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Morpho-Structural Expression of Active Thrust Fault Systems in the Humid Tropical Foothills of Colombia and Venezuela

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with 12 figures

Summary. Morpho-structural expression of thrust faults in fold-and-thrust belts is largely dependent on several factors, which may act independently of interact jointly. these factors include the dip of thrust fault planes (gentle or steep), kinematics of thrust faults (dip slip or oblique slip), lateral continuity of structures and depth to the active fault plane (exposed or blind thrust). This paper discusses geomorphological indicators and surface geological evidence that reflect the presence of active, pure dip-slip thrust faults in fold-and-thrust belts associated with thin-skinned, flat-and-ramp tectonics in the Llanos (eastern) foothills of the Andes Cordillera of Venezuela and the Eastern Cordillera of the Colombian Andes.

Along these foothills areas, the most frequent and best exposed geomorphic evidence of ongoing tectonic activity are (1) flexural scarps; (2) drainage patterns and anomalies, and (3) progressive deformation with increasing time.

The drainage patterns and anomalies, which reflect very subtle topography modifications, include staircased alluvial terraces exclusively present in the hangingwall block. These tectonically induced changes are reflected as radial drainages, densely dissected morphological scarps, river pattern inversion with flow from basin to range, river diversions, beheaded drainages and stream captures, changes in incision depth and river gradient along river course, dammed creeks and rivers, wind gaps (abandoned river gaps), imbalances between current river flow and river gaps, rivers that are parallel and close to the thrust front on the down-thrown block (i.e., tectonic "gutters"), and broom-shaped river patterns on the basinward side of these foothills. These changes are superposed on an increase of tilt of ground surface or stratigraphic dip with increasing age of Quaternary allluvial ramps and even older formations (progressive unconformities). Collectively, these features provide firm evidence for active deformation of the Llanos (eastern) foothills of the Andes Cordillera of Venezuela and the Eastern Cordillera of the Colombian Andes.

Introduction

For over a century now, the study of topographic relief and its diverse forms has been useful for demonstrating the presence of tectonic activity. For instance, since the beginning of this century, either erosional surfaces or staircased alluvial terrace systems (planar features) have been commonly used in Europe to show ongoing regional tectonic uplift (see for instance DAVID 1920, ELLENBERGER 1938, GEORGE 1943). Towards the same objective, raised Quaternary marine terraces have been studied all over the world in recent times. The application of these latter studies have greatly benefited from the development of more accurate absolute-dating methods and a new understanding of the earth's hydrosphere resulting from the Deep-Sea Drilling Project (DSDP). Almost simultaneously, in the 1960's and 70's, many other geomorphic features became recognized along seismically active strike-slip faults, mainly in California (but also in the former Soviet Union, New Zealand, Japan or China; even in Venezuela), which became the modern basis of seismic

