ELSEVIER

Tectonophysics 257 (1996) 137–151

TECTONOPHYSICS

Neotectonics of the Subandes–Brazilian craton boundary using geomorphological data: the Marañon and Beni basins

J.F. Dumont

ORSTOM, Laboratoire de Géodynamique sous-marine, BP48, 06230 Villefranche s / mer, France

Received 16 November 1994; accepted 29 November 1995

Abstract

Active and abandoned fluvial traces are used together with neotectonic, seismotectonic and subsurface structural data to study the neotectonic evolution of the Peruvian and Bolivian foreland basins. The Marañón Basin to the north and the Beni Basin to the south are located near the ends of the Peru–Bolivia Andean segment. This segment lies above the flat-slab subduction of the Nazca plate beneath the Andes. The surface of these basins shows a complex network of present-day rivers and fossil river traces. A relative chronology of the river traces deduced from morphological criteria allows the identification of successive shifting of fluvial belts up to the present position of the main rivers.

As it enters the Ucamara Depression, the Ucayali River is deflected to the northeast. Successive shifts of the deflection point are directed upstream along the upper reaches of the river along the foothills. Simultaneously the Marañón River is deflected to the north, lining up with the straight, NE-trending lower reaches of the Huallaga River. In the central part of the depression the rivers trend northeast–southwest, parallel to the main strike of the basement faults. This regional trend is also parallel to (1) the greatest principal stress observed both to the east and the west of the depression, and to (2) the neotectonic faults on the margin of the Brazilian craton.

The Beni Basin is characterized by a counterclockwise shift of the Beni River. Successive shifts of the river involve the northward migration of the deflection point of the Beni River as it enters the basin. A fault connected to the foothill margin controls this downstream movement. Recent erosion of the flood plain surface to the east suggests a tendency of the craton margin to ascend. No coaxial stress resulting from either plate motion or from collapse of the Andean topography seems to control the directional shift of rivers in the basins.

1. Introduction

Neotectonic study is mainly based on geomorphic data combined with fault kinematics. Most neotectonic data of the Andean belt come from the uplifted areas. The subsiding parts of the orogenic belt escape nearly totally to neotectonic investigations, because none of the usual neotectonic methods are operating in very flat landscape covered by wetlands. In the case of a stable basement the question would not have received special interest. The present case involves flexural basins linking the downwarped Brazilian craton to the east to the Andean orogenic belt to the west. Subsurface structural data from the Subandean basins come mainly from seismic reflection sections and stratigraphic drilling. They are published (Sanz, 1974; Laurent and Pardo, 1975; Pardo, 1982; Laurent, 1985). These data give only a rough estimate of the recent evolution of the basin, which is principally based upon the thickness of Quaternary deposits.

Mike (1975) suggested the use of present and

SSDI 0040-1951(95)00200-6

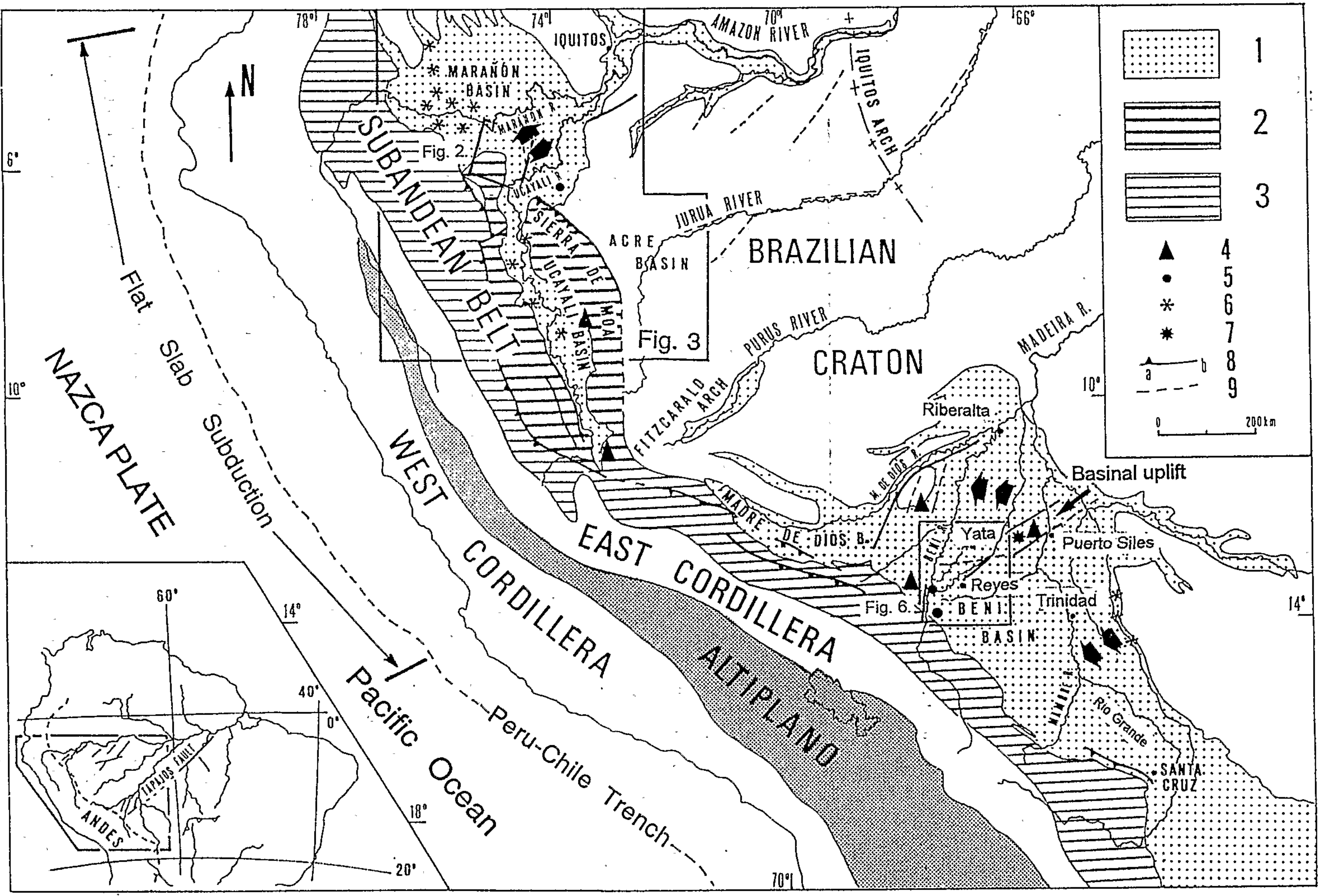

Fig. 1. Structural scheme of the Subandes of Peru and Bolivia, redrawn and complemented from Dumont and Fournier (1994). *1* = Main areas of Quaternary deposits; *2* = Subandean Tilted Block Zone (STBZ) in central Peru; *3* = Subandean Thrust and Fold Belt (STFB); *4* = indications of uplift tendencies; *5* = indications of block or limited area of active subsidence; *6* = ria lakes related to flood plain aggradation; *7* = ria lakes related to tilting; *8* = main reverse (*a*) and vertical (*b*) faults; *9* = inferred faults. Large arrows show the main trend of river shiftings.

fossil fluvial traces to investigate the deformation of the surface of the Pannonian Basin (Hungary) during the Late Pleistocene and the Holocene. Potter (1978) underlined the importance of multidisciplinary approach combining structural, neotectonic and morphological data to study the setting of big rivers in relation to geological structures. As frequently observed in multidisciplinary approaches, the combination of several sets of data gives access to a more complex level of knowledge, and the uncovering of new data.

