	channel sediment, gravel	wood	-30.1	$39300\pm^{2400}_{1900}$
	Ua-1213	RD 87-1B	"	"	"	"	"		>40000
	Hel-2586	RD 87-17	Puerto Maldonado	69°10'15"	12°30'30"	channel lag, gravel	wood	-28.2	$36600\pm^{1800}_{1500}$
	Ua-1214	"	"	"	"	"	"		36650±1465
	Hel-2587	RD 87-21	Puerto Maldonado	69°11'20"	12°38'55"	channel lag, gravel	wood	-28.6	$32000\pm^{1300}_{1050}$
	Ua-1215	"	"	"	"	"	"		>40000
Pastaza fan	Hel-2527	RD 87-6A	Corrientes	74°58'20"	03°46'40"	overbank sediment	wood	-29.6	>43000
	Hel-2528	RD 87-8	Corrientes	75°06'55"	03°49'15"	sheetflood deposit ?	wood	-28.8	7650±120
	Hel-2529	RD 87-9	Corrientes	75°06'55"	03°49'15"	overbank sediment	wood	-31.9	8180±120

Thermoluminescence dates

Object dated	Field no.	Site	Coordinates (long.W,lat.S)		Facies collected	Mineral used	U ppm	Th ppm	K(ext) %	K(int) %	AD Gy	Dose rate Gy/kyr	Age kyr
Surficial beds	TL 86-2	Santa Teresa	73°07'10"	03°34'05"	fine overbank	FK	2.26	11.7	1.99	7.56	337	3.56	95±15
						FN				0.81	328	3.27	100±15
	TL 87-48	Laberinto	69°34'15"	12°42'30"	channelfill	FK	2.89	14.2	2.02	14.4	737	4.19	176±25
Pastaza fan	TL 87-36B	Corrientes	75°06'55"	03°49'15"	sheetflood ?	FK	2.10	8.71	0.91	4.64	53	2.31	23±5

Pleistocene lowland terraces in the Madre de Dios–Beni basin, as we assume in our depositional model for the asymmetric terraces along the Madre de Dios.

In conclusion, the diachronism of the western Amazon *terra firme* alluvium, which spans the period from the suggested Oligo-Miocene (Vaupés arch) to late Pleistocene (central parts of the Madre de Dios-Beni and Ucayali basins), is partly due to the offlap of the weakly deformed *terra firme* alluvium and the sequential system of younger aggradational *terra firme* plains and terraces at different levels. This general relief diversity is accentuated by the existence of other younger Holocene depositional regimes in the basins (Fig. 3).

DEFORMATION REORGANIZES THE LOWLAND RIVER SYSTEMS

Foreland deformation has modified the drainage of the older non-aggrading and dissected *terra firme* areas. The strong tectonic partitioning of the Ucayali basin (Fig. 1), has had the most wide-reaching consequences for the overall