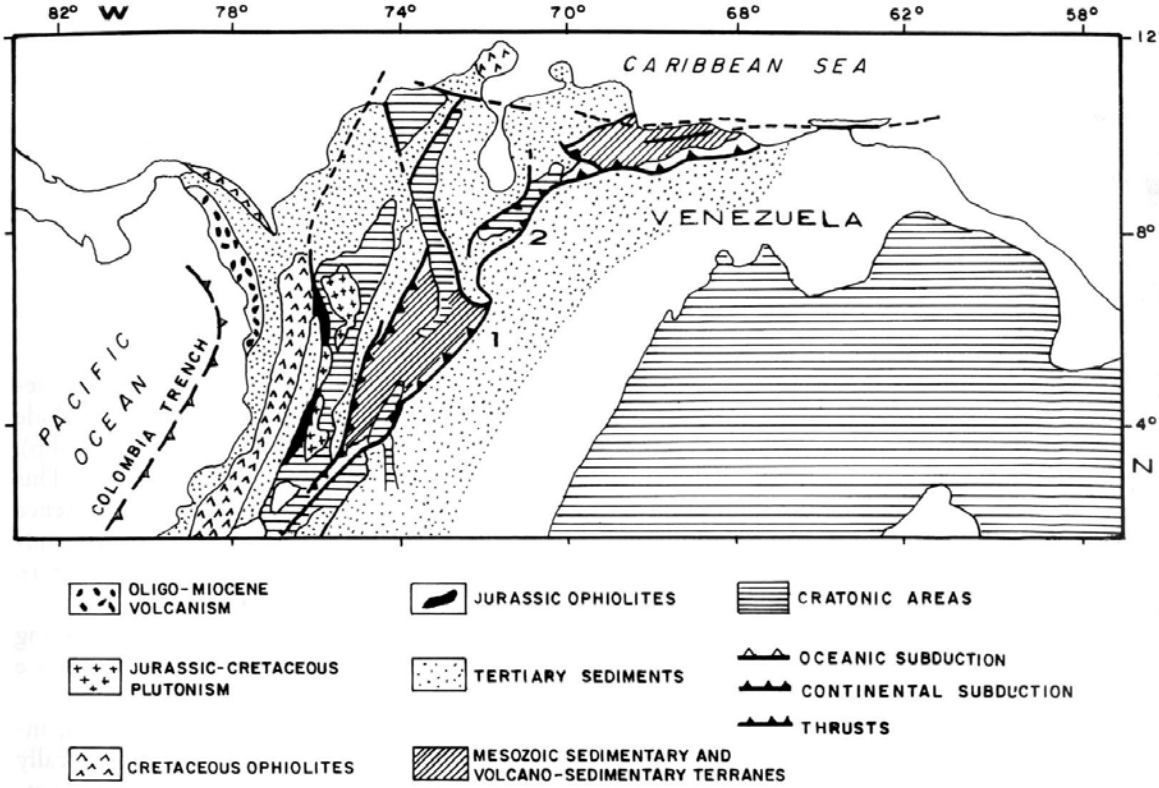


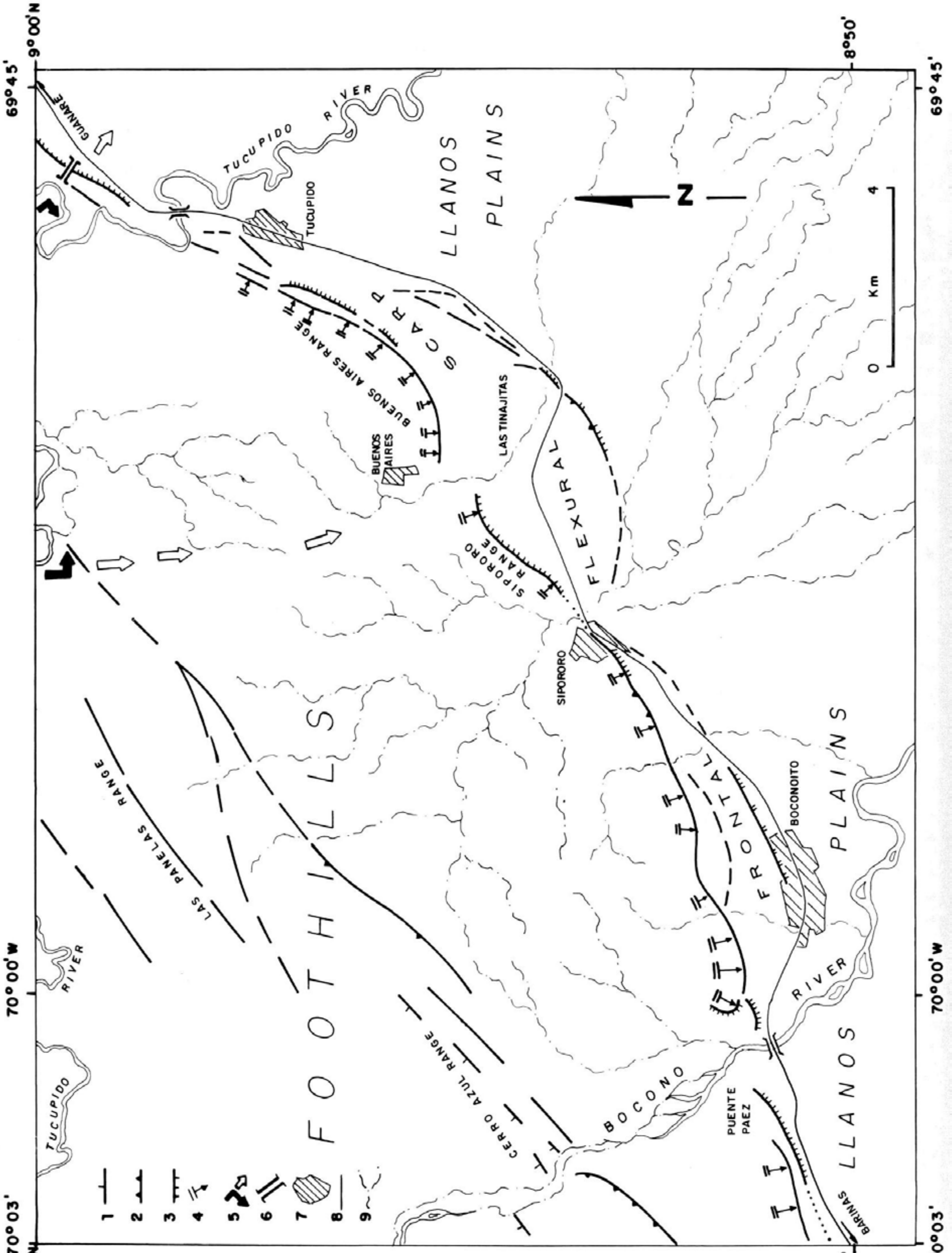
Fig. 1. Schematic geologic map of northern South America, showing relative location of the fold-and-thrust belt of the Andean chain along the Llanos foothills, in Colombia and Venezuela (simplified from HEBRARD 1985). Areas marked 1 and 2 indicate study areas.

