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Morphological and mathematical analysis of asymmetrical fluvial pattern: A study case from the Ucayali River (Peru)

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with 9 figures

Summary. We analyze the asymmetrical pattern of the lower part of the Ucayali River. The asymmetrical pattern is expressed at different scales: meander belt, channel pattern, and rate of meander migration. Relations that exist between river trends, floodplain margin, and neotectonic faults suggest that active deformation controls the river pattern. The use of mathematical analysis of images allowes a more accurate analysis of meander migration. Shape entities related to fluvial morphology have been delimited on the initial SPOT XS scene. The image has been processed using non-linear methods, *morphological opening* and *geodesic reconstruction.* Then, we used the *Adonis processing* to analyze the remaining curves, that are related to the most prominent elements of the scroll pattern. Traces of the meander evolution are obtained, more accurately and quicker than by eye. The floodplain side meanders are developing independent of the river trend, and the meanders on the bluffline side of the floodplain are controlled by the bluffline trend. This result is coherent with other neotectonic data, and suggests that rivers are affected by ongoing deformation of the flood plain along the craton margin.

Zusammenfassung. *Morphologische und mathematische Analyse der asymmetrischen Flußgestalten: der Fall des Flusses Ucayali (Peru).* – Wir haben die asymmetrischen Verhältnisse im unteren Flußverlauf des Ucayali untersucht. Diese asymmetrischen Verhältnisse sind auf verschiedenen Stufen zu beobachten: Ufergestaltung der Flußwindungen, Fahrrinnenverlauf und Wanderungs-Verhältnis der Flußwindungen. Die Beziehungen, die zwischen der Flußrichtung, dem Randverlauf der Schwemmebene und den neotektonischen Spalten bestehen, lassen vermuten, daß der Fluß durch aktive Veränderungen bestimmt wird. Die mathematische Analyse der Bilder erlaubt eine genauere Studie der Wanderung der Flußwindungen. Teile von SPOT XS Ausschnitten mit elementaren Flußverläufen wurden bestimmt. Das Bild wurde mit nichtlinearen Techniken untersucht, morphologisch aufgegliedert und geodesisch wieder zusammengesetzt. Dann haben wir das Adonisverfahren angewandt, um die übrigen Kurven zu analysieren, die den wichtigsten Elementen der Schwemmfaltenbildung entsprechen. So kamen wir genauer und schneller auf die Spur der Entwicklung der Flußwindungen, als durch reine Beobachtung. Die Flußwindungen auf der Seite der Anschwemmung entwickeln sich unabhängig vom Flußverlauf, und die Flußwindungen auf der Seite des Steilhangs am Rande der Ebene werden durch diesen Steilhang bestimmt. Dieses Resultat deckt sich mit anderen neotektonischen Erkenntnissen und läßt vermuten, daß der Fluß durch aktive lokale Veränderungen entlang der Anschwemmungsebene am Fuße des Steilhangs, der die Ebene begrenzt, in seinem Lauf beeinflußt wird.

Résumé. *Analyse morphologique et mathématique des formes fluviales asymétriques: le cas de la Rivière Ucayali (Pérou).* – Nous avons étudié la disposition asymétrique du cours inférieur de l'Ucayali. Ces morphologies asymétriques sont observables à différentes échelles: bande enveloppe des méandres, forme du chenal, et taux de migration des méandres. Les relations qui existent entre l'orientation de la rivière, la direction du bord de la plaine alluviale et les failles néotectoniques suggèrent que la disposition de la rivière est contrôlée par des déformations actives. L'analyse ma-

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thématique des images permet une étude plus détaillée de la migration des méandres. Des portions des scènes SPOT XS initiales comprenant des morphologies fluviales élémentaires ont été délimitées. L'image a été traitée par des méthodes non linéaires, *ouverture morphologique* et *reconstruction géodésique*. Ensuite nous avons utilisé le traitement *Adonis* pour analyser les courbes restantes, qui correspondent aux éléments les plus importants des rides alluviales. Les traces de l'évolution des méandres sont ainsi obtenues, plus précisément et plus rapidement que par une observation visuelle. Les méandres situés du coté de l'escarpement bordant la plaine sont controlés par l'orientatin de cet escarpement. Ce résultat est cohérent avec d'autres données néotectoniques, et suggère que la rivière est affectée par des déformations actives localisées le long de la marge de la plaine alluviale, au pied de l'escarpement qui la borde.

1 *Introduction*

An asymmetrical flood plain development is the most obvious criterion of the effect of lateral tilting on a valley (VON BANDAT 1962). The river channel tends to migrate down the slope of the tilt, abandoning meander loops on the upper side of the flood plain, which are all concave in the direction of river migration. Generally, the river response to tectonics is only observed if the process is effective during a relatively long time, and over a flood plain three or four times wider than the amplitude of the river sinuosity. In similar cases described on the surface of tilted blocks in the Basin and Range (U.S.A.), LEEDER & ALEXANDER (1987) established a relation between a steady directional river migration over about 7000 years and surface deformations generated by active faults. It may be inferred from the continuity of the phenomenon that at any time during the period of lateral migration tectonics is active. Thus, it should be possible to obtain evidence of tectonic activity by investigating variables acting over short time scales, particularly channel pattern and meander development. This point has been questioned by NANSON (1980), who described asymmetrical development of the meander loops in a region that was subjected to post glacial regional uplift and tilting.

