Journal of South American Earth Sciences, Vol. 4, No. 4, pp. 373–381, 1991
Printed in Great Britain

0895–9811/91 $3.00+.00

Morphostructural provinces and neotectonics in the Amazonian lowlands of Peru

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(*Received December 1990; Accepted April 1991*)

Abstract—The Amazonian lowlands of Peru are composed of the Subandean Zone (foreland), the Marañón Basin (foredeep) and the Iquitos Geanticline (Brazilian Craton). The Subandean Zone includes the Subandean Thrust and Fold Belt (STFB) to the west, which crops out mostly in the foothills, and the Subandean Tilted Block Zone (STBZ) to the east, which is principally exposed in the Amazonian lowlands of central Peru. The main trends of river belts are related to structural style. Main rivers in the STFB are antecedent, and secondary drainage is subsequent. In the STBZ, river basins are channelized, parallel to structural grain. The special asymmetric pattern of the Subandean drainage network depends on these two juxtaposed structural regions. As a result, fluvial migration in Peruvian lowlands is more controlled and limited by neotectonics than previously supposed.

Resumen—En la Baja Amazonia Peruana, se pueden distinguir la Zona Subandina (foreland), la Cuenca de Marañón (foredeep), y el Geanticlinal de Iquitos (Cratón Brasileño). La Zona Subandina comprende al Oeste una Faja de Sobre-corrimientos y Pliegues (Subandean Thrust and Fold Belt, STFB), que corresponde aproximadamente a las zonas de colinas altas, y una Zona Subandina de Bloques Inclinados al este (Subandean Tilted Block Zone, STBZ), mas desarollada en la Amazonia baja del Perú central. La orientación mayor de los rios principales depende del estilo estructural. En la STFB, los rios mayores son antecedentes, mientras que la red hidrográfica segúndaria es subsecuente. En la STBZ, las cuencas y los ríos principales están canalisados, siguiendo paralelamente a las estructuras principales. La asymetria de la red de drenaje del Subandino Peruano depende de la juxtaposición de estas dos provincias estructurales. De esto, resulta que la migración fluvial en la Amazonia baja esta mas controlada y limitada por neotectónica que lo que se habia reconocido anteriormente.

INTRODUCTION

ALTHOUGH THE NEOTECTONIC EVOLUTION of both the coastal and cordilleran parts of the Peruvian Andes is relatively well known, very few studies are available from the Amazonian region. Recent studies in Amazonian Peru have emphasized the close relationships between neotectonics, fluvial dynamics, and ecology (Campbell and Frailey, 1984; Salo *et al.*, 1986; Räsänen *et al.*, 1987). The relationship between neotectonics and river pattern was first investigated in Brazilian Amazonia by Sternberg (1950, 1955, 1957) on the basis of floodplain anomalies related to structural grain, and later by Iriondo and Suguio (1981) on the basis of regional neotectonic tendencies. In western Amazonia, Koch (1959b) recognized antecedent or superimposed and subsequent river valleys.

Because of Andean tectonism, western Amazonia exposes good examples of the influence of neotectonics on river valley settings. The physiography of Amazonian lowlands is more complex than is usually supposed. Relief is low, but some extended uplands (Iquitos, Contaya-Sierra de Moa, Fitzcarrald Arches) are important drainage divides. We present here field evidence for a morphostructural scheme of the Subandean regions of Amazonian Peru based on analysis of neotectonic style and its relationship with former structures in the substratum. We show that river drainage patterns are closely related to neotectonics.

GEOGRAPHIC SETTING

Amazonian Peru includes the Subandean foothills on the eastern Andean piedmont (300-2000 m elevation) and the Amazonian lowlands toward Brazil (below 300 m elevation). These lowlands include, first, the Subandean lowland of the central and southern Ucayali Basin. This area has a relatively rough topography, river belts hemmed in by steep hills, and watersheds originating up to 300 meters above the river floodplains. The Amazonian lowlands also include the Marañón Basin, where the main rivers converge—the Marañón, Huallaga, Tigre, and Ucayali Rivers. Changes in relief do not exceed some tens of meters and the topography is very smooth. The antecedent rivers that come down from the High Andes cross the Subandean Foothills toward the Amazonian lowlands through narrow canyons. Then, the rivers flow roughly northward, oblique to the NW-SE trend of the Andean range. All the rivers converge and join in the Marañón Basin, forming the Amazon River on the eastern