hazard assessments of a given region using a neotectonic approach. However, these geomorphic indices or evidence are characteristics of strike-slip regimes and have not been adapted for the assessment of tectonic activity of thrust fault systems. This paper intends to present observations of geomorphic and geologic evidence in the Eastern Andan foothills of Colombia and Venezuela, where a well-developed fold-and-thrust belt is currently growing. In this type of tectonic setting, the analysis of drainage has proved to be a powerful tool because drainage system are highly sensitive to slow vertical tectonic processes related to subtle folding and thrust faulting.

General Setting

Central Colombia and Western Venezuela are characterized as regions having sharp contrast of relief; for example, the Andes mountains in the west and the Llanos plains, be-

Fig. 2. Neotectonic map of a short portion of the active Venezuelan frontal South-Andean flexure between the Boconó and Tucupido Rivers, Portuguesa State (after Funvisis 1997). Refer to Fig. 9 for relative location. Legend: 1 - strike and dip of beds; 2 - SE-vergent thrust fault; 3 - fault scarp with ticks on downthrown block; 4 - surface tilt of flexural scarp; 6 - wind gap; 7 - village; 8 - asphalt road; 9 - drainage.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BUENOS AIRES
LAS TINAJITAS
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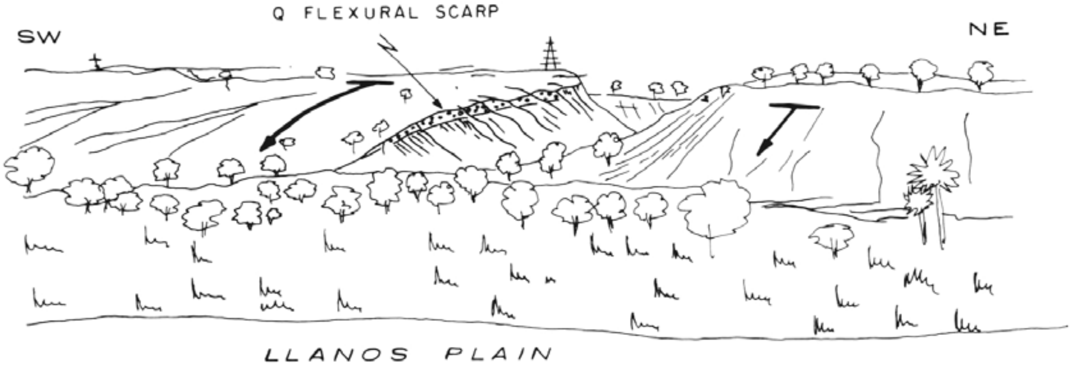

Fig. 3. Ground view of the Venezuelan frontal South-Andean flexure, showing a beheaded river channel (after Funvisis 1997). High-voltage powerline tower on top of the flexural scarp is about 25-30 m high.

longing to the Orinoco-Amazon basin, in the east. Both study areas in the Llanos foothills – one in each country – correspond to two parts of the frontier (1 and 2 in Fig. 1) between these two hugely contrasting geographic and geological terrains. This border area is mainly composed of low-lying hills that are less than a few hundreds meters above the rather flat topography of the Llanos plains. Due to their position at the foot of the Andean chain, this region is characterized by high rainfall that is distributed over a six-month period, though strong short-duration storms are frequent. This region is the east-vergent frontal fold-and-thrust belt of the Andean Chain, which basically involves the entire Mesozoic-and-Cenozoic sedimentary sequence of the Llanos basin (CAZIER et al. 1995, COOPER et al. 1995, OSUNA et al. 1995). This sequence is affected by thin-skinned tectonics where shortening is accommodated by both folding and flat-and-ramp thrust faults rooted under the Andean chain.