The objective of the paper is to present a study of an asymmetrical fluvial pattern with consideration of the different scales of morphologic observations, and a special emphasis on short term analysis using meander migration. A new method of meander analysis is presented, based on geometrical analysis of meander migration on images, using mathematical processing.

2 *Geological setting*

The Marañón basin is a sub-andean flexural basin, the basement of which is downswarped along the front of the subandean foothills to the west, and which rises progressively to the east toward the Brazilian Craton. Recent deformations are characterized by thrust and faults in the foothills (MÉGARD 1984), and block tectonics in the basin (DUMONT 1993) and along the border of the Brazilian Craton.

The flat surface of the basin extends over 500 km W–E and 400 km N–S, and is sharply delimited by a bluffline from the upland of the Brazilian Craton to the east. The bluffline is an escarpment 10 m to 20 m higher than the flood plain (DUMONT et al. 1988). The main flood plain overlaps on the upland in the Nauta Depression, where the Marañón and Ucayali Rivers merge to form the Amazon River. The Nauta Depression is a triangle

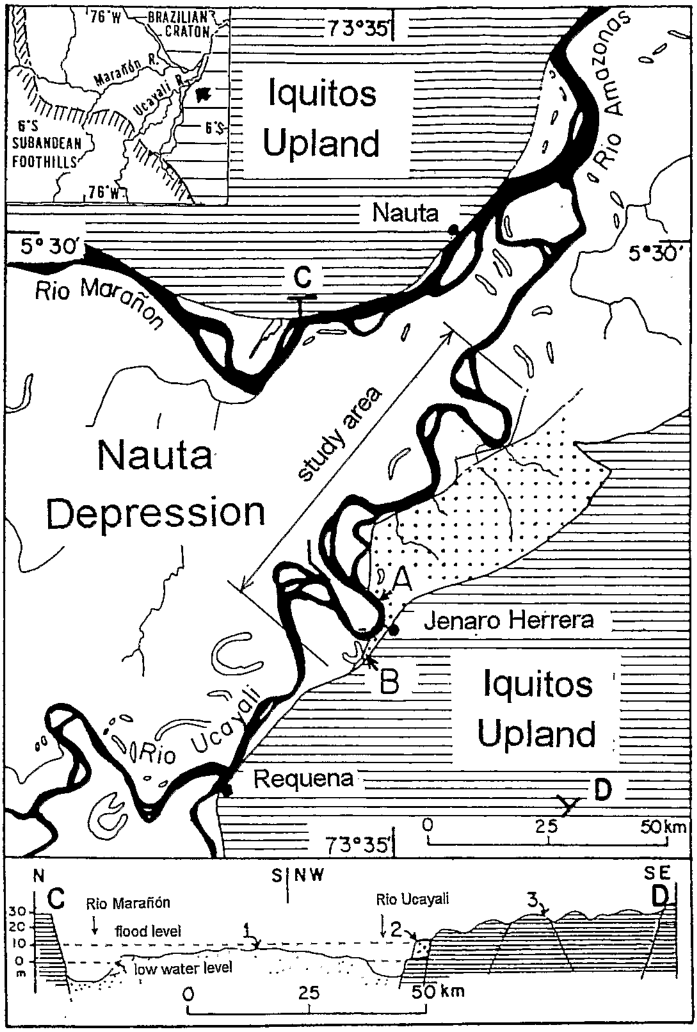

Fig. 1. Location of the study area (upper left) and morphostructural scheme of the Nauta Depression. Horizontal lines (3 in the section, below): uplands of the Brazilian Craton, mostly covered by early quaternary fluvial deposits. Dot pattern (2 in the section): late Pleistocene and Holocene deposits, lower terrace, dated 13 000 years BP in A, and upper terrace dated 32 000 to over 40 000 years BP in B. Without pattern (1 in the section): flood plain. C–D: location of the section.

shaped graben edged by the Iquitos uplands (Fig. 1). The existence of the graben is supported by normal faulting observed in the Quaternary fluvial deposits of the upland (DUMONT et al. 1988). The bluffline segments on the margin of the Nauta Depression trend parallel to the faults observed in the upland (Figs. 1 and 4). Cohesive silt and clay of the Pebas Formation of late Pliocene to Early Quaternary age in Iquitos (DUMONT et al. 1991) crop out below the more erosive Pleistocene deposits. Wood samples from a fluvial terrace visible along the bluffline near Jenaro Herrera have given a radiocarbon