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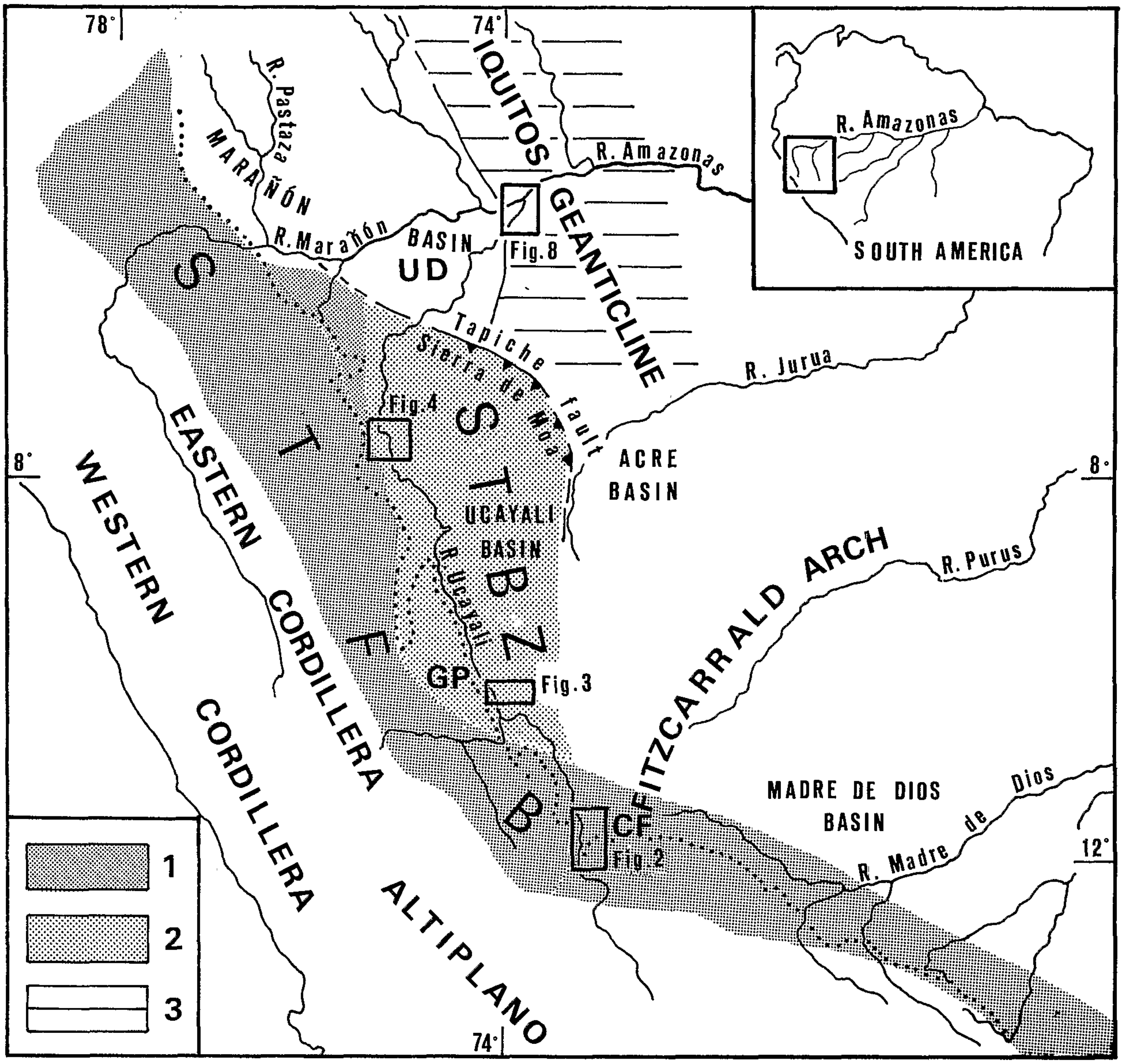

Fig. 1. Morphostructural scheme of eastern Peru: 1, Subandean Thrust and Fold Belt (STFB); 2, Subandean Tilted Block Zone (STBZ); 3, upland of the Iquitos Geanticline; dotted line, 300 meter elevation; CF, Camisea folds; GP, Grand Pajonal; UD, Ucamara Depression.

border of the basin just before crossing the Iquitos Geanticline.

GEOLOGIC BACKGROUND

The Andean foreland, or Subandean Zone (Fig. 1), is a region of eastward converging compressive structures that have decreasing magnitudes of deformation toward the Brazilian Shield. The main tectonic zones, from west to east, are the uplifted Subandean Zone, the subsiding foredeep (Marañón and Madre de Dios Basins), and the uplifted craton border (Iquitos Geanticline).

The sedimentary deposits of the Subandean Zone represent the previously wider Cretaceous basin, infilled mainly with continental detrital sediments. According to Rüegg (1952), the Subandean Zone includes the area subjected to late Tertiary and Quaternary tectonics. Recent studies have distinguished two subzones (Fig. 1):

- The Subandean Thrust and Fold Belt (STFB; Ham and Herrera, 1963; Pardo, 1982; Mégard, 1984), which extends along the eastern flank of Eastern Cordillera, consists mostly of foothills of more than 300 meters elevation. Uplift began during the mid-Tertiary (pre-Miocene), but the major tectonic movements occurred during the late Miocene and Pliocene. Major thrust faults are located along the morphologic borders of the foothills area, along the Cordillera Oriental piedmont to the west (Dumont and Arana, 1987), and along the border of the Amazonian lowlands to the east (Ham and Herrera 1963; Martin and Paredes, 1977; Pardo, 1982).
- The Subandean Tilted Block Zone (STBZ) is located in central Peru, east of the STFB. The limit between the two subzones does not fit exactly with

the foothills border: the STBZ consists of the Grand Pajonal (eastern foothills) and the Ucayali Basin (lowlands), which reach their highest points at their eastern uplifted borders—in the Shira Mountains and the Sierra de Moa, respectively. Uplift occurred along reactivated faults, the more recent episodes during the late Pliocene and Quaternary. The STBZ is limited to the east and north by the Tapiche fault, which extends along the northeastern border of the Sierra de Moa (Mégard, 1984), and to the southeast by the Fitzcarrald Arch, a NE/SW-striking, faulted and folded structure (Oppenheim, 1975). The STBZ overlies a flat slab subduction segment and may be compared in width and structural style with the Sierras Pampeanas of northwestern Argentina (Jordan *et al.*, 1983).

