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GEODYNAMIC ENVIRONMENT OF QUATERNARY MORPHOSTRUCTURES OF THE SUBANDEAN FORELAND BASINS OF PERU AND BOLIVIA: CHARACTERISTICS AND STUDY METHODS

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The Quaternary evolution of western Amazon basins is considered using morphostructural analysis of fluvial belts and lakes. Meandering rivers from the basin surface are analyzed using three scales of elements: the ridge and swale pattern, the mosaic pattern and the fluvial belt. Lake patterns are differentiated according to their shape, the hydrological environment and the structural context. Influences of basement structures and neotectonic deformations, when known, are considered. The morphostructural patterns are discussed in the context of a balance of internal (tectonic) and external (hydraulic and sedimentologic) processes. Special attention is focussed on the effect of neotectonics, which is generally neglected, on the formation and the location of Quaternary morphostructures. The adaptation of study methods and sampling to the characteristics of the different morphostructures is considered.

INTRODUCTION

Foreland tectonics and their control on surface deformation and deposition of Quaternary deposits in western Amazon are poorly understood, largely because few direct elements and methods are available for the observation of such processes. The objective of this paper is to present an overview of the most characteristic lake and river patterns observed on the surface of subandean foreland basins, in order to determine how they can help to understand the Quaternary evolution of these regions. This paper will focus on the extended floodplains of the basins, which are presently subsiding.

We challenge here the idea commonly held that fluvial dynamics and avulsions act randomly on the surface of subsiding basins. Our demonstration is based on considerations of basement structures as well as neotectonic and seismotectonic data from the basin margins. Climates, as well as sedimentary and hydrological processes, are also very important, and can play a major effect in some cases, but these external processes are not determinant in most cases.

GEOLOGICAL BACKGROUND

The Andean foreland basins are characterized by extended and flat Quaternary deposits. Three types of landscape are observed: (i) very flat extended floodplains at elevations between 100 and 300 m; (ii) poorly dissected uplands; and (iii) fairly uplifted areas with hills up to 700 m in elevation, called the 'Montaña' by geographers and early travelers. Most developed in central and eastern Peru (Sierra de Moa), the Montaña was formed during the Pliocene and Quaternary, when some parts of the former and more continuous subandean basins were uplifted (Fig. 1). The Marañón and Beni basins are the main extended floodplains covering about 25% of the western Amazonian lowlands. They represent the areas of active subsidence related to flexural basins.

Flexural basins are generated by compressive tectonics in front of the eastern margin of the Andean range, and by overloading of the Brazilian Craton border, which is downwarped as a result. The basins are filled by asymmetrical sedimentary prisms, thick on the range side and thinning toward the Brazilian Craton (Plafker, 1964; Pardo, 1982; Mégard, 1984). A bulge effect of the continental crust is observed on the eastern margin of the basin (Lyon-Caen *et al.*, 1985). The formation and development of these basins is related to the rising of the Andes as a result of the Quechuas phases, during Mio-Pliocene time (Lavenu and Marocco, 1984; Sempere *et al.*, 1990). Two main basins, the Marañón and the Beni Basins, are located respectively to the north and to the south of the Peru–Bolivia Andean segment (Fig. 1). Between these two large basins, in central and south Peru (Ucayali and Madre de Dios Basin, respectively), the foreland basins are narrow and elongated parallel to the range. In the center of the segment the Fitzcarrald Arch is a main structural and interfluvial axis trending ENE–WSW (Oppenheim, 1975), which connects the Andes (to the west) to the Brazilian Craton (to the east) without the occurrence of any active basin.

Up to 5000 m of late Cretaceous and Cenozoic sediments are deposited in the Marañón Basin (Seminario and Guizado, 1976; Sanz, 1974), as well as in the Beni Basin (Sempere *et al.*, 1990). Unpublished seismic reflection data suggest that the Upper Ucayali and Upper Madre de Dios basins have registered lower amounts of subsidence. Before the Miocene, the area which extends from the Altiplano to the west and the Iquitos Arch to the east was characterized by the deposition of the well known 'red beds' of late Cretaceous to Eocene–Oligocene age (Mégard, 1984; Marocco, 1978). These widespread deposits, which are not restricted to

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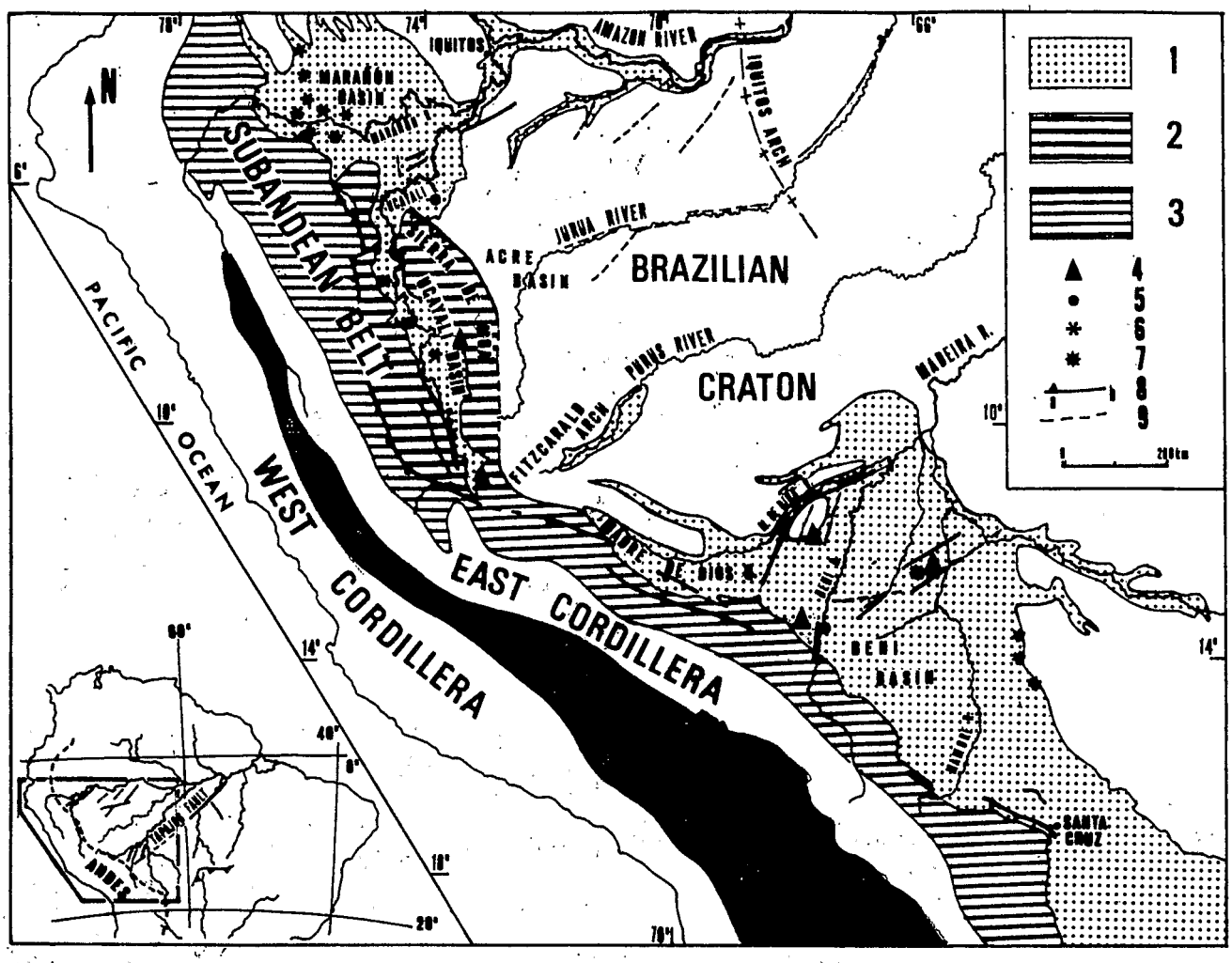


FIG. 1. Structural scheme of the Subandes of Peru and Bolivia. (1) Main areas of Quaternary deposits. (2) Subandean zone of block tectonics in central Peru. (3) Subandean Thrust and Fold Belt. (4) Indications of uplift tendencies. (5) Indications of block or limited area of active subsidence. (6) Ria lakes related to floodplain aggradation. (7) Ria lakes related to tilting. (8) Main reverse (a) or vertical (b) faults. (9) Estimated faults.

foreland regions, have been deposited in relatively smaller tectonic basins, surrounded by mountains of probably low elevation (Lavenu and Marocco, 1984). Before the Miocene, foreland basins were probably not flexural basins as they are presently, and the Andean drainage pattern at that time probably has little similitude with the present fluvial network. A rough rising of the Andes during the Miocene in relation to the formation of the Subandean Thrust and Fold Belt (STFB) (Mégard, 1984) bracketed the previous intraforeland basins in a line of flexural basins located between the Andean Piedmont to the west and the bulge of the overweight Brazilian Craton to the east. As a result, the drainage of the Subandes was collected along the Piedmont in the flexural basins, finding an outlet eastward to the Atlantic Ocean, through the Brazilian Craton.