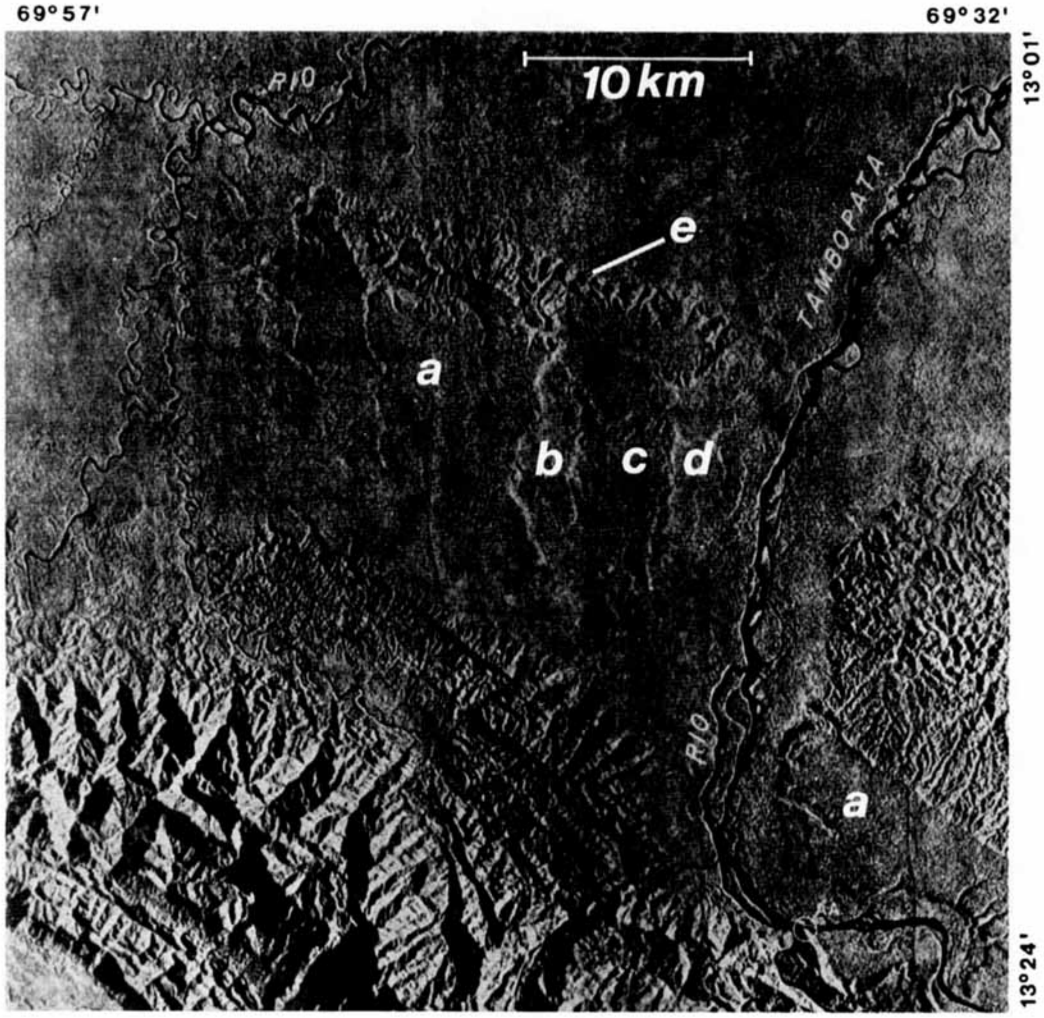

Fig. 4. *A sequence of terraces (b,c,d) along the upper Tambopata in the Madre de Dios–Beni basin. The terraces have developed on the flank of a rising anticline in the Sub-Andean zone. The anticline trending NW–SE is elevated along the thrust zone (e) in relation to the eastern lowlands. Original deposurface of the anticline (a).*

relief evolution of the western Amazon, caused by Plio-Pleistocene upward thrusting of the reverse faults exposed on the eastern side of the Sierra do Moa uplift (Cunha, 1988; Dumont, 1989) (Fig. 3). The partitioning was promoted by uplift of the igneous peralkaline massif crystallized 5–10 Ma, and now exposed close to the Serra do Moa (Stewart, 1971). During the general uplift around the other anticlinal structures and the Fitzcarrald and Vaupés arches, the old deposurfaces of the *terra firme* alluvium gradually reached their present higher elevations above the level of modern sedimentation (Fig. 3).

In the Ucayali basin, the upper deposurface of the *terra firme* alluvium is relatively downwarped at the western edge of the increasingly westward-tilting monocline between the Ucayali and the Serra do Moa. Recent sedimentation is transgressive, and a few blocked valley *ria* lakes (Inuria) have formed in the submerged erosional relief of the *terra firme* alluvium (Fig. 5a). The Ucayali and several other rivers (e.g. Tamaya, Fig. 5b and Sheshea) have recently relocated their courses towards the locus of relative subsidence, close to the reverse fault zone along the eastern edge of the Shira mountains (Fig. 3). As suggested by the poorly developed new floodplain, the latest great avulsion west of the Ucayali channel (Räsänen *et al.*, 1987, Neller *et al.*, in press) is fairly recent in age and probably indicates modern tectonic activity.