Because of continuous subsidence, more than 5000 meters of Mesozoic and Cenozoic sediments accumulated in the central part of the Marañón Basin (Sanz, 1974). The Tertiary deposits (1300 m) lap eastward onto the Iquitos Geanticline (Fernandes, 1962). The Iquitos Geanticline (also known as the Iquitos Arch), is a very wide, shallow dipping, NW/SE-striking structure (Fernandes, 1962). The recent evolution of these units is presented below.

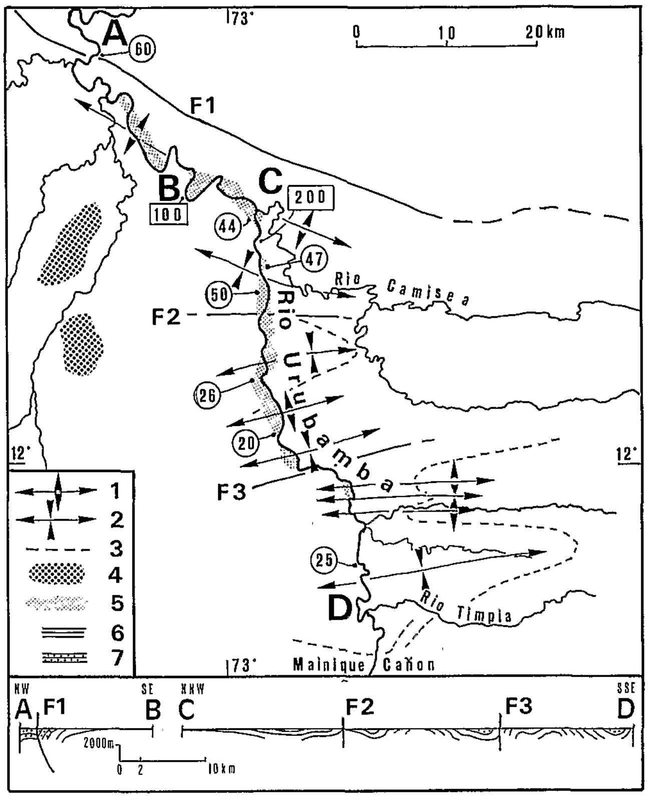

Fig. 2. Structural sketch of the lower Urubamba region: 1, anticline; 2, syncline; 3, structural lines of fold limbs; 4, remains of an old peneplain; 5, floodplain. Circled numbers indicate the elevation in meters of the highest Quaternary terrace over the floodplain; numbers in rectangles indicate the height of the river side topography. On the cross section: 6, Tertiary red beds; 7, Miocene conglomerates.

FOLDING AND TILTING EFFECTS IN THE SUBANDEAN LOWLANDS

Most outcrops in the Subandean lowlands consist of Tertiary continental red beds that are conformably overlain by Miocene conglomeratic fluvial deposits (Kummel, 1948; Koch, 1959a; Buffeteau and Hoffstetter, 1977; Martínez, 1975). Late Tertiary folding uplifted the region and a paleotopography was incised to depths of 200 meters. This paleotopography has been partially infilled with fluvial deposits containing the remains of wood and bones. Near Shepahua, Pleistocene vertebrate bones of *cf. Glossoterium* sp. (Edentata; Gravigrada) have been found in fluvial deposits close to the present Urubamba River channel (de Muizon, pers. commun., 1989). This implies that the Pleistocene paleotopography was already more or less similar to the present-day paleotopography. Remains of an erosion surface have been observed at several places: west of the Urubamba River (Fig. 2), to the east of Atalaya (see Fig. 3), and in the Contaya region (see Fig. 5). Koch (1959b) thought this erosional surface was developed during the Pliocene.

Lower Urubamba Region

The Urubamba River (Fig. 2) flows northward from the Eastern Cordillera through Mainique Canyon. North of the canyon, N65°W-striking folds (folds of the Camisea gas condensate field) are exposed in the Subandean lowlands, parallel to the border of the Peru-Bolivia Andean segment. Faults are mainly located on the north flank of the large anticlinal limbs. A major fault (F1 on Fig. 2) limits the folded southward-dipping basement (STFB) from the horizontal or low-dipping basement northward (STBZ).

The Urubamba River cuts orthogonally through the folds of the Camisea region. Paleocurrent data from the upper levels of the red bed units show a south to north mean drainage direction in the upper Urubamba region (Marocco, 1978), and also, according to data we collected from the Camisea region, in the Subandean lowland as well. This is interpreted as a constant drainage orientation existing prior to, and antecedent over, the folded and uplifted terrains of the region. Antecedent patterns are common in the STFB and are well expressed by the main rivers coming down from the Andes through deep canyons: the Marcapata, the upper Madre de Dos, and the Ene-Tambo Rivers—to mention only the rivers closest to this area.

A 25-km segment of the Urubamba River follows a WNW/ESE-trending anticline before turning northward and crossing the boundary fault of the STFB (F1 on Fig. 2). Two phenomena may be related to this feature:

- The river in this segment is controlled by the structures in the basement because it follows an anticlinal axis. SLAR imagery shows some patches of a peneplain on the western side of the Urubamba valley, which may be correlated with the surface on which the river was flowing before it became superimposed.

- Structural control by the boundary fault may explain the sudden change in flow direction for this segment. The rising of the southern limb prevents the river from crossing it locally.

The latter hypothesis is strengthened by observations of Quaternary fluvial terraces. High stepped terraces extending more than 100 meters above the valley bottom occur along the structurally controlled river segment, whereas the average height is about 30 meters in the other segments—to the south (bottom of Fig. 2) or to the north in the Atalaya region (Fig. 3). Abnormally elevated terraces suggest an uplift of the southern margin of the fault during the Quaternary, but this uplift has not be able to change the trend of the river valley over a long distance. North of Shepahua, progressive elevation of Quaternary terraces observed along the Urubamba River suggests the occurrence of a recent bulge.