The model of flexural basins suggests a development parallel to the mountain belt. In fact, subandean flexural basins are rather discontinuous. In the Andes, three elements appear to determine important anomalies in the development and the location of the flexural foreland basins: (i) planar curvatures of the foreland belt, (ii) the geometry of the subducted plate beneath the Andes and (iii) the inheritance of old structures, especially the Paleozoic ones.

The first point (i) is relative to the main curvatures of the Andes. Classically, concavity of a thrust belt (toward the foreland) increases shortening and the overloading effect, and increases the subsidence as a result. On the contrary, foreland areas in front of a convex thrust belt are less subsident, with periods of relative uplift. The northwest (concave) and southeast (convex) ends of the Peru–Bolivia Andean segment are concerned here: the trend of the STFB changes from NNW–SSE in Peru to NNE–SSW in south Ecuador, and the concavity fronts the Pastaza depression (West Marañón Basin). On the contrary, in south Bolivia the STFB trend changes from NW–SE to NS, convex towards the Amazonian plain, and there fronts the uplifted area of the Bañados del Izozog and the Amazon–Parana basin interfluve, with outcrops of the Brazilian Craton only some kilometers from the Andean Piedmont.

Regarding the second point (ii), it is now generally accepted that 'flat' subduction segments, such as occur between 3° and 13°S (central Peru) and 27° and 33°S (central Chile), determine a wide zone of foreland deformation characterized by block tectonics (Jordan *et al.*, 1983), and related to a stronger coupling between the subducted plate and the crust. As a result, the effect of overweight is weaker. Such block tectonics have developed in central Peru since the Pliocene, leading to the formation of the present day

Upper Ucayali Basin, located on the downwarped side of the Sierra de Moa (Dumont *et al.*, 1991).

The effect of old structures (iii) is probably the most important and also the most difficult to determine. The effect of Paleozoic structures on the shape of the present structural zones of the Andes has been recognized: the Abancay Deflection (Marocco, 1978), which determines eastward the Fitzcarrald Arch, the Iquitos Arch (Radambresil, 1977) and the western (Grand Pajonal unit) and eastern (Sierra de Moa) parts of the Upper Ucayali Basin (Martin and Paredes, 1977; Benavides, *oral commun.*, 1989). Other structures are less known and their effect is more speculative, like the Panafrican lineaments which extend westward to the Andes. The Marañón Fault Zone of Laurent (1985), which has a determining effect on the development of the south Marañón Basin, is an example (Dumont, 1992). Another is the SW end of the Tapajos Fault (CERESIS, 1985), which determines a significant limit in the Beni Basin. In the remainder of this paper these structures will be mentioned if necessary, but it is our opinion that most of the explanation of most of the structural anomalies must be attributed to inherited basement structure from Hercynian or older times.

BALANCE OF INTERNAL AND EXTERNAL PROCESSES

External processes are dominated by a wet tropical climate generating dynamic fluvial systems. At the exit of the subandean basins toward the Brazilian Craton, the upper Amazon River in Iquitos and the Upper Madeira River in Guajá Mirim are already among the largest rivers on earth (Gibbs, 1967; Guyot, 1992). These rivers contribute 15% of the total discharge of the Amazon River. Running down from the eastern Andes these rivers are charged with traction and suspended sediments, and are called 'white water rivers'. Sediment loss in the foreland basins is high: according to a detailed hydrological survey, about 60% of the sedimentary charge of the Mamore River is trapped in the Beni Basin (Guyot, 1992).

A wet tropical climate in the Amazonian plain results in extensive wetlands, swamps and lakes, fed by local precipitation and drained by small 'black water' rivers, rich in organic acids. The surface of the foreland basins has a mean slope lower than 10 cm/km. Swamps and lakes represent 3.4% of the surface of the Marañón Basin (Kaliola *et al.*, 1991) and 3% of the Beni Basin (Plafker, 1964).

The rainy season occurs in the foothills and in the flatlands at the same time, between December and May. Flooding of the flatlands by local precipitation can contain and limit water coming from the rivers and remote precipitation in the Andean Piedmont. Thus, levees cannot develop on the margins of the rivers, and only suspended fines reach remote parts of the floodplain. Unfortunately, the hydraulics during floods is quite unknown, but may be important for the understanding of the filling of the basin. For example, it is said by settlers in the south Marañón Basin that during extensive floods, overbank flows from the Marañón and Ucayali Rivers tend to drain S–SE, through the Ucamara Depression, to the floodplain of the Tapiche River. Extensive clay deposits observed away from the river belts may be explained by these particular flows established through the floodplain during higher water stages, in some cases more than 150 km before the normal confluence of the rivers. Because precise topography and hydraulic data are lacking, hypotheses are speculative.

Internal processes are evidenced by active subsidence, especially during the Quaternary. More than 500 m of Quaternary sediments have been deposited in the Marañón Basin (Seminario and Guizado, 1976; Sanz, 1974), and about 800 m of late Tertiary and Quaternary sediments in the Beni Basin (Plafker, 1964). To give an idea of the importance of the subsidence, note that we observe the same mean ratio of subsidence during the Quaternary (0.25 mm/year) to the ratio of uplift of the Andes since the late Oligocene. The high rate of subsidence, especially with respect to the output of the basin, means that internal processes cannot be neglected, and probably compensate more or less for the effect of fluvial aggradation. Large rivers on a very flat plain will probably be very sensitive to any change in the position of the subsidence axis and depressed blocks. Internal and external processes will combine to give the present pattern of the floodplain, but we hypothesize that internal processes are more important and can explain most of the special morphological pattern observed on the surface of subsiding areas.

IDENTIFICATION OF THE MORPHOSTRUCTURAL ELEMENTS

Meandering Rivers

Studies of fluvial patterns — active and relict — are very numerous. Nevertheless, from a practical point of view, the interpretation of samples collected from a river belt is not easy, because several short term and local changes (like point bar deposits) are combined with longer term changes such as those due to climatic changes and tectonic activity. So, most authors remain in the field of general fluvial processes and leave aside the questions dependent upon regional or specific influences. In fact, the problem of the evolution of a meandering river belt may be handled from a structural point of view, and mapping the successive elements in space and time. This work is easy and relatively accurate with satellite imagery like TM or Spot.

Three space/time related elements constitute the active fluvial belt (Fig. 2), from the smaller to the larger: third order (small) elements are represented by the ridge and swale morphology (scroll pattern) observed on Spot images as well contrasted and thin curved lines; second order (intermediate) elements are represented by the mosaic pattern which represents areas of continuous growth of scroll pattern; and the first order (large) element is represented by the belt of recent occupation by the river. These elements will be presented in more detail in the same order.