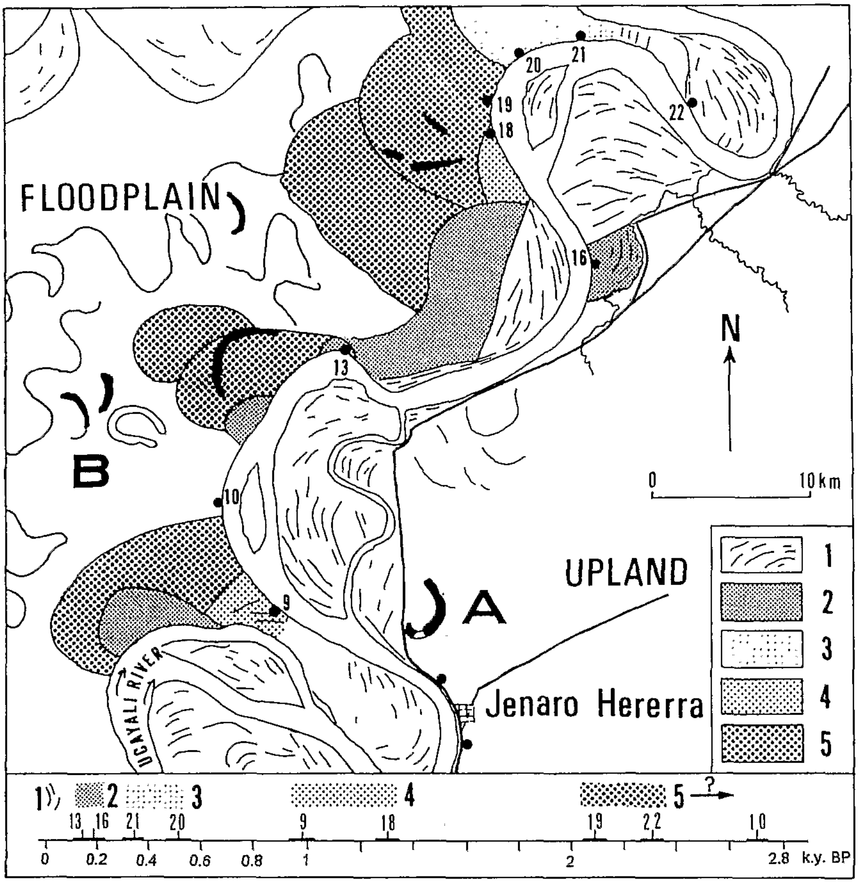

Fig. 2. Mosaic pattern of the Ucayali River, from DUMONT & FOURNIER (1994) (see Fig. 1 for location). Age of the Mosaic elements (on the scale large numbers refer to the same mosaic pattern, and small numbers to n° of sample): 1: ridges and swales of the present stage of mosaic construction. 2: 140–190 years BP. 3: 340–520 years BP. 4: 990–1310 years BP. 5: 2100–2310 years BP. Numbers on the map: points of collection of samples, age in years BP (between brackets is the laboratory number): 9(850): 990±50; 10(825): 2720±40; 13(832): 140±540; 16(834): 190±40; 18(863): 1310±40; 19(862): 2100±40; 20(848): 520±50; 21(858): 340±50; 22(860): 2320±40. Carbon dating made by M. Fournier (ORSTOM Laboratory).

age of 13000+2090/-1660 years BP (DUMONT et al. 1988). Similar traces of ancient small rivers are observed on the surface of this terrace and in the innermost and oldest part of the flood plain (Fig. 1), between the Ucayali and Marañón river belts (DUMONT et al. 1992). This suggests on one hand that the graben was active more recently than 13000 years BP ago. On the other hand, the oldest and inner parts of the Ucayali meander belt have been dated to about 2000 to 2700 years BP (DUMONT & FOURNIER 1994), suggesting that the asymmetrical migration of the river has been active at least since that time. As a result, the graben which controls the trend of the Amazon River outside of the Marañón Basin is suggested to have been active between 13000 and 3000 years BP.

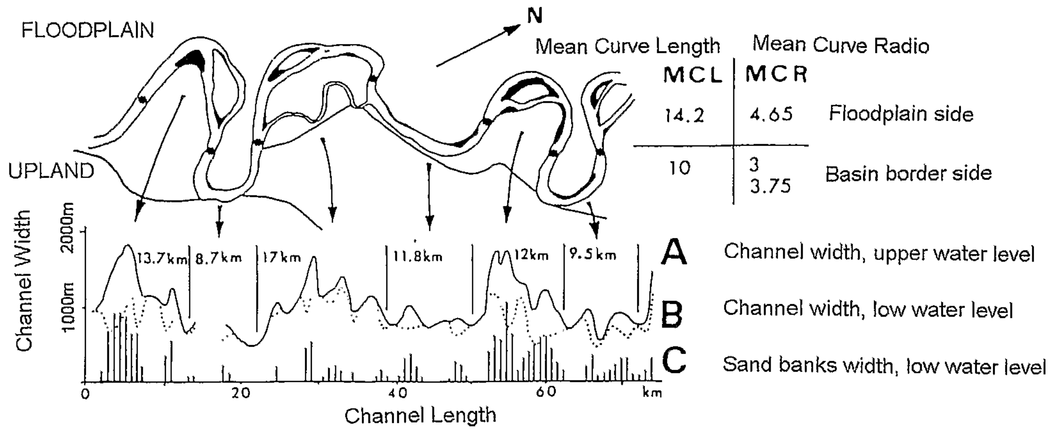

Fig. 3. Channel width along the asymmetrical portion of the Ucayali River, same location as on Fig. 1. (A) bank-full width, (B) channel width at low water stage, (C) sand-bank width at low stage, (MCL) Mean Curvature Length, (MCR) Mean Curvature Radio.

3 *Study methods*

The following steps have provided evidence of a relation between the channel pattern and the neotectonic environment.

3.1 A map of the fluvial mosaic (Fig. 2) was established from a Spot image, giving evidence of the asymmetrical pattern of the meander belt.

3.2 A comparison has been made between the channel pattern of the Ucayali River in the basin and along the craton margin in the Nauta Depression. Meanders have relatively symmetric developments in the basin (compound, wide, and divided in two or three parts), but they are asymmetric in the Nauta Depression, with a single and narrow channel on the bluffline side. Meander curves are also wider on the flood plain side than on the bluffline side (Fig. 3).