Regarding the use of fluvial traces in subsiding basins, it is necessary to clear a potential conflict before going ahead the demonstration. The approach followed here emphasizes the interpretation of river shifting as related to the deformation of the basin surface. Fluvial geomorphologists have reported several cases of river migration controlled by faulting or block tilting (Schumm, 1977, 1986). Nevertheless, this idea is frequently opposed by fluvial sedimentologists, who put forth the view of random external processes generated by levee construction and rapid aggradation of the river belt above the general land surface (Smith et al., 1989; Räsänen et al., 1991; Bryant et al., 1995), without any consideration to neotectonic processes. Three considerations lead to challenge this view in Subandean basins, and probably in all flexural basins: (a) an active subsidence limits the differential aggradation of the fluvial belt with respect to the surrounding flood plain, and canalizes rivers along structural depressions and depocenters; (b) the foothill margin comprises piggy-back basins trapping most of the coarse sediments, thus preventing the formation of alluvial fans at the outlet from the foothills to the basin; and (c) high precipitation (over 2 m in eastern Peru) occurring simultaneously in the basins and in the foothills generates contemporaneous floods of rivers external and internal to the basin. This phenomenon impeaches or reduces the construction of levees along the channel margins.

The Subandean foreland comprises a continuous belt of deformation to the west, the Subandean Thrust and Fold Belt (Mégard, 1984) and the Subandean Tilted Block Zone (Dumont et al., 1991a) to the east, in central Peru. The formation of the Subandean Thrust and Fold Belt (STFB, Fig. 1) occurred from Late Oligocene to Pliocene times (Martinez, 1980; Mégard, 1984; Lavenu and Marocco, 1984; Sempere et al., 1990). The Subandean foreland comprises two flexural basins which are presently actively subsiding, the Marañón and the Beni basins, located, respectively, at the northern and southern tips of the Peru–Bolivia Andean segment (Fig. 1). Between these two basins the Subandean foothills extend from the piedmont of the Eastern Cordillera to the Brazilian Craton eastward. In central Peru the Subandean Tilted Block Zone (STBZ, Fig. 1) is a wide margin including to the west the Ucayali Basin, with a piggy-back structure. The Madre de Dios Basin is a similar structure located in front of the STFB of the Peruvian and Bolivian Subandes (Fig. 1). These elongated basins collect the drainage from the eastern slopes of the Andes, and canalize it either to the norhwest toward the Marañón Basin, or to the southeast toward the Beni Basin. The Fitzcarrald Arch (Fig. 1) makes the drainage divide between the two drainage areas. According to Jordan et al. (1983) the Benioff zone dips only 5–10° east from about 2 to 15°S (Fig. 1). This "flat-slab" subduction was fully developed at about 5 Ma, leading to the uplift of the Sierra de Moa and to a divergent drainage on both sides of the Fitzcarrald Arch.

The Marañón and Beni basins are asymmetric troughs that form as the flexural effect resulting of the eastward motion of the Andean belt with respect to the Brazilian craton. The loading of the edge of the continental lithosphere by the overriding orogenic belt produces the subsidence (Beaumont, 1981; Jordan, 1981). In western South America, earthquake focal mechanisms show approximately E–W (N80°E)-directed compressional stresses, observed both in the Subandean region and in areas of low altitude (Assumpçáo and Suarez, 1988; Assumpçáo, 1992; Assumpçáo and Araujo, 1993).

This paper is the third and last part of a presentation of the Subandean basins of Peru and Bolivia. A previous paper (Dumont, 1993) presented the case of lake patterns related to active tectonics in the Ucamara Depression. Then, Dumont and Fournier (1994) presented the methodological approach, including sampling problems and climatic versus tectonic interpretation of some drainage and lake patterns. This paper is focused on the extended flood plains of the Subandean basins. Study methods involve accurate surface data like fluvial traces. The approach emphasizes relationships between shifting of river belts and deformation of the basin surface.

2. Study methods

The approach involves the combination of three types of data: (1) morphological data from the analysis of active and fossil fluvial traces; (2) subsurface structural data from the basin and his basement; and (3) neotectonic and seismotectonic data from the basin and its margins.

The use of fluvial traces is not very familiar to structural geologists, and thus I will present some details about their use. Fluvial landforms observed on the surface of large subsiding basins comprise active (or present) traces formed by the present flowing rivers, and fossil (or ancient) traces related to abandoned channels (Fig. 2). According to Dumont and Fournier (1994) the most important morphological elements are the following:

– Mosaic elements with an internal pattern of curved swales and ridges define areas of steady meander development between two cut offs. Several elements combine to give a mosaic pattern. The size, clearness and possibly the asymmetrical arrangement of these elements characterize the pattern of active and fossil fluvial belts.

– A drainage network of small rivers forms inside the basin. Frequently, these small rivers are observed inside wide belts of fluvial traces. According to Dury (1970) this feature suggests underfit streams, which are streams having experienced a drastic reduction of discharge. This is a typical pattern, characterized by a narrow channel but wide meanders (Fig. 2).

– The identification and tracing of the drainage network use various types of aerial and satellite images. The geometrical characteristics of ancient river traces (meander radius, wavelength) are observed on these images, and compared to the pattern of present rivers. This comparison suggests that fossil traces are former positions of the present rivers (Mike, 1975). Crosscutting of old courses by more recent ones, and burying of the most ancient river traces below successive floods, thus giving discontinuous or shadowy morphologies, give a chronological criterion of succession. Other important factors have to be considered as well, as climate and paleoclimate conditions. Because conditions have not drastically changed since the end of the last glacial period, a comparison between ancient and present river patterns is possible. Short periods of dry climate occurred in the Amazon Basin during the Holocene (Servant et al., 1981), resulting in temporary underfit patterns (Baker, 1978). Underfit patterns are observed In the Marañón Basin prior to 13,000 yr B.P., and short periods of low discharge of the Tapiche River between 4500 and 1000 yr B.P. allow the development of separate layers of paleosoil on river banks (Dumont et al., 1992). Nevertheless, the main position of rivers is probably not affected by lower discharges, because channel underfitness tends to fix a river belt instead of increasing its mobility (Dury, 1970).

3. The Ucamara Depression

The Marañón Basin extends over about 375 km with a W–E strike and 475 km with a NW–SE strike (Fig. 1). It comprises two parts: the Pastaza Depression to the northwest (Laurent and Pardo, 1975); and the triangle-shaped Ucayali–Marañón Depression (shortly Ucamara, according to Villarejo, 1988) to the southeast and east. Up to 5000 m of Late Cretaceous and Cenozoic sediments are deposited in the Pastaza Depression, which represents the deepest part of the basin. This includes more than 500 m of Quaternary sediments (Sanz, 1974; Seminario and Guizado, 1976). The structural axis of the Pastaza Depression (Fig. 3) is parallel to the foothills, N–S directed to the north and NW–SE directed to the south, toward the Ucamara Depression (Sanz, 1974). A cluster of ria lakes is superimposed over the structural axis of the depression, with a tighter bend to the west than the one made by the depression axis (Fig. 3). Ria lakes are similar to lakes made by a dam (Fig. 3A). They formed in the lower reach of a tributary when quick deposition blocks the access to the trunk river (Dumont and Fournier, 1994), either by raising the base level, or by regional subsidence. The structural and regional context suggest that the second case is more likely here. Similar ria lakes are observed to the south, along the Ucayali Basin, which is a piggy-back basin between upper and lower foothills (Räsänen et al., 1990).