Ridge and swale elements

These are the most elementary components of fluvial morphology of meandering rivers (see Walker and Cant,

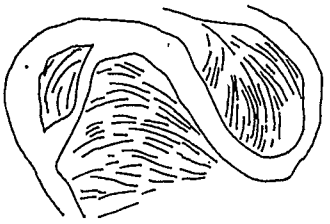
RIDGE AND SWALE PATTERN

Scale: up to 200m spaced and 3km long.

Cycle: 6 to 10 years.

Influence: Climate, hydrology.

Interest: short term managing of river bank, navigation, minor risks.



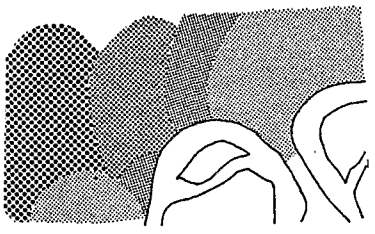
FLUVIAL MOSAIC

Scale: elements of up to 50 km^2.

Cycle: 40 years to 150 years.

Influence: Climate, hydrology, local tectonic.

Interest: long term river bank managing, major risks, placer deposits.



MEANDER BELT

Scale: Tenth of kilometers wide, hundred of kilometers long.

Cycle: 1 to 3 thousand years.

Influence: Neotectonics, hydrology, sedimentary processes.

Interest: Land use planification and recovering of materials, major risks.

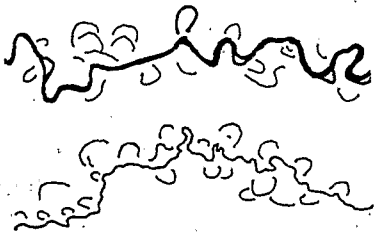


FIG. 2. Scale classification of fluvial landforms in western Amazon.

1984). According to Nanson (1980), a single scroll bar element of fine sediments develops on a point bar platform of relatively coarse sediments. With continuous sedimentation the scroll bar grows, becoming a floodplain ridge.

Large ridge and swale morphology in the western Amazon is related to rivers with a high migration rate. Along the lower part of the Ucayali River, the scroll elements are 50–100 m apart, and up to 3 km long. Multistory image studies of the Ucayali River have shown a migration rate of about 40 m/year (1972–1988) from the Ucayali River in the central part of the basin (Dumont, 1992), and of 60 m/year (1972–1975) from the lower Ucayali (Dumont, *in press*). Relatively smaller values of around 10 m/year have been obtained from the Manu River in the Madre de Dios Basin by Räsänen *et al.* (1991a).

Some data dependent upon historical testimony exist on the rate of construction and abandonment of the scroll pattern. Building and abandonment of an element occur with an average period of 4–6 years (Lamotte, 1990) in the lower Ucayali River. A similar value is indicated by Fawcett (1953) from a survey of the rivers of the Peru–Bolivia border. Critical flow conditions are necessary to initiate a new scroll bar construction, but it is unclear how exceptional floods contribute to the process. Catastrophic floods generally result in neck or chute cut-off (during 1982/1983 for the Beni River and 1991/1992 for the Mamore River, according to P. Cholet, Expert for the COTESU, Swiss Technical Cooperation). On the contrary, it is probable that low to moderate levels during high water stages gently increase the deposition without drastically changing the position of river banks, allowing temporary settlements on the river banks. Change from a wet to a drier climate may generate stability of the river channel due to underfit fluvial conditions (Baker, 1978). These conditions result in paleosol occupation of the lower part of the previous scroll topography (Dumont *et al.*, 1992).

Mosaic elements

An element of fluvial mosaic represents an area of continuous meander evolution, until a neck cut-off or an abandonment of the channel occurs. This is a time/space related structural element (Fig. 2): an element crosses and partly or completely erases the previous ones. The mosaic elements from the lower Ucayali cover areas up to 20 km^2. Clearness of morphological structures, more affected by the erosion when older, may be compared with the structural succession of the mosaic elements to define the successive stages of mosaic development. The map which is obtained constitutes a basic document for the study of the structure of

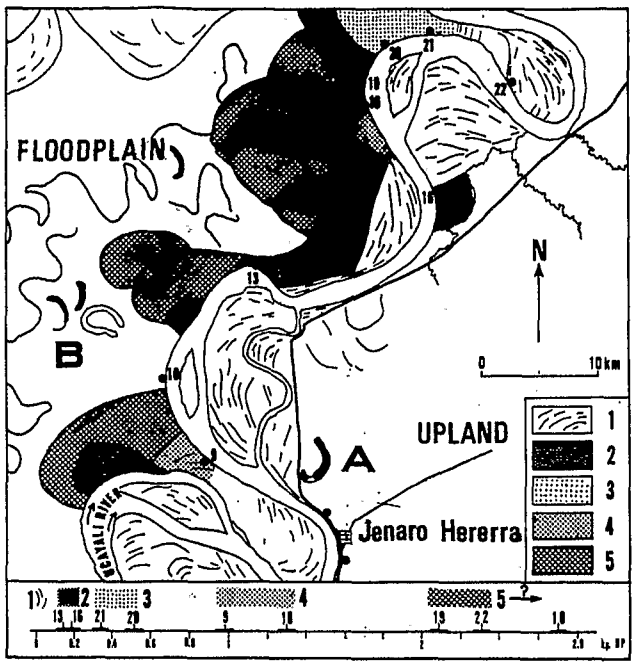


FIG. 3. Mosaic pattern of the Ucayali River (see Fig. 4 for location). Age of the mosaic elements: (1) ridges and swales of the present stage of mosaic construction; (2) 140–190 BP; (3) 340–520 BP; (4) 990–1310 BP; (5) 2100–2310 BP. Numbers: points of collection of samples, age in years BP (laboratory number in parentheses): 9 (850): 990 ± 50; 10 (825): 2720 ± 40; 13 (832): 140 ± 40; 16 (834): 190 ± 40; 18 (863): 1310 ± 40; 19 (862): 2100 ± 40; 20 (848): 520 ± 50; 21 (858): 340 ± 50; 22 (860): 2320 ± 40. Dating made in the ORSTOM Laboratory in Bondy.

the meander belt, and for determination of where sampling of river bank deposits should be done.

The rate of scroll bar construction obtained from historical relations suggests the full development of a mosaic element in a span of time ranging between 65 and 160 years. A comparative value is determined from historical reports for the Amazon River in Iquitos. During Hispanic times, the river has successively threatened to destroy the city or migrate to the opposite side of the river belt, leaving the harbor without fluvial access, with a mean period of 60 years (from 40 to 80 years) (Garcia and SHNA, 1987). According to Räsänen *et al.* (1991a), the Manu River (a small tributary of the Madre de Dios River) has an average lateral migration rate of 12 m/year, and a life expectancy of meander loops of about 160 years.

The map of mosaic succession has permitted a coherent sampling of the river bank. Radiocarbon dating has given ages from 140 to 2720 BP (Fig. 3), which are consistent with the respective position of the samples with respect to the mosaic structural map. Only one age is not consistent (no. 22, Fig. 3), but is too old with respect to the relatively recent position of the mosaic element from which it comes. Reworking of fossil wood is possible, as observed by Räsänen *et al.* (1991a). Nevertheless, from more than 20 analyses performed in the area and published elsewhere, this is the only case of an inconsistent age.

The ages obtained for the mosaic elements, combined with the surface aspect (more or less erased morphology), suggest the development of five successive major stages of mosaic construction, which are successively dated (Fig. 3): (1) the present one, (2) 140–190 BP, (3) 340–520 BP, (4) 990–1310 BP and (5) 2100–2310 BP. The second period is differentiated from the present active development of meanders because it is preserved in concave river banks, and predates the present meander migration. Also, the present stage (1) is probably near its end, because two of the present meanders are close to being cut off (Fig. 3). The oldest stage (5) is in fact a complex one and includes at least two stages of mosaic construction. The oldest mosaic elements have not been sampled and dated directly, but their age is probably close to the age obtained for the floodplain outside of the mosaic belt, which is 2700 BP. Due to the limited number of available ages, the separation in successive periods remains relatively arbitrary. We must only consider this as a practical means of presentation, supported by the morphological aspect. Nevertheless, the relatively small number of successive meander constructions observed on the image (three to four stages before the present one) contrasts with the ages obtained, and is older than what would be expected from a regularly constructed meander belt.