3.3 The trends of the blufflines and of the river (Fig. 4A) have been compared with neotectonic data from fault analysis in the upland (Fig. 4B). Each straight segment of the bluffline is considered separately, and the river trend has been defined as successive segments between the inflection points of meanders (Fig. 4). The result shows two main trends; the most important being NE–SW, and the other near NS. They are reported from faults, blufflines, and river segments. The closer relation is between faults and bluffline trends, which supports the interpretation of bluffline segments as fault planes.

3.4 The trend of meander migration has been established using the method presented by HICKIN (1974), using the orthogonal lines to the ridge and swale pattern to define the direction of development of meanders (L and R on Fig. 5). The recent tendencies of meander evolution were determined by comparing a 1972 Landsat image and a 1988 Spot image (DUMONT 1994). The result has been compared with the river trend as defined before, and the bluffline trend near the meander. The main tendencies (DUMONT 1994) show that meanders on the bluffline side (R) are migrating down river, parallel to the bluffline direction close to the meander (Fig. 5B). One exception is observed on the

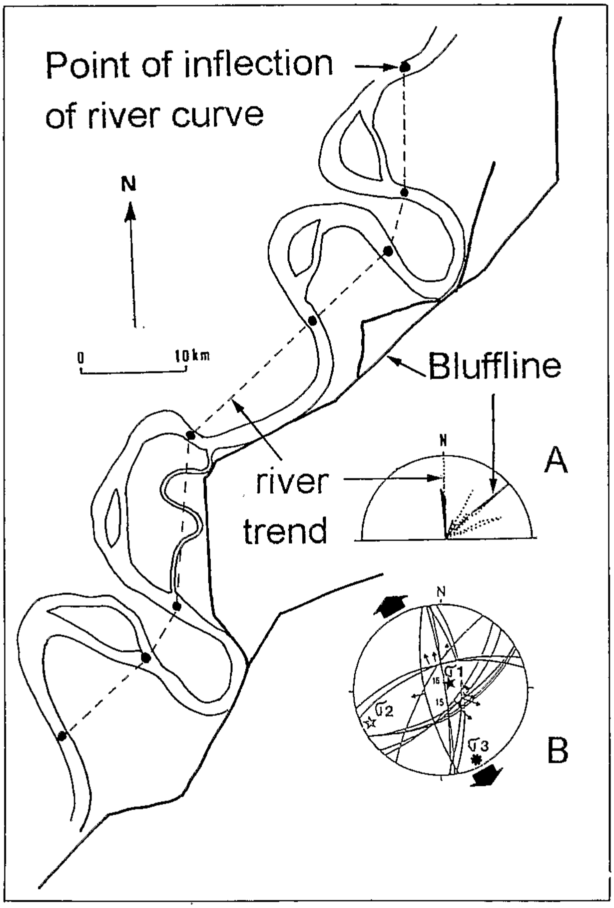

Fig. 4. A: Trend of the river segments defined by the inflection points (dashed line), and trend of the bluffline segments (straight lines). B: Fault planes from DUMONT (1993); sigma 1, sigma 2 and sigma 3 correspond respectively to the maximum, intermediate and minimum stress directions, arrows showing the direction of extension.

bluffline side meanders, marked with a star on Fig. 5. Nevertheless, an oxbow left behind shows that this meander was previously migrating down river, parallel to the bluffline, but it is now blocked in an angle formed by the escarpement. Meanders on the flood plain side develop principally orthogonal to the river trend (Fig. 5 L1), with a later and secondary development down river, which precedes, and in some part anticipates, a cut off (Fig. 5 L2).

4 *Extraction of ridge and swale pattern by image analysis*

Our purpose is to define shape entities that are thematically significant; that is, the ridge and swale pattern of alluvial flood plain from the initial SPOT XS scene (Fig. 6). The pattern is evidenced by morphological and botanical contrasts between the swampy grass land in the swales and forested ridges. In order to extract these forms, widely-known methods of multispectral classification are of no use since these objects have no specific spectral signature when they have a typical sub-circular shape. On grey level images such as any of the XS channel, one can perceive these objects as very thin sub-circular lines

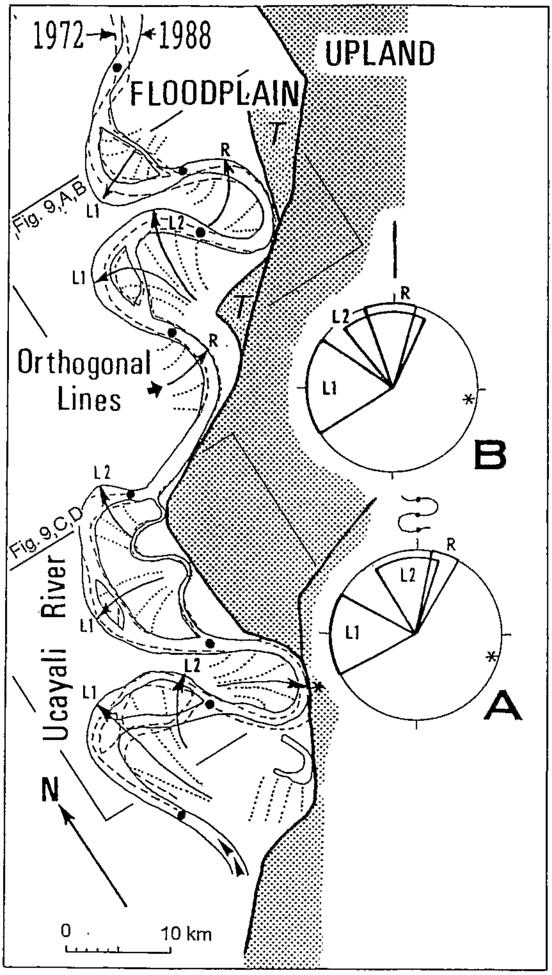

Fig. 5. Directional migration of meanders in the lower Ucayali reach. Hawks represent the axis of erosion observed on a 1988 Spot image, and correlated with the position of meanders on a 1972 Landsat image. R: migration trend of right hand meanders; L1 and L2: main and secondary migration trend of left hand meanders. These directions are plotted in reference to the main river trend between near inflection points of the meanders (A), and in reference to the near bluffline trend (B). T represents areas of low terraces.