Other evidence that part of the uplift of Serra do Moa is younger than some *terra firme* deposurfaces comes from the area between the southern Ucayali, Acre and Madre de Dios basins (Fig. 6a), where geomorphic features and general drainage indicate reversal from NE to E into the Acre basin and from NW to W towards the Ucayali basin (Fig. 6b). During the rainy season this divide is covered with extensive forested wetlands with poor drainage (Oppenheim, 1937). The Ucayali–Urubamba river system has captured the earlier northeastern flowing drainage by gullying its headwaters into 100-m deep canyons

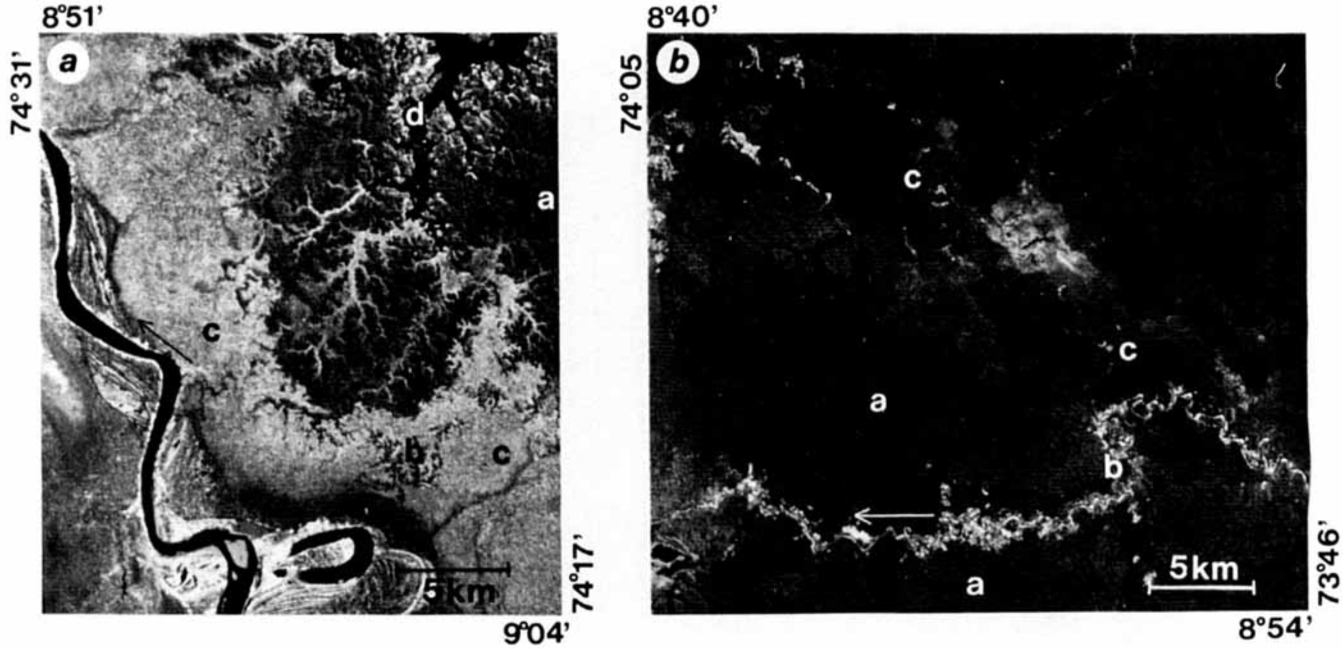

Fig. 5. *False colour Landsat Thematic mapper images (path 6, row 66QX July 14, 1985) of the downwarped central part of the Ucayali basin.* **a** *The downwarped, brownish, dissected upper surface topography of the* terra firme *alluvium (a) is buried under the modern overbank sedimentation of the recently cut new course of the Ucayali (Räsänen* et al., *1987), forming a brown dendritic net of buried crests (b) in the greenish area of modern overbank sedimentation (c). A part of the large blocked valley lake (Inuria) formed in the submerging erosional topography (d).* **b**, *The Tamaya (b) has abandoned its former asymmetric floodplain (c) and relocated its new channel through the dissected* terra firme *alluvium (a) owing to the increased westward tilt of the landscape. Arrows show the direction of the flow.*

(Oppenheim, 1975) to the south (Fig. 6b). During this process the modern Ucayali–Urubamba became one of the largest longitudinal trunk rivers in the area.