The successive stages of mosaic development are separated by periods of time of 265, 720 and 1055 years, increasing in length towards the past. It can hardly be argued that the time span for the development of a mosaic element was up to 10 times longer in the past. Two phenomena can be suggested to explain this phenomenon. The first is related to the lateral migration of the Ucayali River due to neotectonic faulting along the Brazilian Craton Border (Dumont *et al.*, 1988). The result is a unidirectional migration of the river channel leading to an asymmetrical river belt, with abandoned river scarps and oxbows, all concave toward the direction of migration (criterion defined by Von Bandat, 1962). It may be suggested that the successive periods of preserved mosaic elements are related to tectonic quiescence. Tectonic crisis reactivated river mobility toward the downwarped margin of the floodplain.

As suggested by Baker (1978), fluvial systems adjust to climate in tropical regions. A dry period leads to a lower discharge of the river, a reduction of the mobility or even a stability of the channel due to temporary underfitness. If a wet period occurs again, the discharge increases and reactivates the fluvial migration toward the more depressed areas determined by the downwarped edge of the faulted zones. According to Servant *et al.* (1981), Holocene climate period fluctuated with a periodicity of about 1000–2000 years in the southern part of the Beni Basin. Such fluctuation has been registered in the south Marañón Basin (Dumont *et al.*, 1992). The ages which are available are not enough to correlate climate fluctuations with the stages of mosaic formation, but periodicity in both cases is similar in scale.

Fluvial belts

Fluvial meander belts are the most prominent morphological features on the surface of large subsiding basins. Such patterns have been identified in the Beni Basin (Plafker, 1964; Allenby, 1988; Dumont and Hanagarth, 1993), the Marañón Basin (Dumont and Garcia, 1990; Räsänen *et al.*, 1991b) and in the European Pannonic Basin (Mike, 1975). According to Salo *et al.* (1986), the areas of

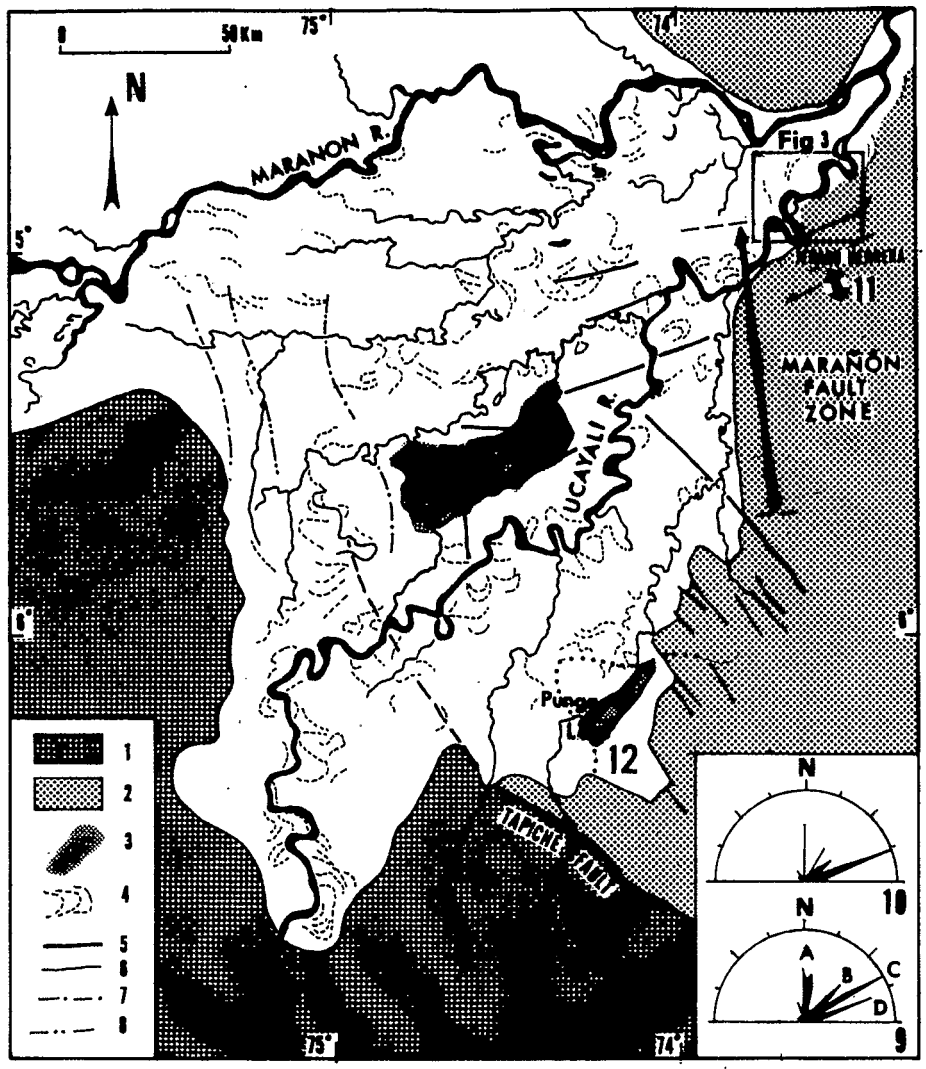


FIG. 4. Morphostructural scheme of the south Marañón Basin (Ucamara Depression). (1) Subandean low foothills. (2) Uplands of the Brazilian Craton. (3) Elongated lakes. (4) Fluvial scars. (5) Basement faults. (6) Surface lineaments interpreted as faults. Anticline (7) and syncline (8) in the basement. (9) Statistical trends of rivers: (A) west of the depression; (B) Ucayali and south of the depression; (C and D) central part superimposed on the Marañón Fault Zone. (10) Basement faults reported to the Marañón Fault Zone. (11) Fault lines and direction of extension reported to normal faulting in Quaternary sediments. (12) Paleozoic uplift of Santa Elena.

recent erosion and deposition represent 26.6% of the Peruvian lowlands and 12% of them are present floodplains.

A common characteristic of these basins is the occurrence of both active (present) and inactive (fossil) meander belts. In most cases, the meander belt has not been totally abandoned, but reduced drainage remains with a narrow channel. This phenomenon is known as an underfit pattern. Defined by Dury (1970), underfitness is related to a river where geometry, especially sinuosity and wavelength, does not fit with its present channel width, according to the usual parameters of a graded river. The inactive belts are interpreted as previous courses of the active rivers. The observation of upstream and downstream links between the portions of underfit channel and the remaining active sections testify to the abandonment by shifting of the main trunk of the river (Dumont, 1992). Erosion progressively destroyed the scroll pattern, making it unclear. Thus, older inactive meander belts are characterized by more unclear and erased scroll patterns, and successive shifting of a river from the oldest position to the present one may be deduced (Mike, 1975; Dumont, 1992).

Precise timing of successive river shifting is lacking, because sampling of abandoned meander belts is difficult. Data from the basin border suggest that no river belts are older than the late Pleistocene/early Holocene in the Marañón Basin (Dumont, 1992). Three principal stages of river belt shifting suggest there was a mean river belt occupancy of about 2500 BP. Data from the Great Hungarian Plain suggests shorter stages of about 1500 years (up to seven stages during the Holocene, from Mike, 1975).

The widespread and rather unidirectional tendencies of the river shifting on the surface of large basins has suggested the influence of large scale deformations of the surface of the basin (Mike, 1975; Allenby, 1988; Dumont, 1992). Nevertheless, this aspect is probably less evident than the effect of local structures. Before discussing the effect of neotectonics on river shifting, we will present briefly the case of the south Marañón Basin (Fig. 4).