of light tone. The objective here is to obtain a final binary image containing only those lines obtained by image filtering. Various criteria may be used for image analysis: the grey-tone of the line (lighter than the neighborhood), the thickness (one pixel wide) and the shape (sub-circular). Experiments have shown that on a square grid such as that of satellite images, linear methods such as gradient filtering based on numerical convolutions of the image by preferred masks (PRATT 1978) enhance rectilinear shapes and break curvilinear ones. Moreover, the gradient masks transform all contrasted lines into very thick ones. we prefer here to employ non-linear methods of mathematical morphology (SERRA 1986). A Karunhen-Loeve transformation has been processed on the three channels to obtain a well contrasted single image. The thin and light lines are then enhanced by a *white top hat transformation*, which is the residue of a *morphological opening* (MEYER 1978). The resulting grey-tone image has a narrow histogram, but the lines of the image have the higher values which provide a pertinent binary image by thresholding the grey-

Fig. 6. Grey-tone picture of the SPOT XS scene.

tone function. A high level threshold eliminates the small details but disconnects the lines (Fig. 7), as a low threshold preserves both the connected lines and small entities. The "cleaning up" of this binary image is done by a *geodesic reconstruction* of a high level threshold of the white top hat into a low level threshold of the same image (MERING et al. 1993). This type of transformation is able to provide a binary image where the relevant lines have been preserved (Fig. 8). Finally, in order to submit to a geometric description of one pixel-width structures, we have computed a skeleton by thinning (LANTUÉJOUL 1980), which preserves the connectivity of the initial set. If the skeletonized lines correspond to disconnected segments belonging to the same structure they are eventually connected applying the algorithm proposed by PARROT & TAUD (1993) in order to restore a complete structure. Finally, the structures thus obtained are isolated by a line editor procedure in order to analyze the structures in a single meander environment.

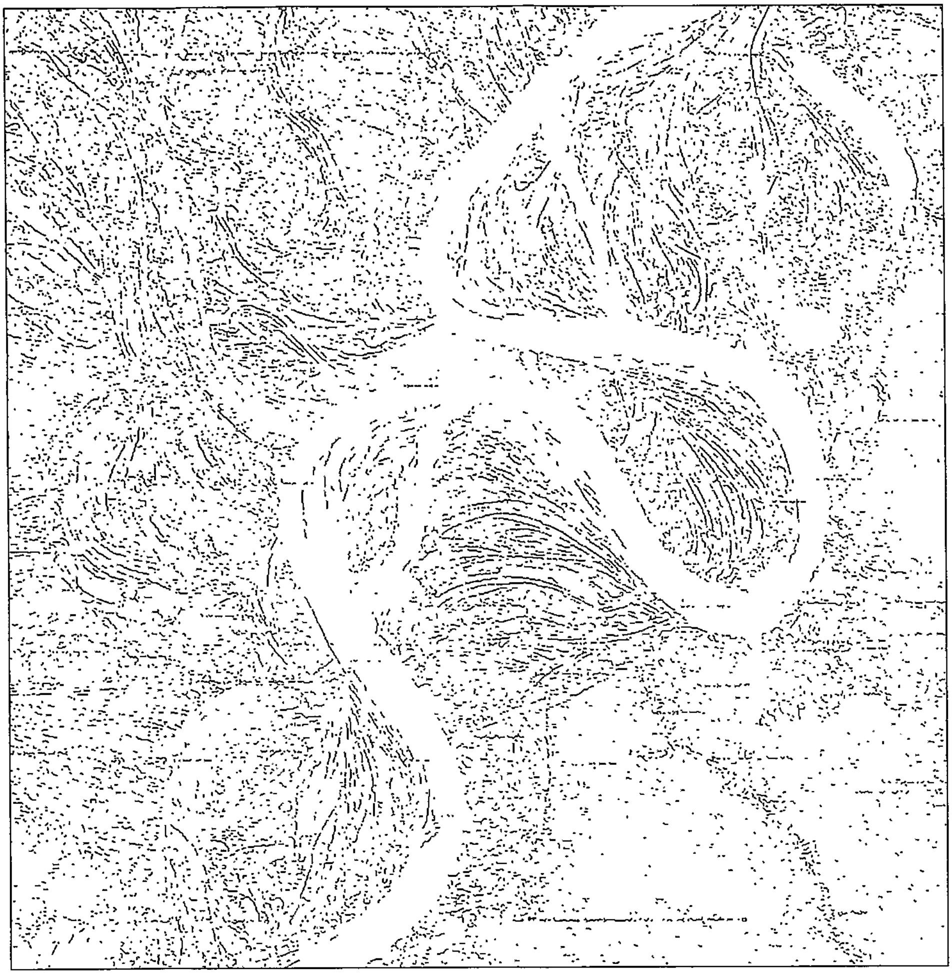

Fig. 7. Binary image from the thresholding grey-tone SPOT XS scene.