Geomorphic Evidence

As a result of our studies, we have identified flexural scarps and 14 types of geomorphic evidence (drainage patterns and anomalies) that suggest current tectonic activity of the fold-and-thrust belt associated with the Llanos foothils.

Flexural scarps

Flexural scarps are the most conspicuous evidence of gently-dipping thrust systems observed at the front of the fold-and-thrust belt underlying the Llanos foothills of both Colombia and Venezuela. These features are comparable in shape to that described by TAPPONNIER et al. (1990) in association with the Luo Tuo Chen thrust in Qilian Shan, China, but the South American feature is 10 to 100 times higher than its Chinese equivalent, implying that Llanos scarps result from a much larger number of repeated earthquakes. The flexural scarps in the study areas define the boundary between the foothills unit and the Llanos plains. In Venezuela, a roughly NE-SW-trending, SE-facing flexural

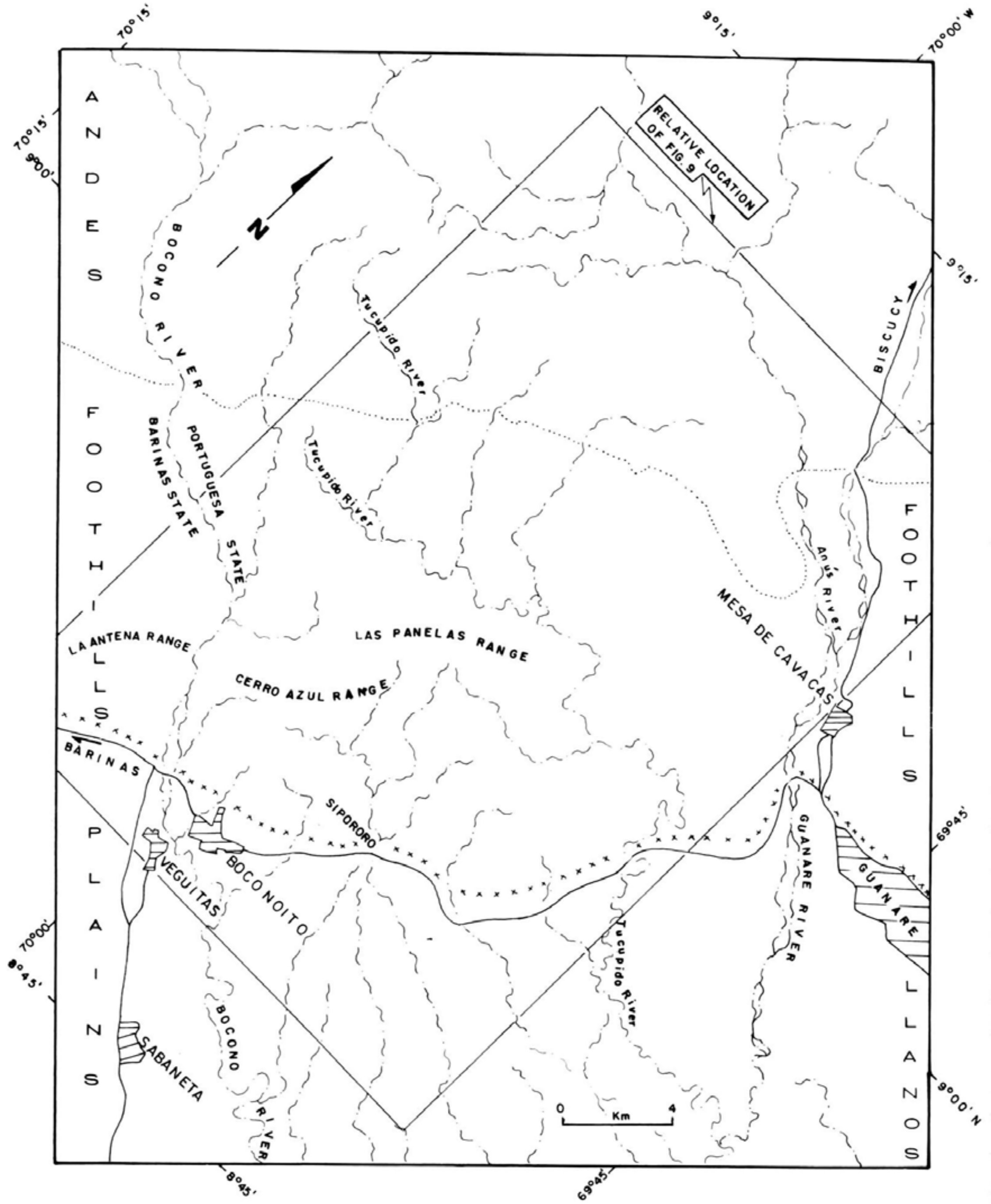

Fig. 4. General drainage pattern of the Venezuelan foothills between the Boconó and Guanare Rivers, Portuguesa State. Notice the anomalous behaviour of the Tucupido River. Location of Fig. 9 is also shown. Legend: 1 - boundary between Andes chain and foothills unit; 2 - boundary between foothills unit and flat-lying Llanos plain; 3 - asphalt road; 4 - drainage; 5 - village/town.