The Ucamara Depression is a vast floodplain of about 25,000 km^2, where the three main rivers join near the outlet of the basin, forming the Amazon River (Solimoes in Brazil). They are the Marañón and the Ucayali rivers issued from the Andean range (Fig. 4), and the Tapiche River, the smallest one, issued from the Sierra de Moa (Fig. 3) in the foothills of central-eastern Peru. In the Ucamara Depression there are no ria lakes such as those observed in the Pastaza Depression and the Ucayali Basin. Another type of lake is observed, characterized by elongated and geometrical shape. They are located along the

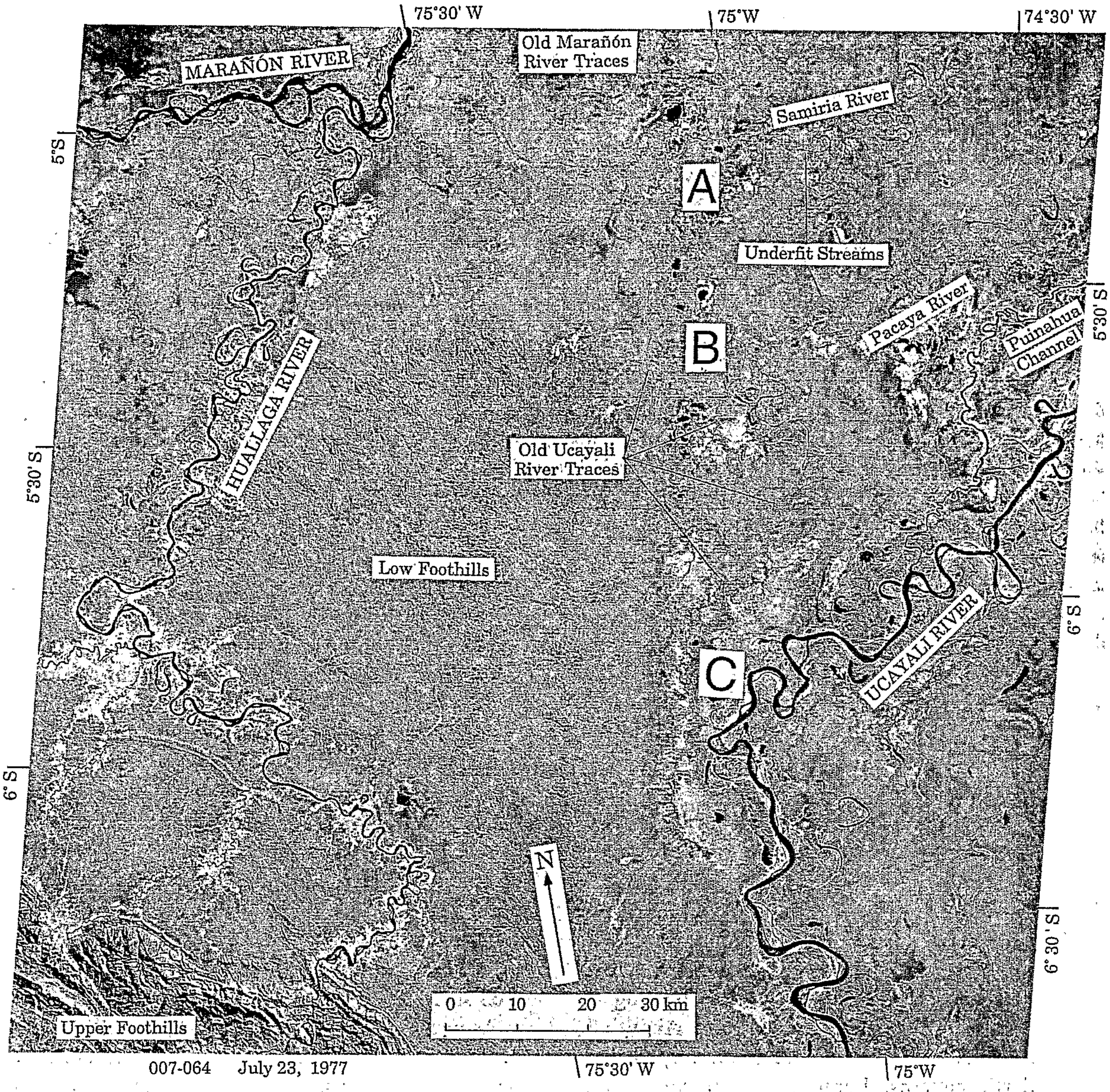

Fig. 2. Landsat image from the western margin of the Ucamara Depression. Note the underfit patterns of small rivers, as well as the successive stages of the Ucayali River along the present Samiria and Pacaya rivers. The successive deflections of the Ucayali River are located on points *A*, *B* and *C*. Landsat MSS, band 7 (0.8–1.1 μ), scene 007-064, 23 July 1977 (low water stage). Location in Fig. 1.

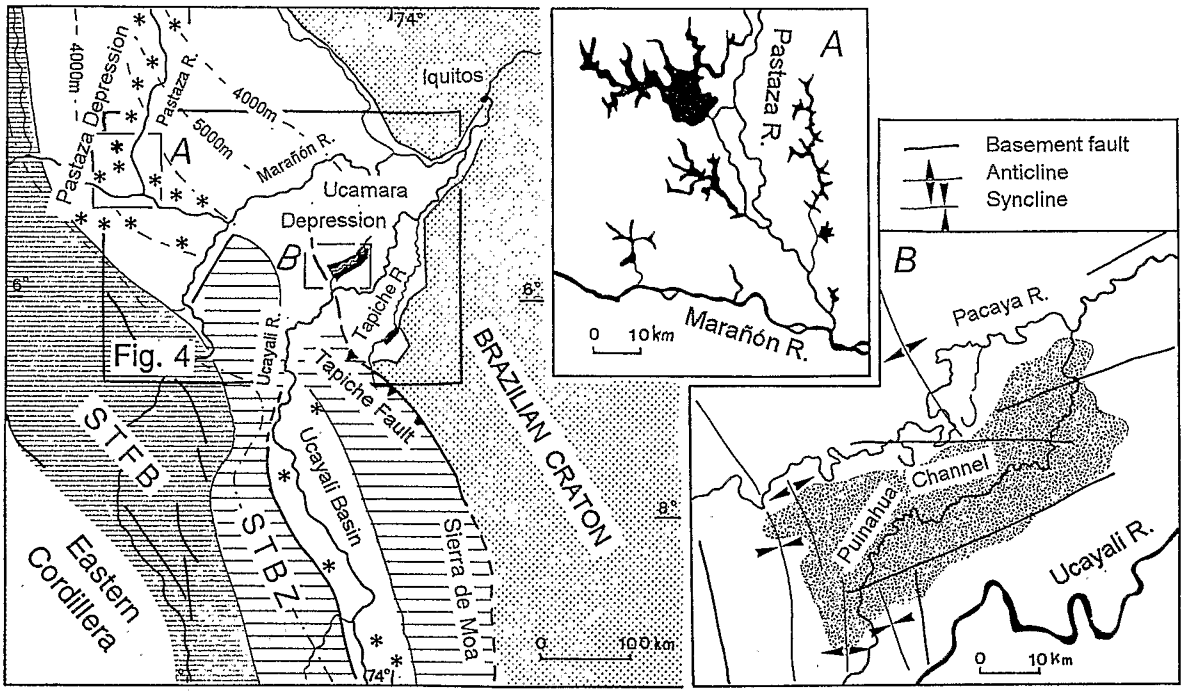

Fig. 3. Structural scheme of the eastern Andes of central and northern Peru, showing the regional location of the two types of lakes, according to Dumont (1993). (A) Ria lakes related to flexural subsidence. (B) elongated lakes related to block faulting. Horizontal shading represents the foothills, closely spaced for the high foothills, widely spaced for the low foothills. In the Pastaza Depression asterisks show the location of the ria lakes, and contours the depth of the pre-Mesozoic basement. Location in Fig. 1.

main rivers: the Punga Lake is drained along by the Tapiche River; and the Puinahua Lake is located along a side channel of the Ucayali River.

3.1. Evidence of river migration

A dense network of small and large streams drains the Ucamara Depression (Figs. 2 and 4). Precipitation inside the depression forms "black water" streams, rich in organic acids. The rivers coming from the Andean relief have "white water," charged with silt. The different types of water are visible on spatial documents. Several, almost continuous, small black water streams cross the depression, from the foothill's piedmont to the Craton margin. The longest are the Pacaya and Samiria rivers (Fig. 4). About all the small streams inside the Ucamara Depression have underfit patterns. Large traces of scroll and mosaic patterns, also big isolated oxbows located besides small streams, help to identify the former big rivers. The similar size between these traces and the present traces of the Ucayali and Marañón rivers (Fig. 2), also the upstream and downstream connections, show that the small streams are old courses of these big rivers (Räsänen et al., 1991; Dumont, 1992). Small graded river traces (with a normal ratio between channel width and meander wavelength) are observed near Jenaro Herrera, both in a remote part of the flood plain and on a 13,000 yr B.P. terrace. This suggests a water discharge only 1/7 to 1/10 the present discharge of the Ucayali River (Dumont et al., 1992). As a result, all the traces attributed to ancient courses of the Marañón and Ucayali rivers and reported in this paper are supposed to be developed since 13,000 yr B.P.