5 *Setting structural parameters*

In order to obtain a quantitative description of the structural features previously detected, specific parameters are computed using the Adonis method (PARROT & TAUD 1992). Each curve is individualized and approximated by a circular arc which is called the reference circle (RC). A set of parameters defined by the curve and its reference circle enables the characterization of the structures. These parameters mainly determine the position of the center and the value of the radius of RC, the number of pixels belonging to the curve, the direction of the normal to the chord, and various coefficients (chord, intersections, symmetry, etc.). This parameterization allows one to sort out different classes of structures.

This process is applied to the image obtained by the previous step of image analysis (see Fig. 8) with a focus on the meander of type L and R, as they are reported in the

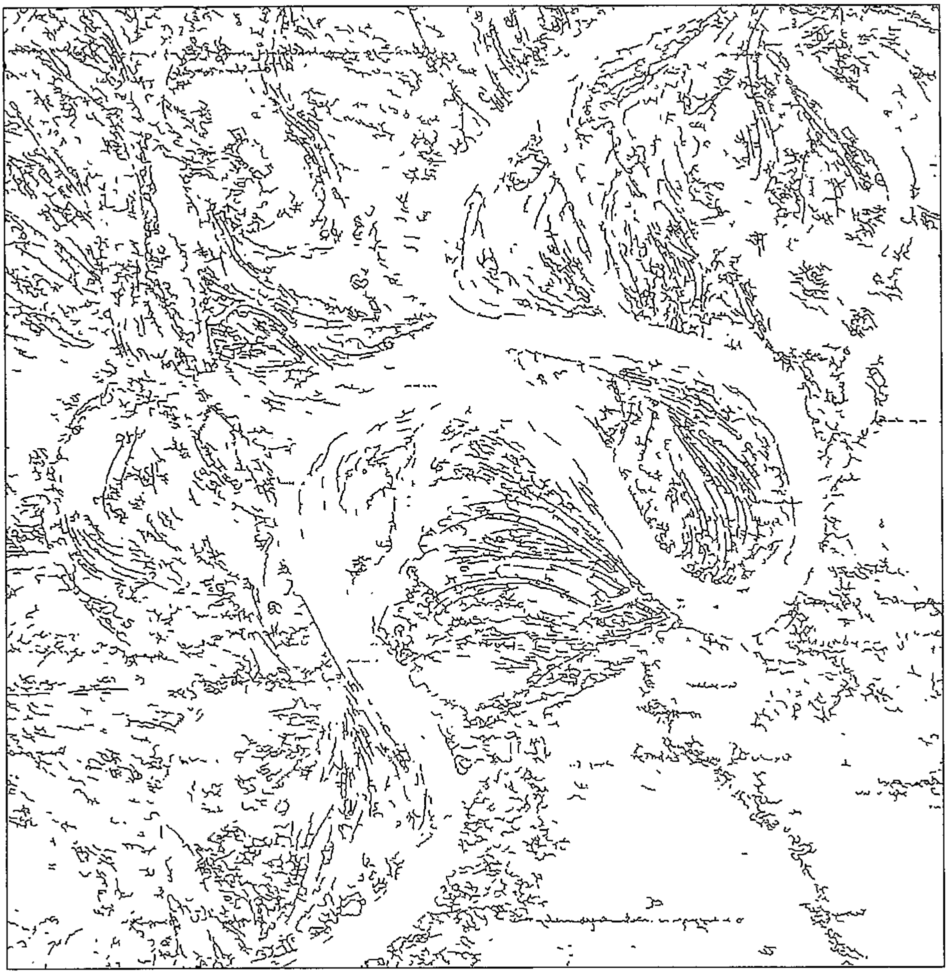

Fig. 8. Binary image obtained from the image Fig. 7 by geodesic reconstruction. The result is that disconnected segments of a same line are connected after the reconstruction. See Fig. 7 for comparison, and text for details.

Fig. 5. Fig. 9 A–D shows the main results obtained by the pattern recognition. In this figure we have represented the individualized structures and their chord. The normal to the chord is computed according to the following rules: it is orthogonal to the chord and passes through the center of the reference circle.

6 *Discussion*

The first important point of the image obtained from Adonis processing, is that the identified curves appear to be superposed over the scroll pattern observed near the development axis of meanders. The point is not surprising because scroll pattern is better