The secondary drainage results from the late Tertiary tectonic uplift and follows the structural trends. Tributaries of the Urubamba River flow westward, and tributaries of the Madre de Díos River flow eastward along the folded structures. The Fitzcarrald Arch, which crosses the Camisea fold belt at a right angle, forms the drainage divide between the two basins (Oppenheim, 1975).

Atalaya Region

This region belongs to the STBZ (Fig. 1). According to seismic reflection data, the Cretaceous transgression discordantly overlies Paleozoic sedimentary deposits dipping gently toward the southwest. The thickness of the Cenozoic deposits increases from northeast to southwest but never becomes greater than 2000 meters. The uppermost Miocene red beds crop out only in the eastern part, along the Mishagua and Camisea tributaries of the Ucayali and Urubamba Rivers (Buffeteau and Hoffstetter, 1977). Scarce thrust faults identified with seismic reflection occur in the Cenozoic cover and are considered to be Paleozoic normal faults reactivated as reverse faults (J. Paredes, pers. commun., 1988).

Observations on SLAR images reveal an extensive structural surface over the east side of the Ucayali River (Fig. 3). The western and lowest part of the surface truncate the red beds. An estimation of the surface slope based on relative altimetric measurements gives a westward dip that does not exceed 1%. This slope seems to have supported the primary drainage over the structural surface (Inuya, Puntijao, and Cohehua Rivers) and seems to post-date the surface development and its tilting. The highest stepped terrace also post-dates the tilt motion. This terrace is constant by 30 meters above the Ucayali

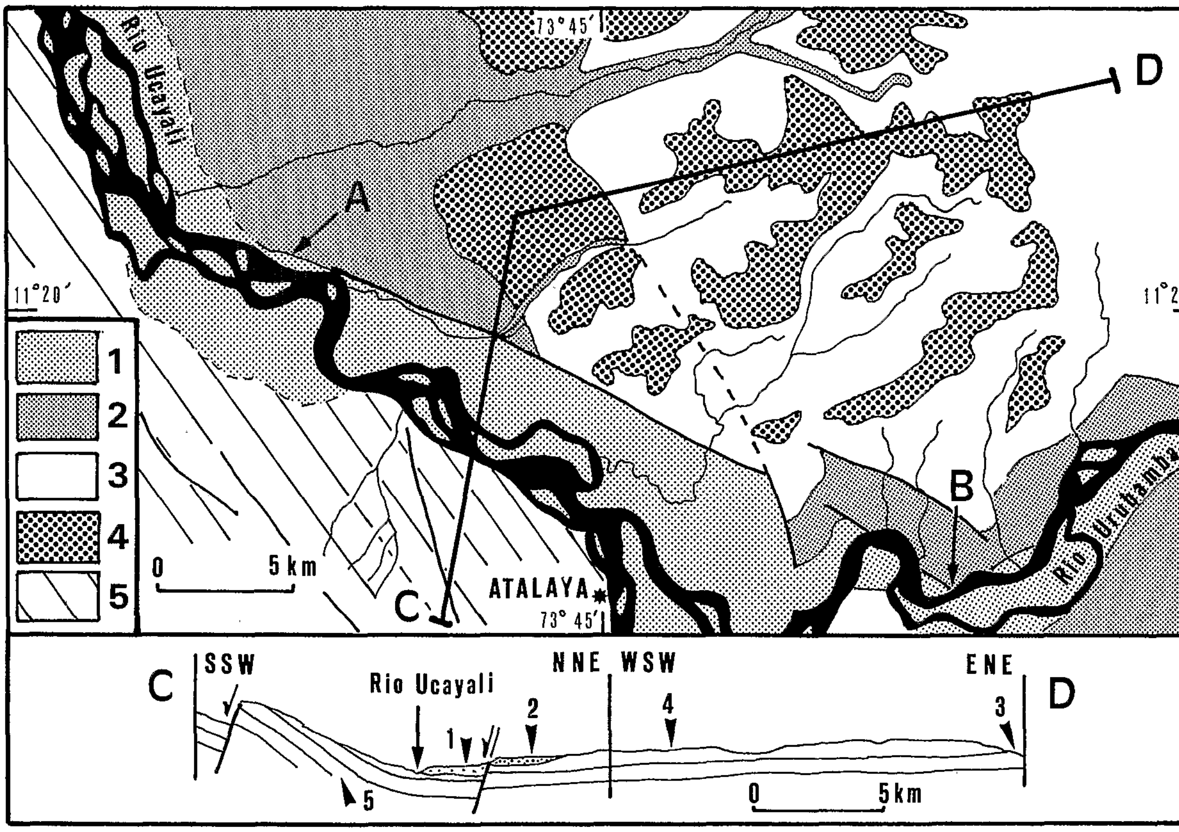

Fig. 3. Morphostructural scheme of the Atalaya region: 1, floodplain; 2, Quaternary fluvial terraces [radiocarbon age from tree trunks in A, 13,850 (+480, −460) years BP, and in B, 8,520 (+440; −420) years BP]; 3, erosional morphology over the red bed deposits (upper Tertiary); 4, west-dipping peneplain; 5, Shira uplift (Mesozoic strata). Numbers on the cross section are the same.