According to the position of the underfit streams, the Marañón River shifted 50 km to the north and the Ucayali River more than 100 km away to the south of a previous common trunk (Fig. 4). The process involves successive directional jumps, each of 10 km up to more than 30 km. The confluence between the Marañón and Ucayali rivers was previously very close to the foothills (point A, Figs. 2 and 4). This point migrated eastward toward the border of the depression. The new path followed by the Marañón River begins at the confluence with the Huallaga River (Fig. 4). The new course shows a deflection to the northeast with respect to the previous ESE trend of the river (see detail in Fig. 2). This new course is an extension of the lower reach of the Huallaga River (see segment D–E, Fig. 4), downstream the confluence with the Marañón River. The counterclockwise deflection of about 90° of the Marañón River is the first step of the northward shift of the river through stages E and F (Fig. 4) up to the present-day position.

Entering the depression, the Ucayali River is deflected to the east. Records of previous paths of the river show a southward upstream shifting of the deflection point. This migration progresses along the trend of the upstream reach of the river (points A, B and C, Figs. 2 and 4), while 30–50 km lateral jumps occurred in the central part of the depression. There is no indication of increasing slope: the sinuosity of

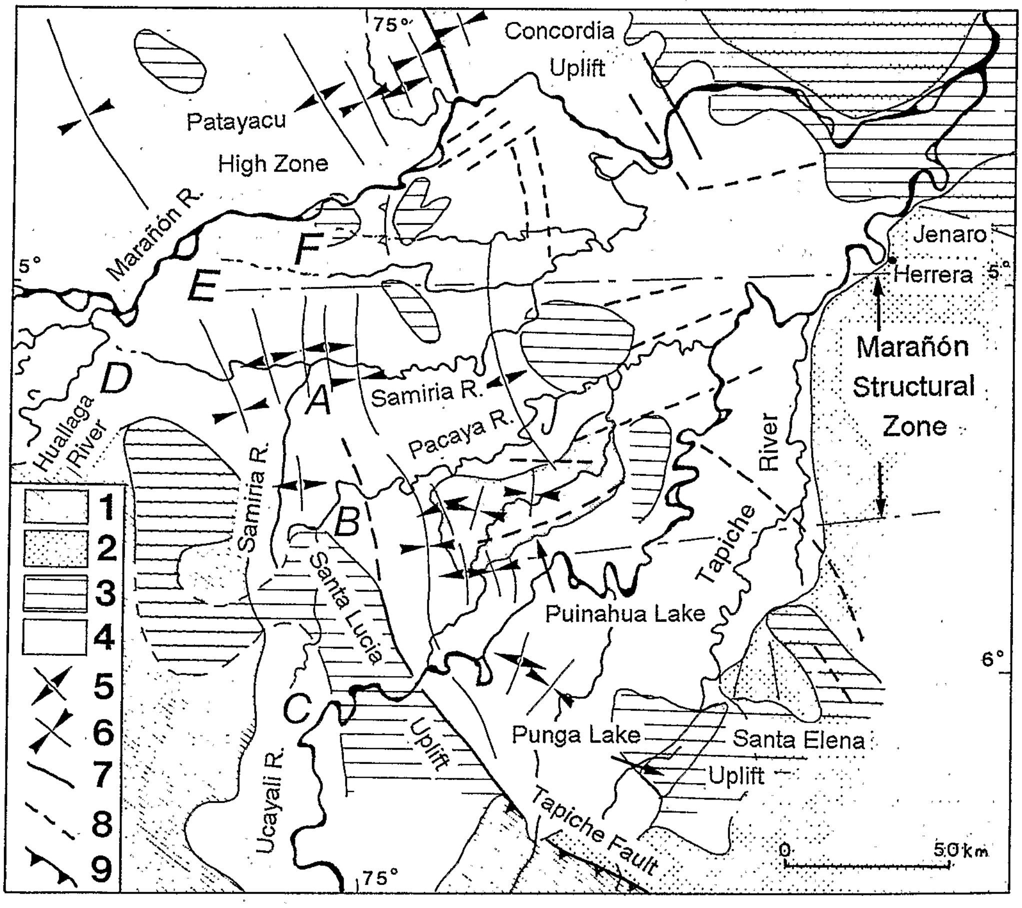

Fig. 4. Sketch of the basement structures of the Ucamara Depression, from Laurent (1985) and Laurent and Pardo (1975), completed with surface morphostructures. *1* = limit of the Subandean foothills; *2* = limit of the Iquitos uplands on the Brazilian craton margin; *3* = late Paleozoic uplifts of crystalline rocks overlain by Cretaceous deposits; *4* = major swamps; *5* = pre-Cretaceous anticlines, and *6* = synclines; *7* = basement faults reactivated during late Tertiary tectonics, northern part of the depression; *8* = pre-Cretaceous basement faults; *9* = Tapiche fault. *A–C* = successive positions of the deflection of the Ucayali River controlled by Andean structures. *D–F* = successive deflections of the Marañón River. Location in Fig. 3.

the channel does not change upstream and downstream of the deflection point, and no sedimentary fan system forms in relation to this angular pattern. In the central part of the depression, the drainage network shows an ENE trend with some left-hand short deflections to the north, linking together the main segments (Fig. 4).

3.2. Structural data

Laurent and Pardo (1975) and Laurent (1985) interpreted the basement structures of the Marañón Basin from seismic reflection profiles. They reported little deformation of the Mesozoic and Cenozoic deposits, but the pre-Mesozoic basement was divided into several faulted and uplifted blocks (Fig. 4). The Ucamara Depression extends mainly over the Marañón Structural Zone (Laurent, 1985), a belt of late Paleozoic NNE- to W–E-striking strike-slip faults (Fig. 4). The major faults shown in Fig. 4 are ENE striking. To the west of the depression, in the part of the basin overlaying the Santa Lucia Paleozoic uplift (Fig. 4), the front part of the Subandean belt of deformation overprints the structures of the Marañón Structural Zone. Meanwhile, no structural morphology appears on the surface of the depression. According to subsurface data the front of Andean deformation extends to the southeast toward the Tapiche Fault. This is a deep fault reactivated with reverse motions during the late Tertiary (Quechua) phases (Laurent, 1985).

3.3. Neotectonic and seismotectonic data

Neotectonic data come from the Craton margin, near Jenaro Herrera, and from the Tapiche Fault, to the south of the depression (Fig. 4). Near Jenaro Herrera, a NNW–SSE-directed extension (Fig. 5) has been identified from normal faults in Pleistocene fluvial deposits cropping out on the uplands (Dumont, 1993). Most of the faults strike N55°E, parallel to the main faults reported in the northern part of the Marañón Structural Zone, just to the west. In this area the meander belt of the Ucayali River is asymmetrical. A detailed study shows that the scroll bar and channel patterns reflect structural deformations, suggesting that normal faulting is still active (Dumont et al., 1996).

The Tapiche Fault makes the limit of the Ucamara Depression to the south (Figs. 4 and 5). Along the foothills side of the Tapiche Fault a Quaternary fluvial terrace overlaying discordantly Tertiary red beds stands 3 m above the high water level of the Tapiche flood plain. The position of the terrace suggests an uplift of the south margin of the fault with respect to the flood plain, during the Quaternary (Dumont, 1993).

According to Pardo-Casas and Molnar (1987) there is a N80°E-directed horizontal compressive stress in the transition zone between the Andes and the Brazilian craton. *P*-axes are parallel to the motion between the Nazca and South American plates. Nevertheless, there are some important exceptions: data from the eastern and western parts of the Ucamara Depression, show NE–SW-trending *P*-axes (Fig. 5, stereograms AS.9 and A 890504; Assumpçáo and Suarez, 1988; Assumpçáo, 1992).

3.4. Interpretation of the Ucamara Depression

The new trend of the Marañón River begins near its confluence with the Huallaga River, the Marañón leaving its previous ESE trend to follow a new one to the north-northeast (Figs. 2 and 4). The straight orientation of the river over 130 km through the Subandean foothills and the basin margin suggests fault control.