The development of the headwaters of the Juruá into a major longitudinal trunk river was also initiated by thrusting along the faults of Bata–Cruzeiro (Fig. 3), which is the easternmost, and also the youngest, clear reverse fault cutting through the *terra firme* alluvium. The adjustment of the Juruá floodplain shows the evolution of the former transversal river system of a peri-cratonic basin into the longitudinal system of an independent foreland basin, parallel to the Andean strike.

Similar adjustments of incised river systems to changing landscape gradients controlled by Pleistocene basement tectonics have been reported elsewhere. Abandonments of the southeastern courses of the Caguan and several smaller rivers in Colombia to the south have been documented (Khobzi *et al.*, 1980; Eden *et al.*, 1982). In Peru, the Nanay has faced a decrease in water flow due to some as yet undocumented change in its upper drainage area, evidenced by a Pleistocene cutoff channel belt wider than the present one preserved only on the northeastern floodplain margins (IFG, 1984). Southward tilting is also indicated by the way the headwater tributaries of the Amazon have captured those of the Orinoco, and by the lateral erosion of the southern edges of the floodplains of the Caquetá and upper Guaviare (Fig. 3), whose major drainage area is on the northern side of the rivers (Khobzi *et al.*, 1980). The southeastern drainage system south of the Vaupés arch has floodplains with higher long-term channel relocation rates to the south due to the predominant local tilting towards the main Amazon trough. Similar drainage features characterize several other *terra firme* areas of Amazonia (Fig. 3), and in the Acre basin they indicate a N–NW–NE tilt towards the main River Amazon (Cunha, 1988).

DEFORMATION REGULATES DENUDATION OF THE *TERRA FIRME* ALLUVIUM

Like the late Cenozoic spatially migrating fluvial aggradation of the *terra firme* alluvium and the relocations of the incised river systems, the denudational history of the lowland relief is controlled by Plio-Pleistocene foreland deformation. Enlargement of the Ucayali basin southwards and uplift of the Serra do Moa and Fitzcarrald arches have markedly constricted the Acre drainage area. Earlier, when the *terra firme* alluvium of the Solimões Formation in the Acre basin was deposited (Petri and Fulfaro, 1988), the river systems at the divide of the Ucayali and Acre basins discharged to a greater extent northbasins is the latest phase in the relief evolution which changed the Tertiary Neotropical (Hoorn, 1988, Petri and Fulfaro, 1988) lowlands into the present Andes. On a large scale, the Andes have been formed through a mechanism of foreland shortening, leading to crustal thickening and subsequent uplift (Suarez *et al.*, 1983; Megard, 1987; Isacks, 1988). In the central Peruvian Andes, late Cenozoic shortening accounts for about 115 km (Megard, 1987). In the central Andes, which constitute the southern margin of the present Amazon rainforest, the shortening has been about 100 km during the last 12 Myr, and 15–20 km during the last 3 Myr (Isacks, 1988). Instead of reflecting locations (and secondary Holocene border zones) of isolated Pleistocene broad-leaved forests (climatic refuges) (Whitmore and Prance, 1987), modern species ditributions in the Western Amazon may be a result of historical species dynamics controlled by landscape evolution.

Owing to late Cenozoic palaeogeographical changes in relief evolution, the forest biota of the western Amazon have probably alternated between allopatry and sympatry, commonness and rarity, and continuous distribution and fragmentation in much the same way as has taken place in temperate zones as a result of glacial oscillations (Bartlein and Prentice, 1989). The biological distribution patterns may also be closely connected to present edaphic differences. These should be considerable due to the age heterogenity of the forest bed, showing variability in weathering status and in degree of preservation of the original fluvial facies.

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