River and is made up of deeply weathered conglomerates characterized by completely decayed granitic and quartzitic pebbles. A similar weathering pattern has been encountered in the lower Quaternary, and highest, terrace of the foothills (Dollfuss, 1965; Dumont and Arana, 1987). Its age is surely older than late Pleistocene, as none of the terraces encountered in the Amazonian regions, and dated as less than 40,000 years BP, shows a similar weathering pattern (Campbell and Frailey, 1984; Dumont *et al.*, 1988).

A N70°W-trending escarpment separates the structural surface from the Ucayali River floodplain (Fig. 3). From northwest to southeast, the escarpment increases in height as the surface rises. This escarpment, which bounds the red bed deposits and the stepped Quaternary terraces from the river floodplain in a straight line, is interpreted as a fault. To the southeast, the escarpment limits a high fluvial terrace from which a radiocarbon age of 8520 ±440 years BP has been obtained (M. Fournier, ORSTOM Laboratory in Bondy). Striations on several pebbles suggest a normal fault movement, but the few measurements are too poor in quality to allow a kinematic study (Fig. 3). South of the Urubamba River, the fault trend changes and strikes NW-SE, as mapped by Martin and Paredes (1977).

Contaya Region

The topography and geomorphology of the Contaya region (Fig. 4) have been studied by Koch (1959b), who made a careful study of what Kummel (1948) called the "Ucayali Peneplain," a paleotopographic surface present on both sides of the Ucayali valley, sloping toward the river (Fig. 5). The Ucayali Peneplain postdates the Late Tertiary folding tectonics. The oldest sedimentary deposits covering the peneplain are greyish-blue clays and peat (probably correlated with the Pebas Formation), which Koch considered to be of Pliocene age.

Stepped Quaternary fluvial terraces of the Ucayali peneplain are probably of climatic and tectonic origin. The peneplain has also probably been tilted, as shown by the increase of the differential height between individual terraces along a profile between the foothills on the west and the Ucayali River on the east (Koch, 1959b, Tables 1 and 2). Major river channels are superimposed on the folded basement.

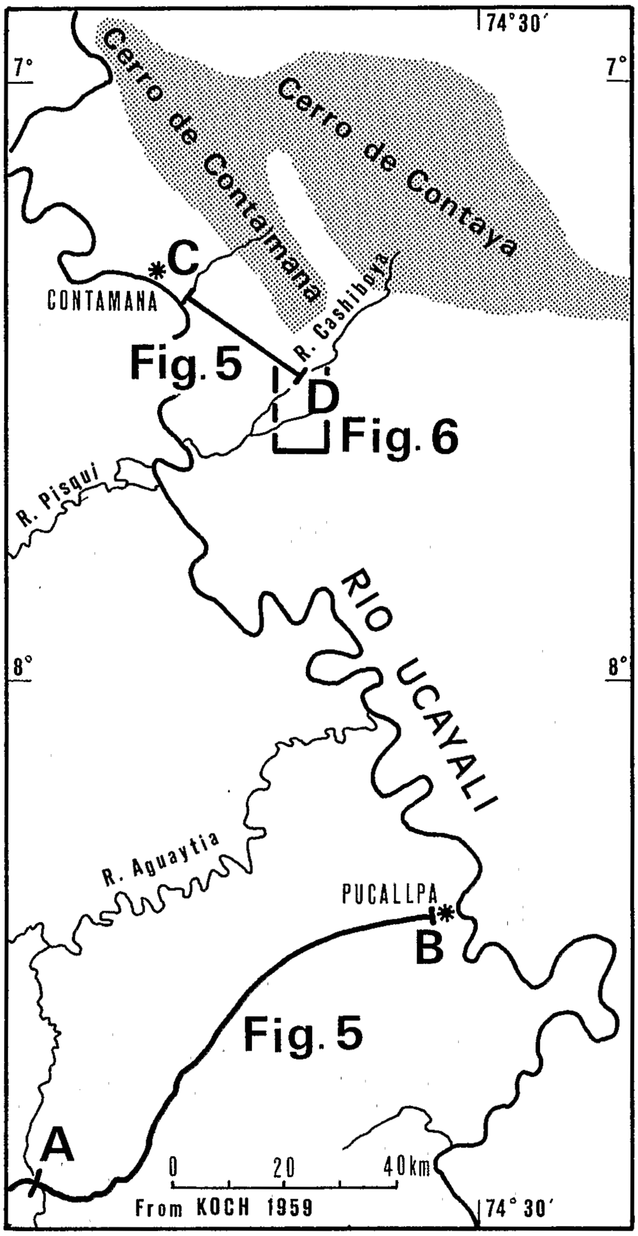

Fig. 4. Location of Koch's studies (1959b) in the Contaya region. AB and CD indicate sections shown in Fig. 5. The AB segment is along the Tingo Maria-Pucallpa road.

Koch (1959b) mentioned the case of the Cashiboya anticline (Fig. 6), which strikes NNW-SSE but is drained by NE/SW-trending rivers (the Cashiboya and Ahuayo Rivers, eastern tributaries of the Ucayali River, near Contamana). Koch related the

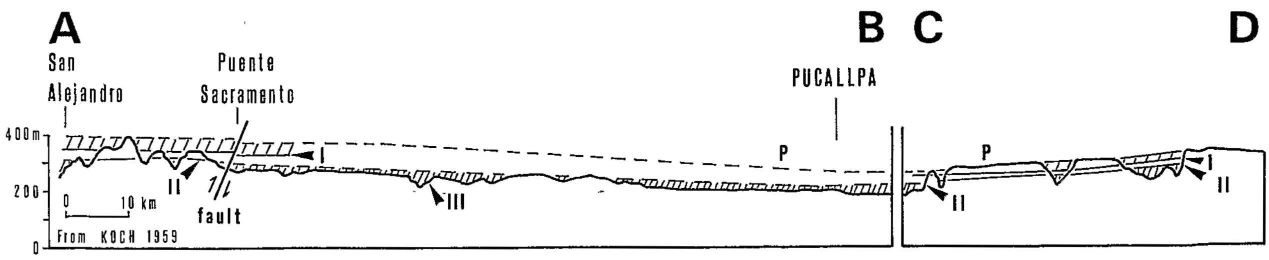

Fig. 5. Sections across the Ucayali valley near Pucallpa (see Fig. 4 for location; from Koch, 1959b): P, Pleistocene peneplain; I, II, and III, stepped Quaternary terraces.