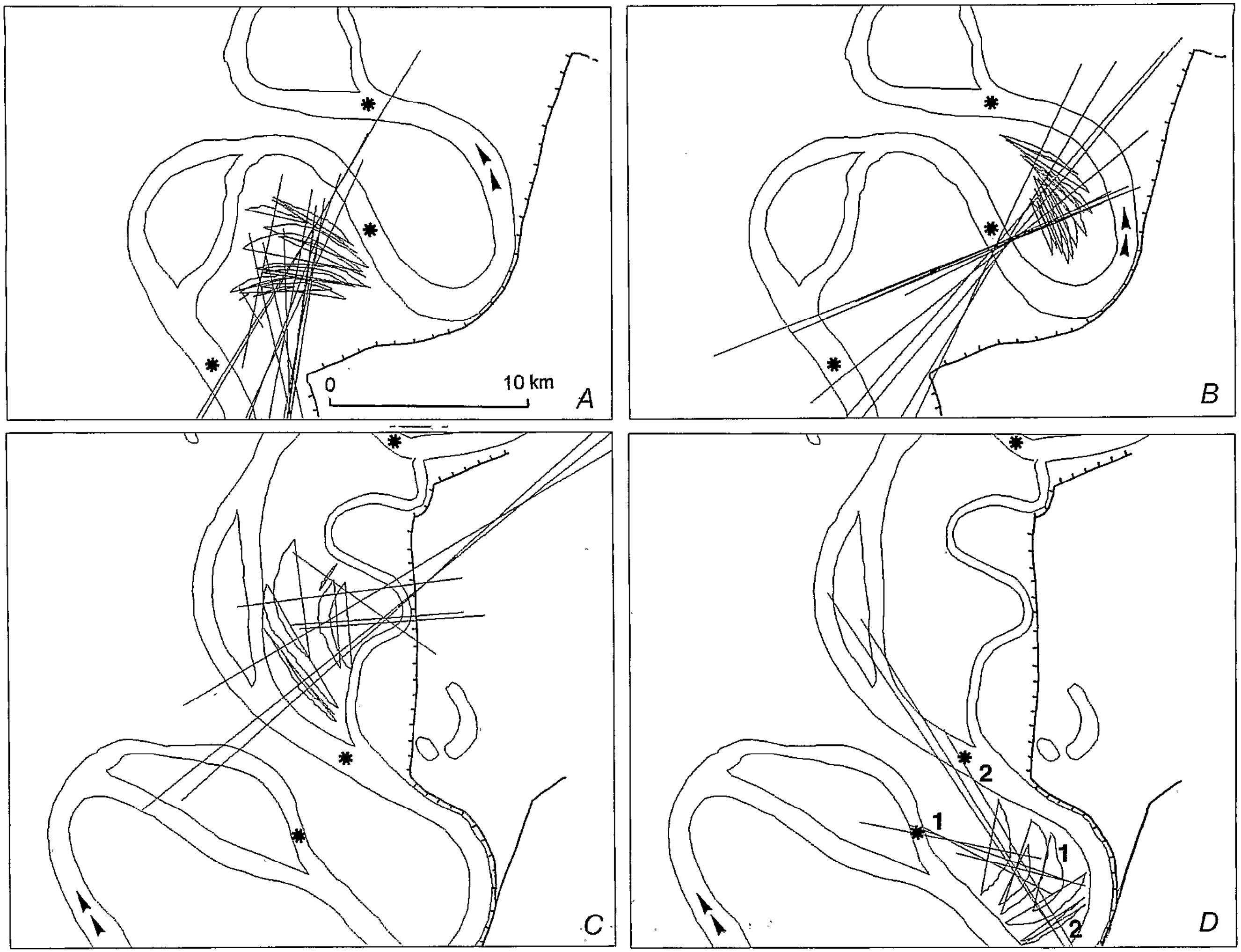

Fig. 9. Adonis method (PARROT & TAUD 1992) applied to meander migration. Same scale for all the figures. See Fig. 5 for location. Barbed line shows the bluffline border of the floodplain, and straight lines other morphological scarps in the upland. Stars represent the points of inflection of meander curves. 1 and 2 are successive stages for the meander migration. See text for details.

exposed with near circular lines near this axis of development, but it qualifies the Adonis processing as a technique to study meander migration. The geological approach suggested a different development of the flood plain side meanders (L, Fig. 5) with respect to the bluffline side ones (Fig. 5R). This process is evidenced by different patterns on the images issued from Adonis processing. Two right (Figs. 9B and D) and two left meanders have been processed (Figs. 9A and C).

6.1 Adonis pattern of flood plain side meanders. The most recent tendencies of the main development of flood plain side meanders have not been clearly identified, probably because the island made by secondary channels disturbs the original ridge and swale pattern. The early tendencies of these meanders are evidenced on Fig. 9C, with a development mainly orthogonal to the main trend of the river (identified between inflection points). The secondary development of the meander lobe (Fig. 9A) tends to be closer to the main trend of the river. The details of both lobe developments suggest local upstream or downstream migration tendencies of the apex curve of the meander, according to a process previously described for free meanders by HICKIN (1974). No specific evolution is observed for the orthogonal lines to the chords, only the occurrence of parallel lines suggesting a tendency to lateral widening of the shape of the meander.

6.2 Adonis pattern for bluffline side meanders. Two different meanders on the bluffline side have been processed; one has a typical down valley migration along the bluffline border (Fig. 9B), and the other is blocked in a corner formed by an inner angle of the bluffline (Fig. 9D, and the meander with a star on Fig. 5). The Adonis pattern of the first case (Fig. 9B) is very typical, as all the orthogonal lines to the chord are directed toward a point which is very close to the upstream point of meander inflection. The line between the two inflection points is also parallel to the bluffline border. It may be interesting to note that at first, the border of the floodplain near this meander had been identified in an inner position. The striking pattern resulting of the Adonis processing suggests that a closer structural control of the meander migration could be expected in a trend parallel to the line joining the inflection points of the meandering pattern. Returning to the image, a low terrace without scroll traces on its surface has been identified (Fig. 5T), and a most complicated lineament pattern of the bluffline margin of the flood plain has been traced. The second case (Fig. 9D) is more complex and presents two different stages: The first stage (Fig. 9D, position 1) is a pattern close to the pattern observed in the Fig. 9B, with orthogonal to the curves oriented toward the upstream point of meander inflection. A second stage develops (2 on Fig. 9D) with an upstream directional progression of the meander. The lines orthogonal to the chords of the processed curves are directed toward the down stream point of inflection of the meander. We interpret this second stage as resulting from the locking of the meander in a corner marked by the trend of the line of bluff, preventing the meander from continuing downstream migration. Indurated sediments from a 13 000 years BP terrace have been identified in the field, giving credit to this hypothesis.