The style of deformation at the front of the Peruvian Subandes involves flat overthrusts with frontal listric upthrusts (Pardo, 1982; Mégard, 1984). The outward progress of foreland structures and the effect on depocenters and time line analyzed by Zoetemeijer et al. (1993) for the Po Basin, Italy show that piggy-back basins developed behind the tectonic front can control the drainage of rivers issuing from the foothills, deflecting it along the piggy-back depocenters. The Tapiche Fault and the Ucayali Basin merge northward, in the Ucamara Depression (Fig. 4). Then the structure vanished, and lost his identity north of the depression. Thus, the northern tip of the Tapiche Fault and Ucayali Basin appears like a transitional structural zone. This structural model suggests that the northward extension of the Ucayali Basin and the Tapiche Fault beneath the surface of the depression can control the southward shift of the deflection point of the Ucayali River (positions A, B and C, Fig. 4). The onset of a tectonic event will result in northward progress of the deformation. A decrease

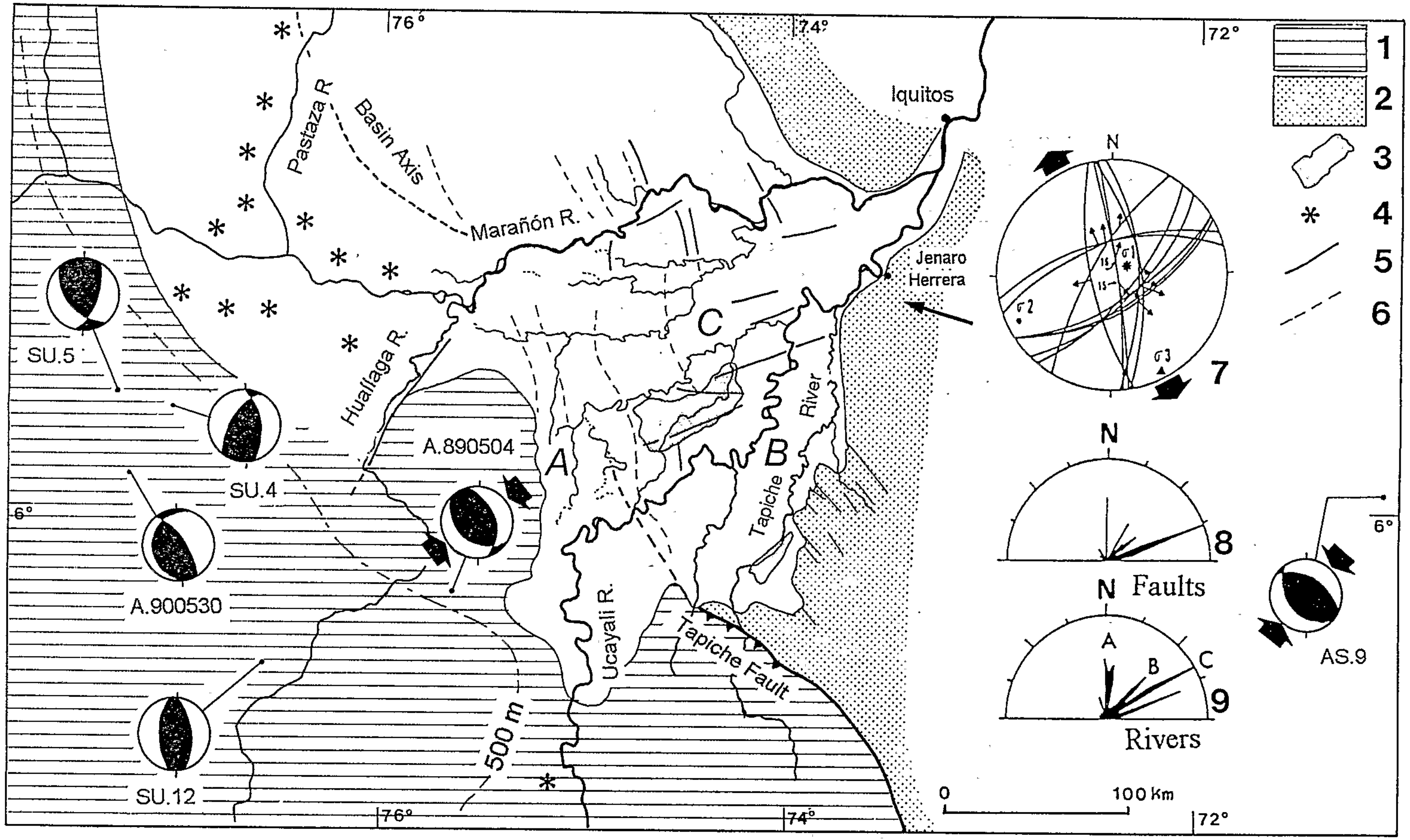

Fig. 5. Neotectonic scheme of northeastern Peru, from Dumont (1993), simplified. *1* = Subandean foothills, with 500 m contour; *2* = border of the Iquitos upland; *3* = elongated lakes; *4* = ria lakes; *5* = main faults in the basement, and lineaments in the Iquitos upland; *6* = main fold axis traces; *7* = stereonet of faults in Quaternary fluvial deposits, from Dumont et al. (1988); the thin arrow shows the location of observations and the large arrows show the minimum stress direction; *8* = strike of faults from the basin basement; *9* = trend of rivers, the letters refer to areas with the same letter on the map. Small stereonets are seismotectonic data: *SU* = Suarez et al. (1983); *AS* = Assumpçáo and Suarez (1988); *A* = Assumpçáo (1992), numbers are those used by the authors. Same location as Fig. 4.

will probably result in a reverse phenomenon by burying under sediments the topographic effect of the fault, as the subsidence progress. In this context, the southward shift of the Ucayali River suggests a decrease of the structural control from the front structures of the Andean deformation. This hypothesis seems contradictory with the observation of offset along the Tapiche Fault. Meanwhile, fluvial shifting refers probably to a younger process (less than 13,000 yr B.P.) than the offset of Quaternary sediments by the Tapiche Fault, reported from the southern tip of the depression.

In the central part of the Ucamara Depression, the orientation of the small (underfit) and present (large) rivers are parallel to identified faults of the Marañón Structural Zone (Fig. 4). A similar direction is observed for the main set of normal faults reported from the Craton margin, and the main orientation of *P*-axes east and west of the depression (Fig. 5). This suggests that active tectonics controls probably the main trend of the drainage network in the central part of the depression.

The occurrence of two lakes, Lake Puinahua and Lake Punga, supports this hypothesis (Fig. 4). As shown in Dumont (1993), these lakes are superimposed over basement structures and are NE–SW trending, parallel to the orientation of *P*-axes reported by Assumpçáo (1992). Their shape and trend suggest down-dropped blocks related to a tensional system. These lakes give probably an example of the effect of tensional fault acting to control the trend of rivers in the depression. They are drained along by white water rivers. The Canal Puinahua, a secondary reach of the Ucayali River, crosses along the Puinahua Lake area (Fig. 3B). This reach is in the way of abandonment according to navigation reports (A. Pardo, pers. commun., 1989), and the lake is mostly filled with sediments, according to image analysis. The historical subsidence of the Punga area generated a shift of the Tapiche River toward the lake. Presently, the river is reconstructing his channel through the lake (personal field observation).

4. The Beni Basin

4.1. Presentation and structural data

The Beni Basin is broader to the northwest (500 km) than to the southeast (150 km), and extends over about 800 km of latitude (Fig. 1). This is a flat area, covered by rain forest to the north and pampas to the south. The western boundary with the Andean foothills is a sharp piedmont line. The transition eastward to the rounded hills of the Brazilian craton is smooth, due to an intermediate zone of incised flat uplands. Three large meandering rivers cross the basin, from north to south: the Madre de Dios, the Beni and the Mamore rivers. They join in the northeast of the basin, forming the Madeira River. East of Riberalta (Fig. 1) the Madeira River exits the basin through rapids on gneiss outcrops (Ahlfeld and Branissa, 1960). The most depressed area, with extended wetlands and fluvial traces, is between the Beni and Mamore rivers.