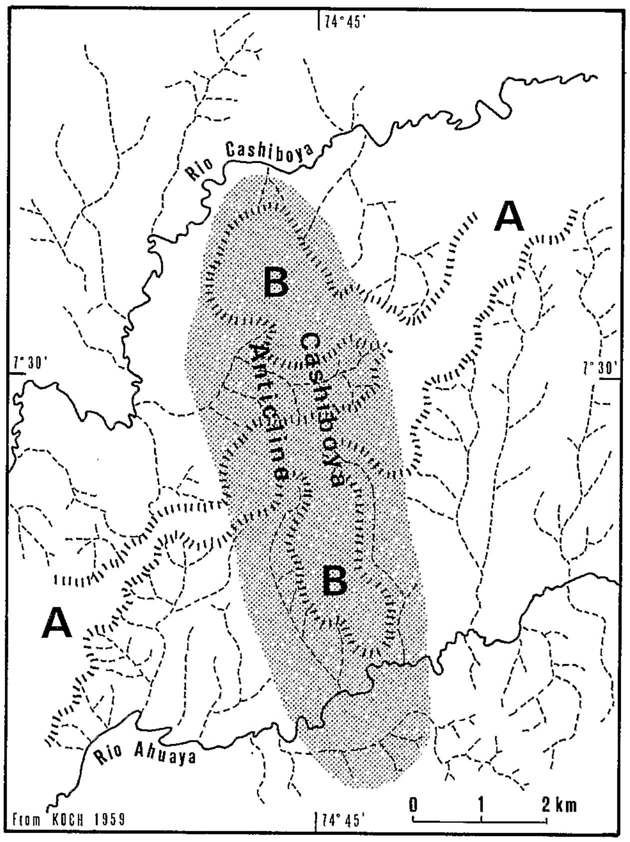

Fig. 6. Morphologic outline of the Cashiboya anticline (from Koch, 1959b): A-A, Drainage divide line between main rivers; B, water divide areas of secondary drainage.

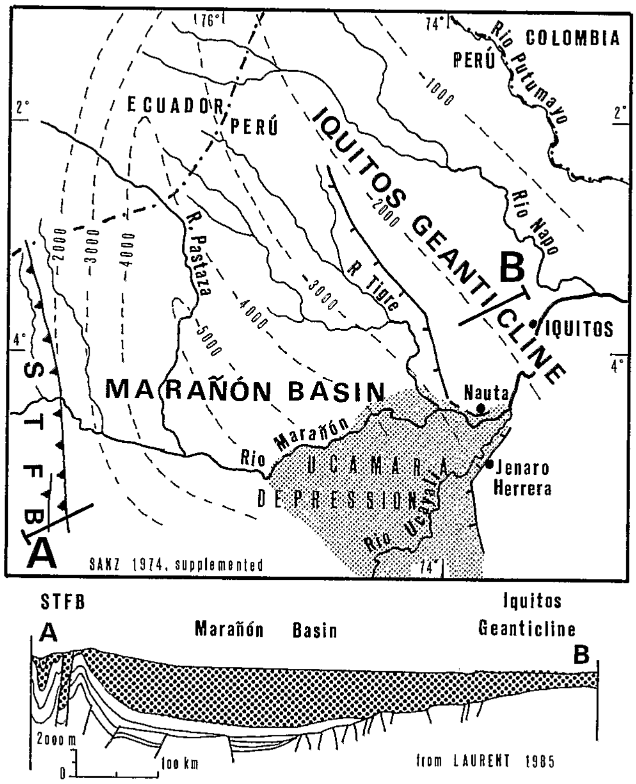

Fig. 7. Top: Structural map of northeastern Peru; numbers on dashed lines are isopach thicknesses of strata above pre-Cretaceous basement (Sanz, 1974, supplemented). Bottom: Section of the Marañón Basin; the dotted area represents the post-Jurassic deposits (Laurent, 1985).

major drainage trend to the original slope of the surface that is superimposed on the previous structures. This resulted in an Appalachian topography—that is, a structurally controlled relief developed on folded strata characterized by homoclinal ridges and subsequent valleys. The secondary drainage is influenced by structural features of the basement and by lithologic inhomogeneities.

What Koch called the "proto-Ucayali" has been controlled, and might have been initiated, by the Ucayali peneplain development and Quaternary tilting tectonics. Increased tilting of eastern and western slopes of the valley during the Quaternary forced the upstream part of the Ucayali River tributaries to trench into the basement and the lower part to join the subsiding floodplain area (Koch, 1959b).