The southeastern part of the Marañón Basin is a vast floodplain of about 25,000 km^2, which is common to the Marañón, Ucayali and Tapiche white water rivers (called Ucamara depression by Villarejo, 1988). The floodplain is

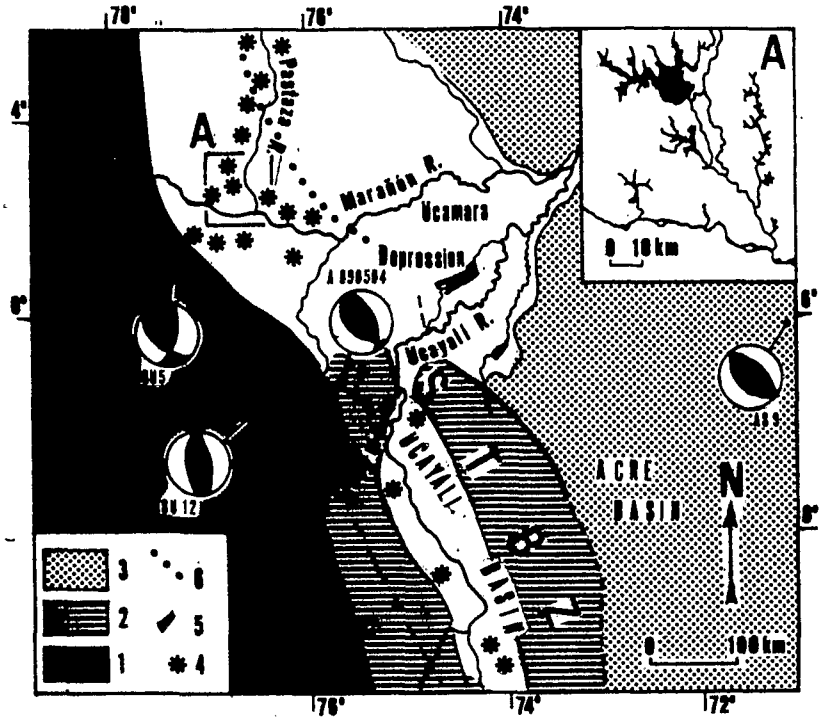


FIG. 5. Neotectonic scheme of the central and northern Peruvian Andes. (1) Subandean Thrust and Fold Belt. (2) Subandean Tilted Block zone. (3) Uplands of the Brazilian Craton. (4) Ria lakes, enlarged in (A). (5) Elongated lakes. (6) Structural axis of the north Marañón Basin. Stereonets from focal mechanisms indicated by index number as the authors: AS9, from Assumpçao and Suarez (1988), A890504 from Assumpçao (1992) and SU5 and SU12 from Suarez *et al.* (1983).

drained by small rivers (Samiria and Pacaya Rivers principally) interpreted as abandoned courses of the Marañón and Ucayali rivers (Dumont and Garcia, 1990; Räsänen *et al.*, 1991b; Dumont, 1992). Respective multi-staged shifting of the Marañón River to the north and of the Ucayali River to the south resulted in a separation of about 100 km apart from a previous common river trunk. The Ucayali River, as well as its previous Samiria and Pacaya stages, are parallel to the main structural lines and faults (mainly of pre-Cretaceous age) in the basement (Fig. 4, nos 9 and 10) (Dumont, 1993). These faults, which belong to the Marañón Fault Zone identified by Laurent (1985), are supposed to have induced preferred flow direction on the basin surface. This is supported by neotectonic data showing normal faults in the Quaternary fluvial deposits from the upland, to the east of the basin (Fig. 4, no. 11) (Dumont *et al.*, 1988; Dumont, 1993). These faults trend N55E, parallel to the main portions of the Ucayali and the other underfit streams in the basin. This direction is also parallel to P-axes from focal mechanisms observed east and west of the depression (Assumpçáo and Suarez, 1988; Assumpçáo, 1992) (Fig. 5, stereograms AS.9 and A 890504). Puinahua and Punga lakes are elongated lakes trending parallel to this direction, the second one (Punga lake) showing historical subsidence (Dumont and Garcia, 1991; Dumont, 1993).

The case of the south Marañón Basin shows that local basement structures and neotectonic faults give a relatively good basis for explaining the main river trends. However, these local phenomena give no explanation for the unidirectional shifting of meander belts from one part of the basin to the other, and how tectonics are implicated remains controversial, and will be discussed later.

Deltas and 'Lake Amazonas'

Fossil delta patterns have been identified in the northern part of the Beni Basin by Campbell (1990), who interprets them as sedimentary deposits from an Andean river entering a huge 'Lake Amazonas' during late Quaternary (Campbell *et al.*, 1985; Frailey *et al.*, 1988; Campbell, 1990). Lake Amazonas is a controversial hypothesis contested by Tuomisto *et al.* (1992), who believe that an extensive fluvial environment may have led to confusing lithostratigraphical correlations, and they suggest an alternative explanation based on tectonically controlled fluvial deposition.

One of the strong arguments presented to support the Lake Amazonas hypothesis is the occurrence of numerous 'bird's foot' fossil deltas in the northern margin of the Beni Basin (Campbell, 1990). In fact, all these deltas are not fossil, and the discovery of an active delta will give a more realistic basis to discuss the significance of these Quaternary morphostructures.

Active delta from the Beni River

The occurrence of an active delta morphology has been discovered about 35 km north of Rurrenabaque (Piedmont border), on the western margin of the Beni River (Fig. 6). The delta structure is about 5 km wide, invading a lake of about 35 km^2. From the west, the lake is supplied by small rivers of black or clear water draining the low Piedmont and the floodplain. To the east, it is connected to the Beni River

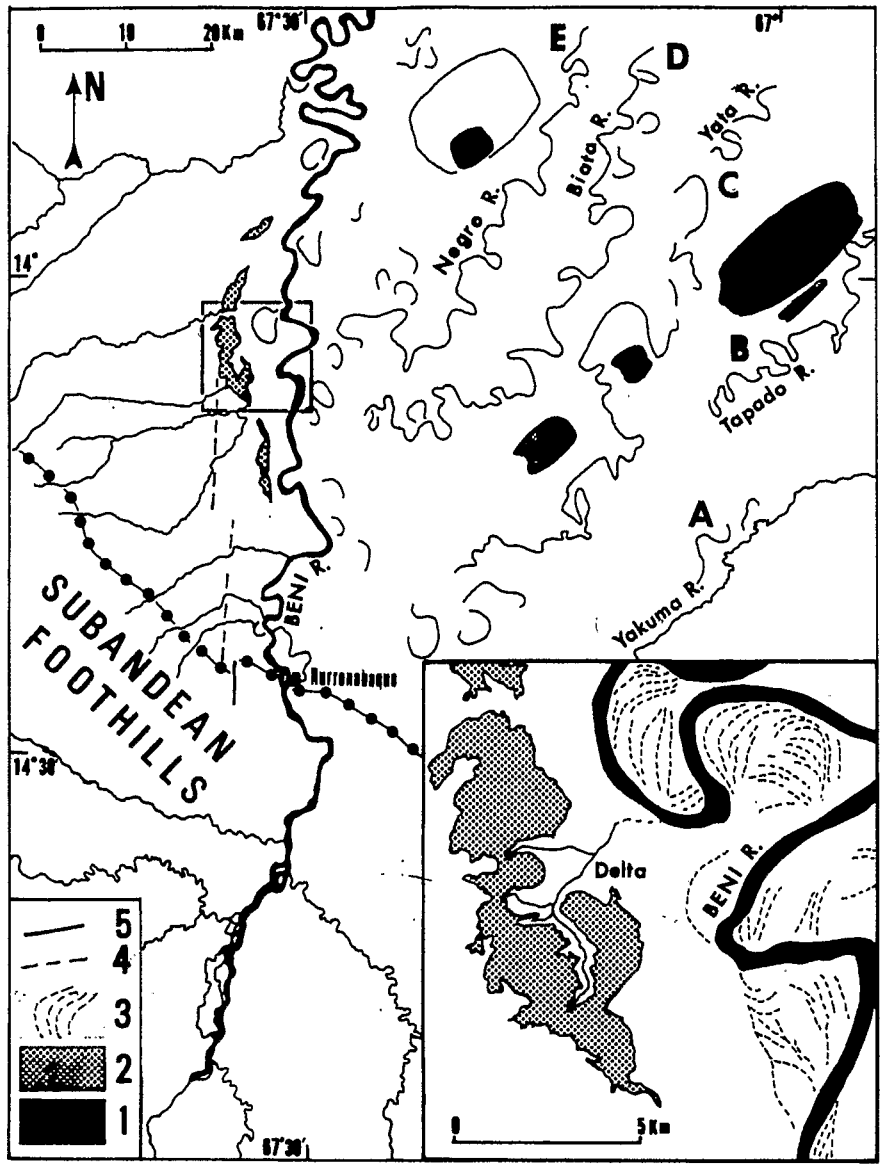


FIG. 6. Morphostructural scheme of the northwest Beni Basin, from an October 25 1975 Landsat image. (1) Subandean Thrust and Fault Belt. (2) Lake invaded by a delta. The enlarged part (lower right) has been drawn from aerial photos taken in 1961 (note, the meander to the north has not yet been cut off). A–E are the successive positions of the Beni River, from the oldest to the recent stages.