The Bolivian Andes result from a major tectonic event lasted since the Late Oligocene to the Early Miocene (Martinez, 1980; Sempere et al., 1990). A N60°E shortening direction during the Pliocene (Martinez, 1980; Lavenu, 1986) leads to the present structure of the Subandean zone. According to Plafker (1964) the basement slopes progressively westward beneath the alluvium deposits at a mean rate less than 19 m/km. The thickness of sedimentary deposits rises to 6000 m in front of the foothills. Poorly consolidated continental sediments of Quaternary, and possibly late Tertiary ages, with a thickness of 800 m, overlay the crystalline basement. They have been drilled at 130 km from the piedmont. Seismic reflection and refraction surveys show no significant topographic relief on the basement surface. Many basement fractures are observed on refraction surveys, but Plafker (1964) reported only one measurable offset of the basement surface. A study of sedimentary transports by Guyot (1992) shows that the Mamore flood plain traps about 60% of the sedimentary charge of the Mamore River.

4.2. Migration of the Beni River

Plafker (1964) identified a counterclockwise shift of the Beni River. Analyzing more precisely the drainage network on satellite images, Allenby (1988) pointed out the occurrence of a basinal uplift (Fig. 1) along a NE-trending belt previously occupied by the ancient course of the Beni River. The uplifted zone extends from Reyes to Puerto Siles (Fig. 1). Crossing this morphostructural zone, the channel of the Mamore River shows a significant reduction of sinuosity and is broken by several rapids north of Puerto Siles. The axis of the structure is parallel to the main trend of lineaments in the Brazilian Craton (Plafker, 1964; Allenby, 1988). This lineament extends in central Brazil toward the Tapajos neotectonic fault (CERESIS, 1985).

From a detailed study of the upstream part of the old fluvial traces Dumont and Hannagarth (1993) identified five successive stages of shifting of the Beni River, three of them clearly connected to the present river (Fig. 6). The oldest traces (A and B, Fig. 6) are discontinuous, following partly the present position of the Yakuma and Tapado rivers, then joining the Mamore River downstream. The successive Yata, Biata and Negro stages (C, D and E, Fig. 6) are more clear, and form continuous underfit streams. Channel width and meander wavelength of these early stages are homogeneous and similar in size to the Beni River. On the contrary, the two early stages, and principally the Tapado stage, show smaller traces, suggesting a lower discharge. According to Servant et al. (1981) drier periods occurred in the southern Beni Basin during the periods 7000–5000 and 3400–1400 yr B.P. Recent data from the northern part of the basin confirm a dry period between 8000 and 6000 yr B.P., and the existence of the Yata fluvial stage by 2500 yr B.P. (Dumont, unpubl. data).

The early traces of the Beni River turn abruptly at the outlet from the foothills, then continue to the northeast. The successive shifts of the Beni River occurred simultaneously with a northward downstream migration of the deflection point of the river entering the basin (Fig. 6). This deflection point shifted northward, as the shifting progressed in the basin (C′ D′ and E′, Fig. 6). This feature shows that

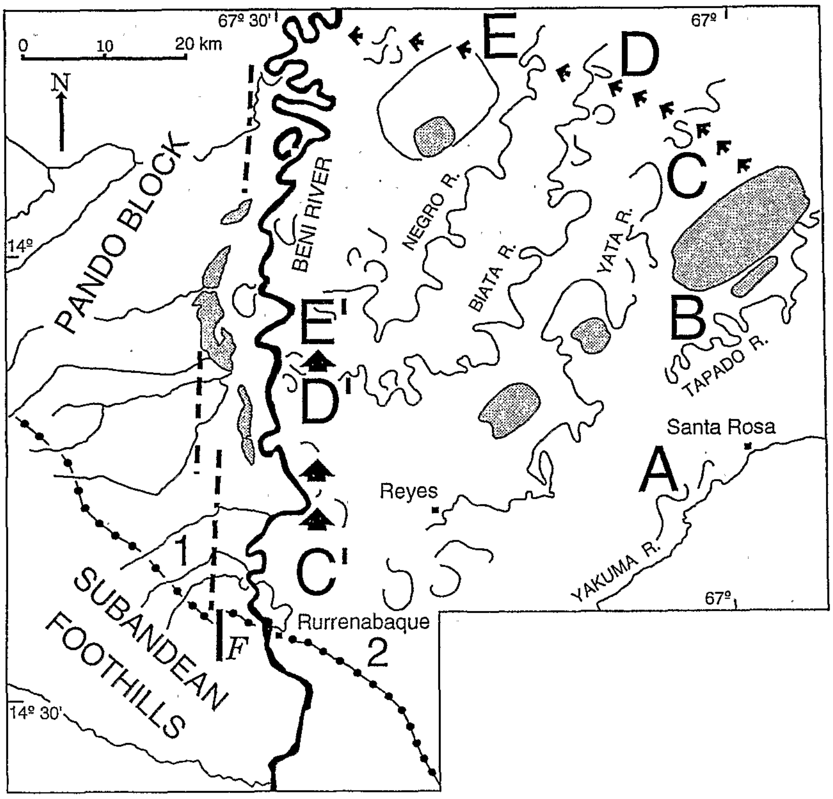

Fig. 6. Morphostructural scheme of the northwestern Beni Basin. Dotted line: foothills piedmont. *A*–*E* are successive stages of the Beni River, and *C′*–*E′* successive position of the elbow. *F* = faults observed in the piedmont, and subdued northern extension of the fault. Location in Fig. 1. Grey areas are lakes.

the shifting of the Beni River initiated from the foothill's border, and progressed downstream by successive increment. This northward trend of the Beni River begins inside the foothills, 50 km upstream from Rurrenabaque (Fig. 6). The morphology of the lower piedmont is different northwest and southeast of the outlet of the Beni River from the foothills. On the northwest side the small streams carry pebbles in incised channels flowing radially to the trend of the Piedmont (Fig. 6, area 1). Two N-striking faults cut the conglomerate and sand layers of an upper terrace of the Beni River. They have an offset of some decimetres, and an upthrow of the west side. Unfortunately, the unconsolidated sediments did not preserved slickenside. The landscape southeast of the Beni River is different. The streams sloping down from the piedmont wander on the surface of very flat and sandy alluvial cones, and the floodplain of the Beni River comes very close to the piedmont (Fig. 6, location 2). The morphology suggests that the area south of the outlet of the Beni River is more depressed than the area to the north. This is consistent with the fault planes observed, and suggests a tectonic control.

Fluvial data are also coherent with the hypothesis of a fault control of the Beni River setting. At 60 km from the foothills in the basin, the Beni River enters an area characterized by high sinuosity and irregular meanders (channel length/wavelength over 2.5), and low river banks (less than 2 m). These are the lowest river banks observed all along the Beni River in the basin (north of Fig. 6). Increasing sinuosity is generally related to an increase of the slope (Schumm, 1977), but this does not fit with the field data in our case. High suspension charge can also induce high sinuosity, especially during floods, according to Xu (1993). Thus, an accelerated subsidence is probably involved in the present case. This is consistent with low river banks, accelerated sedimentary aggradation burying large areas of drowned forest, and a near total stopping of the transit of the gold particles downstream from Rurrenabaque (Dumont et al., 1991b). Slender lakes, are lined up roughly parallel to the subdued fault (Fig. 6). The position, shape and deposition characteristics of these lakes seem to be related to the subsidence. These morphological observations suggest that the effect of the fault may extend northward in the basin, underlining the morphological limit between the Pando Block (west) and the flood plain of the Beni River (east).

In the southern Beni Basin, the Rio Grande exhibits a westward, counterclockwise shift that exceeds 100 km (Fig. 1), suggesting that the southeastern margin of the basin is being uplifted.

4.3. Neotectonic data

Mercier et al. (1992) noticed that there is neither seismic nor field evidence about the tectonic regime along the NW–SE-trending Subandes of Bolivia. South of the Bolivian orocline (the bend to the south marked by the Andean Range at 18°S) neotectonic activity is observed again (Lavenu, 1986). Assumpçáo and Araujo (1993) detected a stress rotation of 30° in the northern part of the Altiplano, around the Bolivian orocline. These authors interpret the local deviation as the border effect of the Altiplano due to a decreasing plate convergence rate since about 20–10 Ma. The effect is more perceptible where the orientation of the Andes is oblique to plate motion.