MARAÑON BASIN: THE PRESENT FOREDEEP

The Marañón Basin consists of extensive subsiding depressions. The Pastaza River area on the north shows dendritic lakes, interpreted as flooded drainage morphology. In the southern part of the basin, the Ucamara Depression (Villarejo, 1988), is a large (more than 25,000 km^2) swampy area, where no upland exists to limit the meander belts of the Marañón, Ucayali, and Tapiche Rivers. The meander belts are characterized by numerous oxbows at

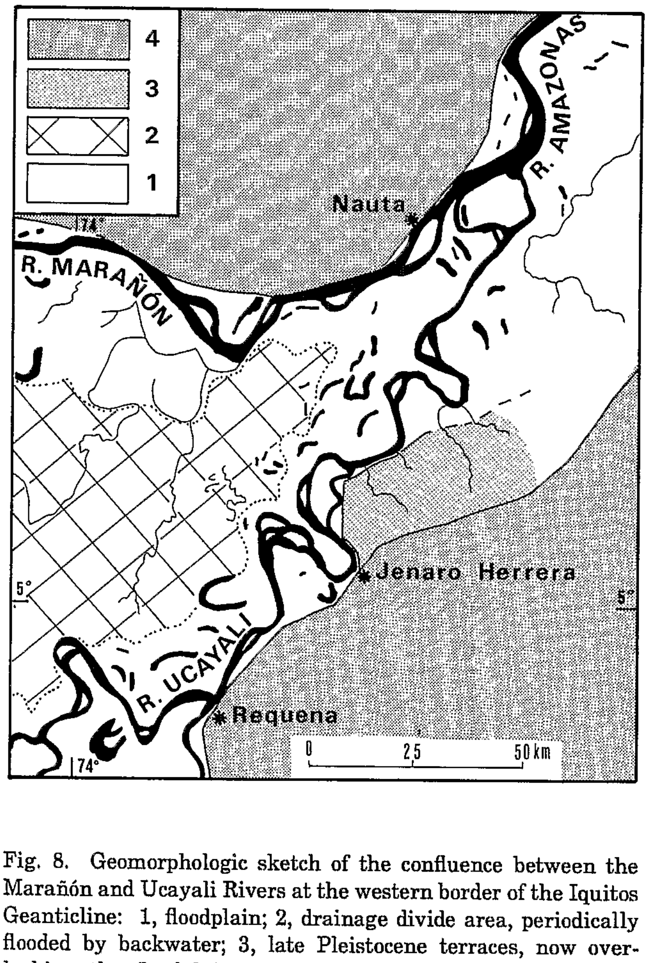

Fig. 8. Geomorphologic sketch of the confluence between the Marañón and Ucayali Rivers at the western border of the Iquitos Geanticline: 1, floodplain; 2, drainage divide area, periodically flooded by backwater; 3, late Pleistocene terraces, now overlooking the floodplain; 4, upland areas (Pebas and Ipururo Formations).

various stages of infilling and by a high meander migration rate, up to 20 m/yr (Campos, 1980). The drainage divides between the rivers have no significant relief and can be flooded during the rainy season. Fluvial interconnections are possible between the Marañón, Ucayali, and Tapiche Rivers for more than 200 km upstream of the normal confluence.

IQUITOS UPLAND: THE BRAZILIAN CRATON MARGIN

The Iquitos Geanticline has had positive tendencies since the early Mesozoic (Laurent, 1985; Sanz, 1974). Nevertheless, subsidence during the late Tertiary led to the deposition of 500-600 meters of sediments (Soto, 1979). Uplift resumed during the Quaternary, giving rise to the present upland some 30 meters above the floodplain. The western limit of the Iquitos Geanticline, which trends NNW-SSE, is parallel to and superposed on an important network of basement faults, as suggested by seismic reflection profiles (Laurent, 1985; Fig. 7). The Ucayali River flows into the Marañón River in a depression that divides the upland in two parts, located to the north (Nauta) and south (Jenaro Herrera), respectively (Fig. 8). Escarpments with straight segments, suggesting a structural influence, limit the floodplain and the upland. Crossing the geanticline, the Marañón and Ucayali Rivers run along northern and southern uplifted blocks. Straight channel segments and asymmetric meander belts suggest structural control of the rivers' beds.

Two main formations constitute the Iquitos upland, the Pebas and the overlying Ipururo Formations. The Pebas Formation consists essentially of cohesive silt and clay with numerous lenses of compacted peat. Various authors have described the molluscan fauna of the Pebas Formation (*e.g.*, Rüegg and Rosensweig, 1949; Radambrasil, 1977), but no consensus has been reached on its age. The synthesis made for the Radambrasil project suggests that the Pebas Formation is mainly Pliocene and Pleistocene. Near Iquitos, the recent discovery of vertebrate bones suggests an early Pleistocene age for the uppermost levels of the formation (de Muizon, pers. commun., 1989). The depositional environment was probably a lake with large areas alternatively covered by vegetation and flooded, forming peat deposits. The subsidence of the area is proven by deposition of more than 400 meters of fine sediments.

The Ipururo Formation overlies the Pebas Formation and consists of 5-10 meters of fluvial conglomerate, sand, silt, and clay. The change from the Pebas lake environment to the Ipururo fluvial system is related to an early Quaternary tectonic phase. Climatic changes may also have increased the rate of erosion and transport during interglacial stages (Dumont and Garcia, 1989).

Late Pleistocene fluvial deposits crop out on the borders of the Ucayali floodplain (Fig. 8) along the escarpment or in stepped terraces limited by lines of bluffs (Dumont *et al.*, 1988). Quaternary terraces currently higher than the high water stages have radiocarbon ages of 32,750 (+3,520; −2,440) years BP and over 40,000 years BP for the higher terrace, and 13,000 (+2,090; −1,660) years BP for the lower (Dumont *et al.*, 1988; dates on wood samples from ORSTOM Laboratory). The late Pleistocene deposits are characterized by coarse sand and gravel with accumulations of wood and leaves.