through the delta, which has been constructed from overbank outflow during upper water stages. It is clear that the delta system is a lateral construction of the Beni River, located between the river belt and the margin of the floodplain. It is not located at the mouth of a large river as is hypothesized for the fossil occurrences, and the relatively large size of the delta contrasts with the relatively small size of the lake.

The eastern margin of the Beni River is a wide floodplain which extends up to the Mamore River. This area is characterized by several underfit rivers and dry channel segments, abandoned from previous courses of the Beni River (Allenby, 1988; Dumont and Hanagarth, 1993). The course of the Beni River was northeast from Rurrenabaque, along the Tapado and probably (this is less clear) the Yakuma Rivers (Fig. 6), from where it gradually swung westward onto its present northerly course.

The area located to the west of the Beni River (Pando) is a relative upland covered with forests and pampas. Near Rurrenabaque and to the west of the Beni River, the upper fluvial terraces (probably of late Quaternary age) are cut by north–south trending normal faults, with a downward movement of the eastern compartment (Fig. 6). The northern extension of the fault fits with the separation between the extensive floodplain to the east and upland to the west, along the western side of the Beni River. Lakes and delta patterns are located on the downwarped block (the exact fault position is not clear on the images), between the fault line and the Beni River (Fig. 6).

To the north of the area where lake and delta are developed, river banks are low (less than 2 m). There, the forest which previously covered the river banks is dead, and this phenomenon has been interpreted as an evidence of increasing flooding due to active subsidence (Dumont *et al.*, 1991b). The sudden flooding of the forest occurred in 1983 (information from P. Cholet), and up to 1 m of sediments has been deposited since this time. The phenomenon probably resulted from the convergence between active subsidence

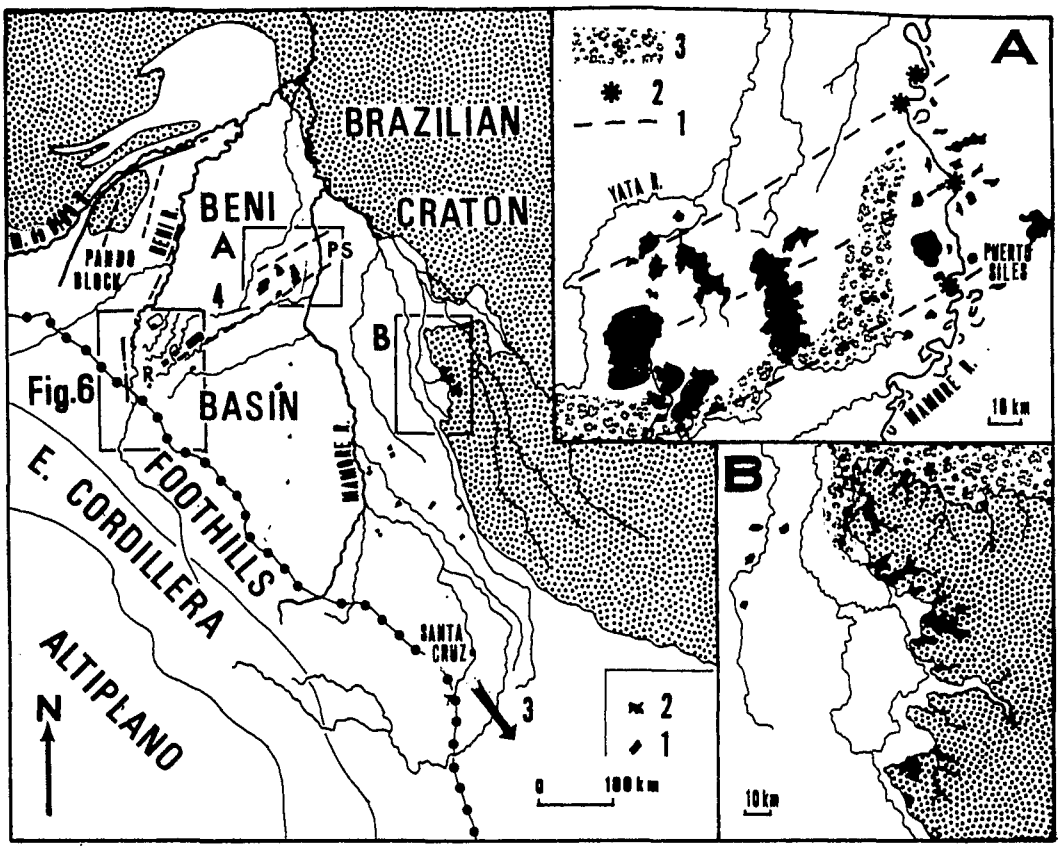


FIG. 7. Morphostructural scheme of the Beni Basin. (1) Rectangular lakes. (2) Ria lakes. (3) Direction of wind according to sand dunes (from Servant *et al.*, 1981). (4) Reyes (R) Puerto Siles (PS) structural axis. A: (1) estimated faults; (2) rapids; (3) swamps. B: same symbols as in A and on the main figure (left).

and exceptional floods due to the ENSO (El Niño) phenomenon.

Fossil deltas

Fossil deltas have been described from the Pando region, between the Beni and Madre de Dios Rivers, and far to the north in the Rio Branco region of Brazil (Campbell, 1990). These regions are uplands covered by pampas and forests, with a low elevation (probably no more than some tens of meters) over the surrounding floodplains of the Beni and Madre de Dios Rivers. Underfit streams and reversed drainage along some delta arms postdate the formation of the paleodeltas (Campbell, 1990). In all the cases, deltas are in the position of lateral construction with respect to river belts, and are driven towards a lake of very limited extension in comparison to the scale of the deltas. Regarding the lake and deltas described on the surface of the Pando Block, it is not sure whether a local fault (not observed) or a main tilting or curvature of the surface of the pampas may originate local subsidence and lakes where deltas were formed.

Fossil deltas similar to the active one have been observed on the surface of the uplifted Pando Block, up to 200 km to the north (Fig. 1). In the light of the active delta we suggest that fossil deltas characterize limited areas of active subsidence, before or during the onset of the uplift of the Pando Block. As a result, the area of active subsidence of the north Beni Basin is probably more restricted now, limited to a narrow belt about 60 km wide, than it was before, when the fossil delta was active up to 150 km to the north of the Piedmont.

Ria Lakes: Where, Why?