Late Pleistocene/Early Holocene hardened clay sediments from backswamp and lake environments crop out in the distal margin of the Beni Basin. They are poorly drained flatlands. To the west this level forms the bottom of the present rectangular lakes (Fig. 6). The transition is observed near Yata, about 150 km from the foothills. This disposal suggests an uplift of the eastern part of the basin during the Holocene. Longitudinal changes of the Beni River channel support also the hypothesis of an uplift. On one hand the channel of the Beni River shows a reach of low sinuosity about 250 km downstream from Rurrenabaque (Dumont et al., 1991b). According to Schumm (1977) and Jorgensen (1990) such longitudinal change is related to a low inclination of the slope located upstream of an axis of transverse uplift, the sinuosity increasing again downstream from this point. On the other hand, the Beni River flows inside high terraces (over 20 m) since about 170 km from Rurrenabaque, giving consistency to the uplift.

4.4. Interpretation of the Beni Basin

Morphological and neotectonic data suggest that the Beni River is forced to the north by a N-striking fault between the Pando Block and the Beni River flood plain. The process involves a more active subsidence along the down-thrown side of the fault, tracking the Beni River. The downstream increments of the Beni River channel shows that the effect of the fault progressed from the foothills to the basin. This northward shift is coherent and probably contemporaneous with the uplift of the central part of the Beni Basin, along the Reyes–Puerto Siles axis of the previous drainage. This NE-trending drainage belt appears now as a basinal interfluve. The river shifting observed are also consistent with the uplift of the distal margin of the basin.

5. Synthesis and conclusion

A directional shift of the deflection point of a river channel is a typical feature of tectonic-controlled river shifting. Three cases are reported here, all from the foothill side of the basins. The deflection point of the river channel migrates upstream or downstream, lining up with the upper reaches of the river. This upper reaches trend parallel to local faults or lineaments (Beni and Huallaga/Marañón rivers) or follow a major Andean structure (Ucayali River). This geometrical pattern makes it difficult to imagine a random river shift process. The deflection point of the Beni River migrates downstream, along a lineament striking obliquely to the structural trend of the foothills. The Huallaga River in the Marañón Basin exhibits a similar feature. The inferred fault strikes orthogonal to the margin of the foothills. Both cases suggest that the structural control progressed from the foothills to the basin. In contrast, the upstream migration of the Ucayali River suggests a decrease of the effect of Andean tectonics.

The relationships between river trend and structure are mainly to be seen in the Ucamara Depression, because subsurface data are available there. In the proximal (western) part of the basin, piggy-back structures control the position of the Ucayali River along the margin of the foothills. In the distal part the drainage network is parallel to basement faults. The trend of the rivers is parallel to normal faults on the craton margin and to the *P*-axes of seismotectonic activity. Block subsidence generates elongated lakes that trend northeast–southwest. All these data suggest that reactivated basement faults control the trend of the rivers. More precisely, this phenomenon emphasizes the effect of gutter generated by tensional and block faulting in accounting for the steady trend of the rivers in the central part of the depression. There is no evidence of the main tilting of the basin surface that is sometimes suggested to explain important modifications of the trend of rivers. On the contrary, although the more active subsidence is located in the southeastern tip of the Ucamara Depression (i.e., the Lake Punga area), the river network trends northeastwards. In this scenario, the successive shifts of the Ucayali River are directed along structural gutters, in successively lower positions toward the southeastern tip of the depression.

In the Ucamara Depression the main trends observed for river trends, block subsidence and seismotectonic and neotectonic phenomena are all orthogonal to the trend of the Andean range, and 20–30° oblique to the direction of plate motion. Assumpçáo and Araujo (1993) suggest that a reduction in the stress from plate motion increases the effect of stress generated by relief collapse of the Altiplano plateau. It is tempting to interpret the movement of rivers in the Ucamara Depression and the Beni Basin as being relationed to the stress oscillation between plates. Increasing far-field stress emphasizes the flexural effect and the control of Andean structures on the fluvial network (thrust belt and piggy-back type basins). A decrease in the far-field stress, in contrast, induces topographic adjustments, with tensional faults emanating from the foothills, and striking in an almost radial fashion to the Andes. This interpretation is consistent with the directional river shift observed in the Marañón and Beni basins. At this point it may be stressed that the orientation of the Andes explains the occurrence of alternating non-coaxial stresses caused by either plate motion during phases of higher convergence, or by topographic collapse during periods of relative release in the convergence. Having said this we lack accurate time correlations that might support this hypothesis. The shift in river courses observed during the Holocene may possibly be related to oscillations of the tectonic stress that are shorter than that suggested by Assumpçáo and Araujo (1993) for the post-20–10 Ma period.

Large-scale shift in river trends is probably the most striking phenomenon observed in the Marañón and Beni basins. River shifts are directed to the southeast at the northwestern tip of the Peru–Bolivian Andean segment (Ucamara Depression), and to the northwest at the other tip (Beni Basin). Thus, they are both directed toward the part of the segment which overlie the flat slab segment of the subducting plate. Stress release between the Andes and the Brazilian craton during recent times is compatible with a relatively higher stress remaining in the part of the Subandes above the flat slab segment. In this view, the directional pattern of river shifting suggests that more active subsidence may occur in the Subandes that lie above transitional areas between flat and normal subduction.

Acknowledgements

This work was completed as part of the Cooperative Research Program between "L'Institut Français de Recherche Scientifique pour le Développement en Coopération" (ORSTOM), the "Instituto Geofísico del Peru" (IGP, Lima), the "Instituto para la Investigación de la Amazonia Peruana" (IIAP, Iquitos), the "Universidad Major San Andres" (UMSA, La Paz) and the "Servicio para el Mejoramiento de la Navigación Amazonica" (SEMENA, Trinidad). A. Aing from the "Laboratoire Photo de Teledetection" of the ORSTOM in Bondy prepared the Landsat scenes from Peru, and W. Hannagarth helped for the photo-interpretation of the Beni Basin. We specially thank A. Tejada (SEMENA) and P. Chollet (COTESU) for their help in field work in Bolivia. The initial manuscript benefited from comment by T.E. Jordan and S.A. Schumm; comment by R. Zoetemeijer and an anonymous reviewer helped to improve significantly the final version.

References

Ahlfeld, F. and Branissa, L., 1960. Geologia de Bolivia. Inst. Pet. Bolivía, La Paz, 245 pp.

Allenby, R.J., 1988. Origin of rectangular and aligned lakes in the Beni Basin of Bolivia. Tectonophysics, 145: 1–20.

Assumpçáo, M., 1992. The regional intraplate stress field in South America. J. Geophys. Res., 97(B8): 11,889–11,903.

Assumpçáo, M. and Araujo, M., 1993. Effect of the Altiplano–Puna plateau, South America, on the regional intraplate stresses. Tectonophysics, 221: 475–493.

Assumpçáo, M. and Suarez, G., 1988. Source mechanisms of moderate size earthquakes and stress orientation in mid-plate South America. Geophys. J., 92: 253–267.

Baker, V.R., 1978. Adjustment of fluvial system to climate and source terrain in tropical and subtropical environments. In: A.D. Miall (Editor), Fluvial Sedimentology. Can. Soc. Pet. Geol. Mem., 5: 211–230.

Beaumont, C., 1981. Foreland Basins. R. Astron. Soc. Geophys. J., 65: 291–329.

Bryant, M., Falk, P. and Paola, C., 1995. Experimental study of avulsion frequency and rate of deposition. Geology, 23: 365–368.

CERESIS, 1985. SISRA Project, Preliminary Neotectonic Map of South America. Publ. CERESIS, Lima.

Dumont, J.F., 1992. Rasgos morfoestructurales de la llanura Amazónica del Perú: efecto de la Neotectónica sobre los cambios fluviales y la delimitación de las provincias morfológicas. Bull. Inst. Fr. Etud. Andines, 21(3): 801–833.