Recent channel migration, characterized by well developed ridge and swale arrays, appears to typify the post-glacial (Holocene) period. Old scroll-bar and oxbow patterns are related to former river reach positions, showing evidence of the asymmetric pattern of the Ucayali River belt near Jenaro Herrera. The river is located close to the southeastern margin of the line of bluffs, whereas the oxbows, all of them concave toward the southeast, are located along the northwestern margins. In an example from the Madison and South Fork Rivers in Montana, Leeder and Alexander (1987) considered the preferred facing directions of the abandoned loops to be critical evidence that the meander belt asymmetry was produced by gradual transposition of the river toward the escarpment due to tilting. Our case suggests a surface tilted along the faulted borders of the floodplain. A symmetric feature may be observed for the Marañón River hugging the northern border of the subsiding floodplain near Nauta. This structurally controlled river belt pattern may be correlated with faults observed in the Ipururo Formation (Dumont *et al.*, 1988).

Stepped terraces suggest that the encasing of the floodplain inside the escarpments occurred during the late Pleistocene. The asymmetric meander belt pattern suggests that the relative rise of the upland and the subsidence of the floodplain probably continues at present.

DISCUSSION AND CONCLUSIONS

Folding vs Tilting Effect on River Drainage

The STFB and the STBZ show two different relationships between neotectonics and river drainage. In the STFB, the main rivers are antecedent along the major part of their reach and are probably superimposed in some part of the lower reach, close to the Amazon Basin. In the STBZ, river channels and river basins are shaped or limited by structures. These differences do not depend on the relief or the magnitude of tectonic movement and uplift in either the foothills or the lowlands. More probably, the tectonic style is what determines the river belt pattern.

The STFB structures comprise large folds and related listric thrusts and sole faults (Pardo, 1982). These structures are due to continuous deformation of the relatively competent and well stratified Mesozoic rocks separated from the Paleozoic basement by saline deposits (Benavides, 1968). Reverse faults are closely related to folding.

On the other hand, the STBZ involves tilted blocks limited by deep faults, along which deformation is concentrated. Infracambrian deposits are visible on the eastern faulted border of the Shira Mountains north of Atalaya (personal observation with G. Laubacher). Folds are very gentle in the STBZ, with dips rarely exceeding 20°, except close to the main faults.

We suggest that the trends of the river belts are related to structural style. Where folding is dominant and relatively continuous (STFB), the rivers are antecedent and fluvial downcutting is assumed to be more important than tectonic uplift. In contrast, where faulting and tilting are dominant (STBZ), the river channels are controlled by structure and fluvial erosion is not enough to maintain the previous river trends.

Floodplain and Upland Limits

The position and significance of floodplain-upland limits have important effects on Amazonian landscape evolution and ecology. Recent hypotheses emphasized a model of river migration due to long-term Subandean tectonics as a determining factor in Amazonian land-species richness (Salo *et al.*, 1986; Räsänen *et al.*, 1987). The model of Räsänen *et al.* (1987) supposes that the higher lying areas (upland, usually called "terra firme" in Brazil) are widely covered by Quaternary fluvial deposits. However, Pleistocene-Holocene deposits are not widely exposed over these areas (Kummel, 1948; Koch, 1959b) and, as reported here, on stepped terraces along the present river floodplains. Consequently, the postulated concept that Quaternary fluvial perturbances were regulated by long-term Subandean tectonics has no basis. On the contrary, the Subandean lowlands exhibit complex structures and have been uplifted since the late Miocene. The morphostructural provinces must be distinguished according to foreland (recent uplift), foredeep (continuous subsidence since the Mesozoic), or even cratonic position (episodic and limited uplift or subsidence). For example, the Marañón Basin (subsiding) and the Iquitos Geanticline (Brazilian Craton) are not affected directly by Subandean tectonics as are the STFB and STBZ (present foreland). Therefore, the different tectonic styles must be separated because of their different effects upon drainage.

The Amazonian Lowlands of Peru: A Special Pattern

A striking point is the highly asymmetric pattern of Subandean drainage in Peru. The general trend of the main rivers on the eastern slopes of the Peruvian Andes is roughly northward, more or less parallel to the Andean structures. The Marañón River concentrates all the rivers of the central Peruvian Andes, from near the Equator to about 14°S, on the northeastern part of the drainage basin. This position is probably related to an important change in direction of the Andean range, the Huancabamba Deflexion in the High Andes (Mégard, 1984) and the Corriente (Laurent and Pardo, 1975) and Marañón fault zones (Laurent, 1985) in the basement of the Marañón Basin. This peculiar drainage system resulted from Quaternary tectonics—particularly from STBZ tectonics, which control channel formation north along the range toward the subsiding Marañón Basin.

Acknowledgments—This work is a UR 105 ORSTOM project supported by two agreements: ORSTOM/IGP and ORSTOM/IIAP. This is a contribution to IGCP Project 279 (Terranes in Latin-America) and Project 281 (Climas Cuaternarios de America del Sur). We thank V. Benavides, J. Paredes, E. Aliaga, F. Fuentes, and H. Valdivia for helpful discussions. L. Ortlieb, M. Sébrier, and A. Lavenu provided many helpful critical comments on the manuscript, and D. Smith revised the first text in English, for which we are grateful. Finally, we thank K. Butler and C. Schubert for their comments and suggestions.

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