A ria lake is a clear water lake formed where the lower part of a tributary is ponded at the margin of the floodplain of the trunk river by more rapid aggradation (Holz *et al.*, 1979). Defined originally in central Amazon as 'ria fluvial' by Gourou in 1949 (in Tricart, 1977), the term 'ria lake' is presently more commonly used. In central Brazil this type of lake is commonly related to postglacial eustasy (Irion, 1984), but the influence of neotectonics on the main trend of these lakes was observed early (Sternberg, 1950). A ria lake, formerly described in east Africa, and mentioned by Schumm (1977, 1986), resulted from a valley which was flooded as a consequence of tilting. This constitutes a second type that may be differentiated from the common type which results from a valley flooded by damming. Occurrences of the two types of ria lake have been observed in western Amazon. Ria lakes are frequent at the margin of large rivers in the western Marañón Basin, in the central Ucayali Basin (Räsänen, *et al.*, 1987; Dumont, 1993), and in the south Beni Basin (Dumont, 1992; Dumont and Guyot, 1993).

The structural axis of the western Marañón Basin is located 100–150 km away from the Piedmont, parallel to the front of the subandean foothills, and following the same curvature concave to the east (Sanz, 1974). An elongated

cluster of ria lakes is superimposed on the axis of the basin, with only an exaggerated curvature (Fig. 5).

In the central Ucayali basin, ria lakes are located on the western margin of the Subandean Tilted Block Zone of central Peru (STBZ, Fig. 5) (Dumont *et al.*, 1991a). The occurrence of a cluster of large ria lakes in specific areas of the foreland basins which are superimposed over axes of active subsidence suggests a structural control for the development of ria lakes.

Ria lakes in the Beni Basin are located on incised topography of the craton margin, east of the Mamore River (Fig. 7B). The alluvial plain which is responsible for the damming of the tributaries is presently drained by small streams which have no connection with the foothills. For this reason, they have little sedimentary aggradation, and the ponded lakes in this region are probably fossil. The fluvial network of the area suggests that the Rio Grande, which has a high sedimentary charge, previously flowed through this plain and is responsible for the alluvial aggradation which ponded the tributaries. The shifting of the Rio Grande towards the west, away from the craton border (as well as a related western shifting of the Beni River) possibly resulted due to the onset of a tectonic event and a rising of the bulge on the craton margin.

Ria lakes related to tilting occur in the central eastern part of the Beni Basin, north of Puerto Siles (Fig. 7A). This area is away from the influence of sediment charged rivers. Some of these lakes are derived from rectangular lakes (see below). Hard rock outcrops and rapids occur where the Mamore River crosses the area and, as a consequence, high sedimentary aggradation cannot be involved here. Rapids located on the upstream border of the area suggest the effect of block tectonics, as proposed by Allenby (1988), and a slight tilting that has resulted in a flooded topography. Block tectonics along a SW–NE axis have been suggested by Plafker (1964) and Allenby (1988). This structural axis is the southwestern extension of the Tapajo fault of central Brazil, suspected of neotectonic activity (CERESIS, 1985).

Elongated Lakes

We use the term elongated lakes in a descriptive sense, applied to lakes which are only approximately rectangular or exposing a more or less geometrical shape. Nevertheless, these lakes appear to be closely related to tectonics, according to the cases of the Puinahua and the Punga Lakes, observed in the south Marañón Basin.

The Puinahua (1324 km^2) and Punga (341 km^2) Lakes are both located in the south part of the Marañón Basin, called the Ucamara Depression (Villarejo, 1988). They are roughly rectangular, slightly arrow-shaped and wider on the foothill side than on the craton side. Their border is not sharply defined on satellite images, because of floating vegetation as well as progressive change to swampy areas.

These two lakes have been interpreted as the surface expression of tensional stress superimposed over reactivated basement structures due to the onset of Andean tectonics (Dumont and Garcia, 1991). Morphological evidence comes from the observation of flooded forest areas previously located out of reach of floods. According to Laurent (1985), the Ucamara Depression extends mainly over an area characterized by NNE–WE late Paleozoic strike-slip faults, which are related to the Marañón Fault Zone, a belt of high fault density. The NE orientation of the Puinahua lake is subparallel to the 'en échelon' system of the Marañón Fault Zone (Fig. 5). The Punga Lake is superimposed over the structure of the Santa Elena uplift (Dumont and Garcia, 1991), interpreted as a crystalline horst surrounded by Paleozoic sedimentary strata (Laurent, 1985). The NE elongation of the lake is parallel to a few of the structural features northward and northwestward from the Santa Elena high zone, according to Laurent (1985). The lakes trend parallel to P-axis orientation of focal mechanisms observed on both sides of the depression (Fig. 5, stereonet A.890504 and AS.9). This trend is compatible with normal faulting showing a NNW–SSE extension observed in the upland border (Fig. 4, no. 11; Dumont *et al.*, 1988).

Rectangular Lakes

Hundreds of rectangular lakes with the same orientation constitute the most striking pattern related to recent Quaternary activity on the surface of the Beni Basin, and until now their very origin is an enigma. The purpose here is to present the most striking aspects of these lakes, and to suggest that complex processes, both internal and external, probably combine in their formation.

Plafler (1964) described these lakes from aerial photos and flights. He gives a structural interpretation, based on similar trends of the lake patterns and of the lineaments in the craton margin in Brazil. On the one hand, this interpretation, which supposed that neotectonic blocks are as numerous as the lakes, is hardly acceptable, for two main reasons: (i) there are a lot of small lakes, which implies tectonic blocks of only some hundreds of meters with a remote basement control through thousands of meters of unconsolidated alluviums, and (ii) all the lakes, small and large, are very shallow, with depths less than 3 m. On the other hand, the structural influences cannot be totally dismissed, especially regarding the main fluvial trend and lake alignments like the Rurrenabaque–Puerto Siles–Tapajo fault line mentioned before. Recently, Plafker's hypothesis has been challenged by a new hypothesis based on external processes, one related to anthropic pre-Columbian agricultural techniques (Barbery *et al.*, 1991), and the other derived from fluvial morphology like oxbows (Guyot *et al.*, 1991, *oral commun.*, 1992).

The lakes are well delimited, rectangular with slightly bent borders in detail (Figs 6 and 8A). Plafker (1964) and Allenby (1988) gave detailed statistical analyses of these lakes: the cumulative length–azimuths of lineaments defined by lake margins are N50E (long side) and N315E on the short side (Fig. 8C). Lake margins are remarkably parallel all over the Beni Basin, which is about 500 km NS and WE.

The largest lakes (over 20 km long) are observed in a backswamp position with respect to abandoned river belts which follow the Reyes–Puerto Siles structural axis (Fig. 7).

Two lakes have been studied: the Laguna Suarez of Trinidad and the Laguna Colorada of Santa Rosa. The characteristics of the two lakes are very similar. Their depth is about 1.3 m during the dry season, and the water level rises less than 1 m during the rainy season. Before roads were built, people used to cross the lakes by horse. The NW