Dumont, J.F., 1993. Lake patterns as related to neotectonics in subsiding basins: the example of the Ucamara Depression, Peru. Tectonophysics, 222: 69–78.

Dumont, J.F. and Fournier, M., 1994. Geodynamic environment of Quaternary morphostructures of the subandean foreland basins of Peru and Bolivia: characteristics and study methods. Quat. Int., 21: 129–142.

Dumont, J.F. and Hannagarth, W., 1993. River shifting and tectonics in the Beni Basin. Ext. Abstr. Third Int. Conf. Geomorphology, Hamilton, Canada.

Dumont, J.F., Lamotte, S. and Fournier, M., 1992. Neotectónica del Arco de Iquitos (Jenaro Herrera, Perú). Bol. Soc. Geol. Perú, 77: 7–17.

Dumont, J.F., Deza, E. and Garcia, F., 1991a. Morphostructural provinces and neotectonics in Amazonian lowlands of Peru. S. Am. Earth Sci., 4(4): 287–295.

Dumont, J.F., Hérail, G. and Guyot, J.L., 1991b. Subsidencia, inestabilidad fluvial y repartición de los placeres distales de oro. El caso del Río Beni (Bolivia). Actes Symp. Int. Gisements Alluviaux d'Or, 3–5 June 1991, La Paz, pp. 43–46.

Dumont, J.F., Garcia, F. and Fournier, M., 1992. Registros de cambios climaticos por los depositos y morphologias fluviales en la Amazonia occidental. In: L. Ortlieb and J. Machare (Editors), Paleo ENSO Records: Int. Symp., Lima, Ext. Abstr., pp. 87–92.

Dumont, J.F., Mering, C., Parrot, J.F. and Taud, H., 1996. Quantitative analysis of asymmetrical fluvial pattern to study active deformation in subandes basins. Z. Geomorphol. N.F., 103: 269–282.

Dury, G.H., 1970. General theory of meandering valleys and underfit streams. In: G.H. Dury (Editor), River and River Terraces. Macmillan, London, pp. 264–275.

Guyot, J.L., 1992. Hydrogéochimie des fleuves de l'Amazonie bolivienne. Thesis, Univ. Bordeaux I, Bordeaux, 362 pp.

Jordan, T.E., 1981. Thrust loads and foreland basin evolution, Cretaceous western United States. Am. Assoc. Pet. Geol. Bull., 15: 2500–2520.

Jordan, T.E., Isachs, B.L., Allmendinger, R.W., Brewer, J.A., Ramos, V.A. and Ando, C.J., 1983. Andean tectonic related to geometry of subducted Nazca plate. Bull. Geol. Soc. Am., 94: 341–361.

Jorgensen, D.W., 1990. Adjustment of alluvial river morphology and process to localized active tectonics. Ph.D. Thesis, Colorado State Univ., 240 pp.

Laurent, H., 1985. El pre-Cretaceo en el oriente peruano: su distribución y sus rasgos estructurales. Bol. Soc. Geol. Perú, 74: 33–59.

Laurent, H. and Pardo, A., 1975. Ensayo de interpretación del basamento del Nororiente Peruano. Bol. Soc. Geol. Perú, 45: 25–48.

Lavenu, A., 1986. Etude tectonique et néotectonique de l'Altiplano et de la Cordillère orientale des Andes boliviennes. Thesis, Univ. Paris Sud, Paris.

Lavenu, A. and Marocco, R., 1984. Continental sedimentation and tectonics in a fold belt related to a subduction zone: the Central Andes (Peru–Bolivia) during the Tertiary. Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine, 8(1): 57–70.

Martinez, C., 1980. Structure et évolution de la chaîne andine dans le Nord de la Cordillère des Andes de Bolivie. Trav. Doc. ORSTOM 119, 352 pp.

Mégard, F., 1984. The Andean orogenic period and its major structures in central and northern Peru. J. Geol. Soc. London, 141: 893–900.

Mercier, J.L., Lavenu, A., Cabrera, J., Bellier, O., Dumont, J.F. and Machare, J., 1992. Changes in the tectonic regime above a subduction zone of Andean type: the Andes of Peru and Bolivia during the Pliocene–Pleistocene. J. Geophys. Res., 97(B8): 11,945–11,982.

Mike, K., 1975. Utilization of the analysis of ancient river beds for the detection of Holocene crustal movements. Tectonophysics, 29: 359–368.

Pardo, A., 1982. Caracteristicas estructurales de la faja subandina del norte del Peru. Symp. "Exploracion Petrolera en las Cuencas Subandinas de Venezuela, Colombia, Ecuador Y Peru", Bogota.

Pardo-Casas, F. and Molnar, P., 1987. Relative motion of the Nazca (Farallon) and South American plates since late Cretaceous times. Tectonics, 6: 233–248.

Plafker, G., 1964. Oriented lakes and lineaments of northeastern Bolivia. Bull. Geol. Soc. Am., 75: 503–522.

Potter, P.E., 1978. Significance and origin of big rivers. J. Geol., 86: 13–33.

Räsänen, M.E., Salo, J.S., Jungnert, H. and Pittmann, R., 1990. Evolution of Western Amazon Lowland relief: impact of Andean foreland dynamics. Terra Nova, 2: 320–332.

Räsänen, M.E., Neller, R., Salo, J. and Jungnert, H., 1991. Recent and ancient fluvial depositional systems in the Andean forelands of the Peruvian Amazon. In: History of the Fluvial and Alluvial Landscapes of the Western Amazon Andean Forelands. Ann. Univ. Turku., Ser. A, 75(3): 1–22.

Sanz, V.P., 1974. Geologia preliminar del area Tigre–Corrientes en el Nororiente peruano. Bol. Soc. Geol. Perú, 44: 106–127.

Schumm, S.A., 1977. The Fluvial System. Whiley, New York, NY, 337 pp.

Schumm, S.A., 1986. Alluvial river response to active tectonics. In: Studies in Geophysics, Active Tectonics. National Academy press, Washington DC, pp. 80–94.

Seminario, S.F. and Guizado, J.J., 1976. Sintesis bioestratigrafica de la region de la Selva del Perú. 2nd Congr. Latinoamericano Geol., Caracas, 1973, II: 881–886.

Sempere, T., Hérail, G., Oller, J. and Bonhomme, M.G., 1990. Late Oligocene–early Miocene major tectonic crisis and related basins in Bolivia. Geology, 18: 946–949.

Servant, M., Fontes, J.C., Rieu, M. and Saliège, J.F., 1981. Phases climatiques arides Holocènes dans le Sud-Ouest de l'Amazonie. C. R. Acad. Sci. Paris, 292: 1295–1297.

Smith, N.D., Cross, T.A., Dufficy, J.P. and Clough, S.R., 1989. Anatomy of an avulsion. Sedimentology, 36: 1–23.

Suarez, G., Molnar, P. and Burchfield, B.C., 1983. Seismicity, fault plane solution, depth of faulting, and active tectonics of the Andes of Peru, Ecuador and Southern Colombia. J. Geophys. Res., 88: 10,403–10,428.

Villarejo, A., 1988 (first edition 1943). Así es la Selva. Cent. Estud. Teologicos de la Amazonia, Iquitos, 330 pp.

Xu, J., 1993. Meanders caused by hyperconcentrated water flow: an example from the loess plateau, China. Earth Surf. Processes Landforms, 18: 687–702.

Zoetemeijer, R., Cloetingh, S., Sassi, W. and Roure, F., 1993. Modeling of piggyback stratigraphy: record of tectonic evolution. Tectonophysics, 226: 253–269.

Reprinted from

TECTONOPHYSICS

INTERNATIONAL JOURNAL OF GEOTECTONICS AND THE GEOLOGY AND PHYSICS OF THE INTERIOR OF THE EARTH

Tectonophysics 257 (1996) 137–151

Neotectonics of the Subandes–Brazilian craton boundary using geomorphological data: the Marañon and Beni basins

J.F. Dumont

ORSTOM, Laboratoire de Géodynamique sous-marine, BP48, 06230 Villefranche s / mer, France

Received 16 November 1994; accepted 29 November 1995

ELSEVIER