7 *Conclusion*

Coherent relations have been shown in an asymmetric meander belt, between the recent evolution of meanders, the trend of river segments and flood plain margin, and neotectonic faults identified in the area. Mathematic analysis of images leads to the identification of several types of meander patterns related to either uncontrolled migration toward the flood plain, steady directional migration along a structural bluffline, or blocked position on special structural features.

The main tendencies observed on the flood plain side involve compound meander migration, with a principal development orthogonal to the river trend and a secondary development which is oblique, and tends to be parallel to the valley slope. Meanders on the bluffline side are simple, with a development which tends to be parallel to the bluffline. The Adonis processing gives very different patterns for free and structurally controlled meanders. In particular, controlled meanders are characterized by orthogonal lines to the chords of curves, which are directed toward the point of inflection of the meander located at the opposite side of the direction of progression of the meander. If this point is confirmed by more examples, the Adonis method may appear as a new and accurate tool to determine if meanders are structurally controlled, even if no structural line is observed on the surface of the floodplain (it may be covered by recent alluvium). The style of asymmetrical meander development which is observed here is in contradiction to the style of meander evolution on a tilted flood plain suggested by NANSON (1980). Meanwhile, the structural constraints appear to be better defined in our case, especially the tilt motion which cannot be directed toward the flood plain, but only toward the bluffline.

Our results suggest that even if a wide asymmetrical flood plain is not present, some structural control of the river may be determined using image analysis. The use of enhanced analysis of images, gives new perspectives for the structural analysis of flood plains in relation to neotectonic and active deformation.

As far as neotectonic evolution of subandean basins is concerned, the evolution of river migration is in agreement with the NNW–SSE extensional trend observed in the craton margin, and this suggests that this process is still ongoing. This state of deformation is compatible with the NE–SW to ENE–WSW compressive state of stress observed in the surrounding parts of the Marañón Basin and along the Andes-Brazilian craton boundaries (ASSUMPÇAO 1992).

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References

ASSUMPÇAO, M. (1992): The regional intraplate stress field in South America. – J. Geophys. Res. 97, B8: 11889–11903.

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

– (1994): Neotectonics and Rivers of the Amazon Headwaters. – In: SCHUMM, S.A. & B.R. WINCKLEY (eds.): The Variability of Large Alluvial Rivers. – 103–113; Publ. Amer. Soc. Civil Eng.

DUMONT, J.F., E. DEZA & F. GARCIA (1991): Morphostructural provinces and neotectonics in Amazonian lowlands of Peru. – South American Earth Science 4: 287–295.

DUMONT, J.F. & M. FOURNIER (1994): Geodynamic environment of Quaternary morphostructures of the subandean foreland basins of Peru and Bolivia: characteristics and study methods. – Quatern. Internat. 21: 129–142.

DUMONT, J.F., F. GARCIA & M. FOURNIER (1992): Registros de cambios climaticos por los depositos y morfologias fluviales en la Amazonia occidental. – In: ORTLIEB, L. & J. MACHARE (eds.): Paleo ENSO Records. – 87–92; Intern. Symp., Extended Abstracts, Lima.

DUMONT, J.F., S. LAMOTTE & M. FOURNIER (1988): Neotectonica del arco de Iquitos (Jenaro Herrera, Perù). – Bol. Soc. Geol. Perù 77: 7–17.

HICKIN, E.J. (1974): The development of meanders in natural river-channels. – Amer. J. Sci. 274: 414–442.

LANTUÉJOUL, C. (1980): Squeletonization in quantitative metallography. – In: HARALICK, R.M. & J.C. SIMON (eds.): Issues of Digital Image Processing. – 107–135; Sijthoff and Noordhoff, The Netherland.

LEEDER, M.R. & J. ALEXANDER (1987): The origin and tectonic significance of asymmetrical meander-belts. – Sedimentology 34: 217–226.

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

MERING, C., Y. CALLOT & J. CHOROWICZ (1993): An application of morphological filtering to geomorphology and structural geology. – In: SALEMBIER, P. & J. SERRA: Mathematical Morphology and its applications to Signal Processing. – 204–211; Internat. Workshop, Barcelona.

MEYER, F. (1978): Contrast features extraction. – Spec. Iss. Pract. Metallogr. 8: 374–380.

NANSON, G.C. (1980): A regional trend to meander migration. – J. Geol. 88: 100–108.

PARROT, J.F. & H. TAUD (1992): Detection and classification of circular structures on SPOT images. – IEEE Trans. Geosc. Remote Sensing 30,5: 996–1005.

– (1993): Connexion directionnelles de contours. – In: Télédétection appliquée à la cartographie thématique et topographique. – 335–343; 4ème Journées de L'UREF, Montréal (21–23 octobre 1991), Presses de l'Université de Québec.

PRATT, W. (1978): Digital imaging processing. – 750pp., Wiley and Sons, New York.

SERRA, J. (1986): Image Analysis and Mathematical Morphology, Rheorica Advances. – 628pp., Academic Press, London.

VON BANDAT, H.F. (1962): Aerogeology. – 350pp., Gulf Publishing Company, Huston, Texas.

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