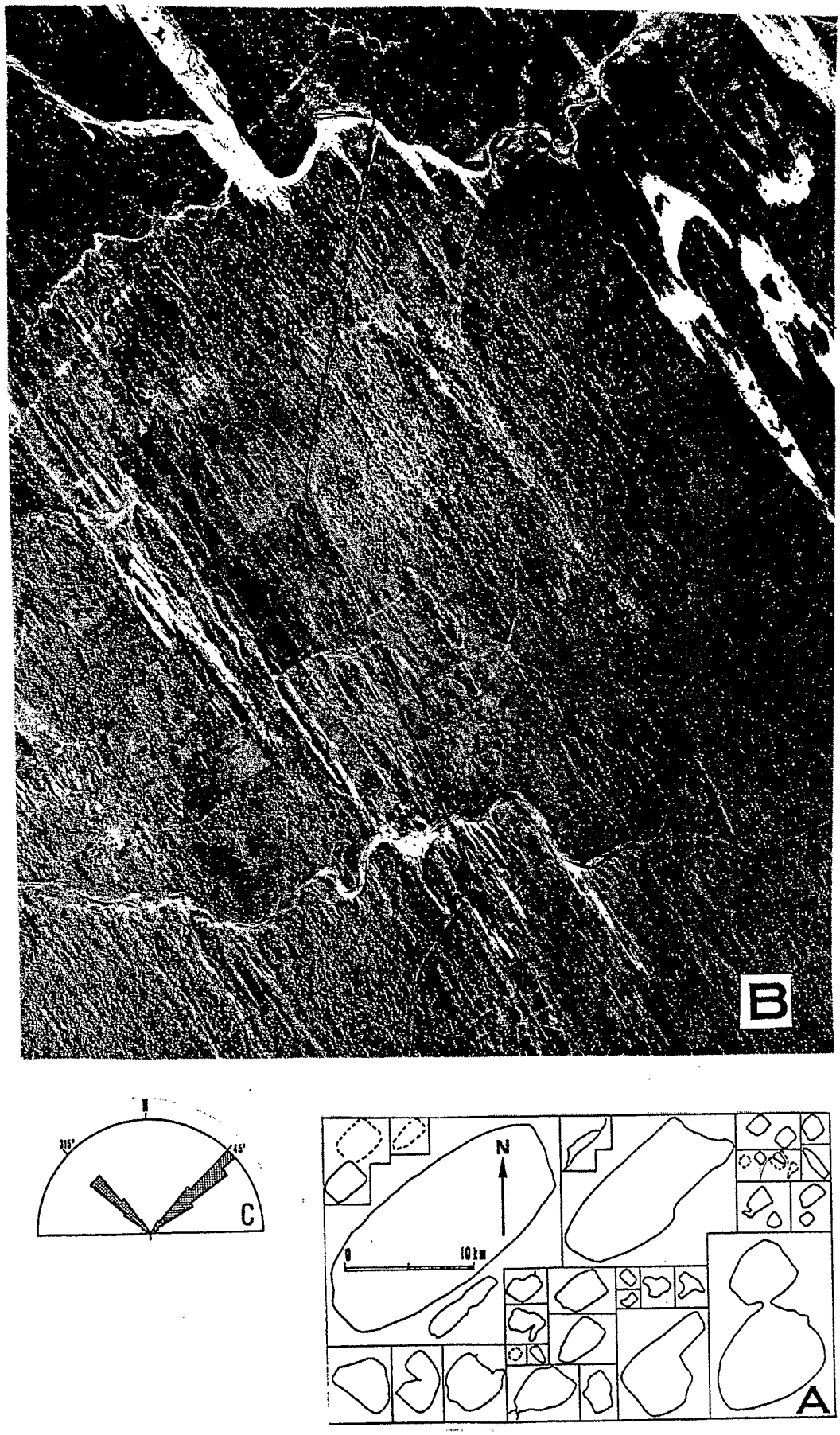


FIG. 8. Upper part (from Plafker, 1964): outline of oriented rectangular lakes from the Beni Basin. Dashed lines are dry lakes. Lower part: aerial photo from the Holocene sand dunes of the Santa Cruz area (location shown in Fig. 7); data from Servant *et al.* (1981), document from M. Servant. Inside (from Plafker, 1964): cumulative length–azimuth diagram of lineaments defined by lake and dry lake margins.

margin of the Laguna Suarez is a swamp of small depth (0.7 m). The limit between the lake and the swamp is underlined by a flooded shallow area, and floating vegetation on the swamp side makes the limit visible. The basement around the lakes consists of a 2–3 m thick layer of indurated gray–green clay, with occurrences of iron nodules. Because the bottom of the lakes is relatively hard, it may be supposed that the layer of indurated clay extends below the lakes. North of Santa Rosa this layer is eroded and weathered, giving over hundreds of kilometers a hard cap of iron concretions called 'cascarosa'. The local drainage of the Laguna Suarez Lake comes from the swamp to the south and goes to the Ibare River to the north. During strong wind periods (which are frequent in the region), the waves remove clay particles from the borders and the bottom of the lake, and we have observed during a visit with M. Tejada (from SEMENA) that entering water is free of suspended sediment, although the water leaving the lake is charged with this sediment. This phenomenon is probably able to maintain and even increase the size of the lakes, by removing clay particles. Because of the limited effect of waves in depth, the depths of lakes remain relatively constant and the bottom very flat.

Similar lakes in other regions have been related to the effect of wind (Carson and Hussey, 1962). Elongation of lakes should be at right angles to the wind directions (Carson and Hussey, 1962; Livingstone, 1954). Plafker (1964) and Allenby (1988) have dismissed the wind effect because of an inaccurate correlation between the present direction of strong wind and lake orientation. Servant *et al.* (1981) have described elongated sand dunes trending N240E in the area of Santa Cruz, to the SE of the area where rectangular lakes are developed. The dunes are related to a period of decayed forest and drier climate, which occurred after 3300 BP, and probably between 3400 and 1400 BP (Servant *et al.*, 1981). These dunes trend exactly at right angles with respect to the long side of the lakes (Fig. 8). The cap of indurated clay on which lakes are developed probably also resulted from a drier climate. As suggested by Iriondo (*pers. commun.*, 1992), lakes may have developed on previous deflation areas. Relatively precarious hydrological and ecological conditions maintain the shape and the depth of these depressions after they have been flooded due to the present wet climate.

DISCUSSION AND CONCLUSIONS

Evaluation of Local Tendencies

The different types of lake constitute a panel of morphostructures to analyze local tendencies of the surface of the basins. Elongated lakes are the most closely related to neotectonics. Nevertheless, it may be difficult to identify such cases of fossil pattern if the structural context, including basement structures and syn-subsidence tectonics, is not considered. Ria lakes combine both subsidence or tilting and contrasted hydrological conditions, with charged water on one side and clear water on the other (the effect of eustasy is not considered here). Study of sedimentary deposits in a ria lake may provide valuable information on the environment as well as on the evolution of the subsidence, because the formation of the lake postdates the onset of tectonic processes, after a period of formation of incised morphology. The interpretation of rectangular lakes remains unclear, and our opinion is that direct tectonic influences are not obvious, while external processes such as drier paleoclimate are probably determinant. From a stratigraphic and sedimentologic point of view, these rectangular lakes do not represent a good target (i.e. for the sampling of Quaternary deposits). These shallow lakes probably export more suspended sediments than they accumulate, and their bottom of indurated clay can hardly be pierced.

Basement structures and neotectonic faults control the local trend of rivers, which is a confirmation of rather classical ideas. In a particular case, asymmetric fluvial mosaics and river belts reflect local deformations, generally the tilting of the floodplain.

These considerations of lakes and rivers suggest that study methods must be adapted to the characteristics of the morphostructural pattern which is studied, and to the objective. Especially, random sampling from lake bottoms without consideration of the history of the lake may be inefficient, just as in the case of river bank sampling without knowing the structure of the fluvial mosaic.

Evaluation of Large Scale Deformations: Are Fluvial Shiftings Representative?

Large scale river shifting is probably the most evident fluvial process observed on the surface of a subsiding basin. Several authors have interpreted the effect of active tectonics on river mobility on the basis of extended unidirectional shifting in the context of a subsiding flexural basin (Mike, 1975; Allenby, 1988; Dumont, 1992).

Besides the academic question of what determines the avulsion process, we think that the question is worth special attention because the disposal of the successive fluvial belts reflects the Holocene sedimentary provinces and large scale evolution during this period. The methods used for the study of the fluvial mosaic are basically the same here, and successive deposition of fluvial belts can be considered as space/time related elements of Quaternary deposits, and constitute a basic document for the study of Quaternary formations and deposits of the floodplain.

Sampling Methods and ^{14}C Dating Implications

The last point and the conclusion will be addressed to sampling and interpretation that may result from ^{14}C dating of samples which have been randomly taken from a river bank, or not accurately located on the map. The case of the Ucayali River shows that a range of 3000 years may be obtained from samples taken from the present river banks, sometimes from two very close points. Only a previous study of the fluvial mosaic can help to point out the significance of the ages which are obtained and, with this precaution, we have obtained relatively coherent ^{14}C dating. The question is the same, or even more difficult, regarding the dating of fossil river belts. Mapping from remote sensing images, the successive river belts must precede any sampling operation, just as a structural map constitutes the framework of the geological study of a region, which allows not only a chronology, but also a relative position of the event in the general history of the region.

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