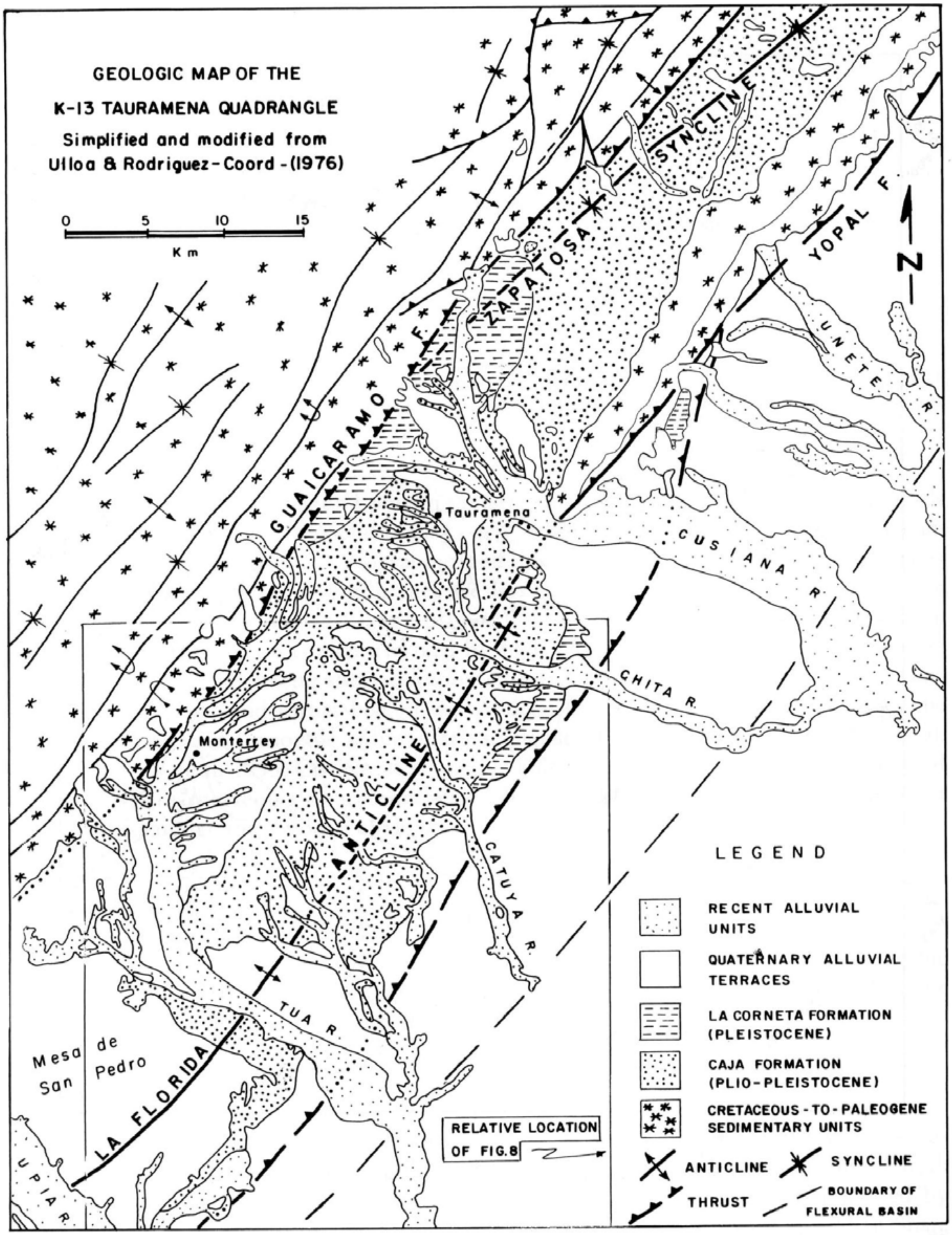

Fig. 5. Simplified geologic map of a short portion of the Llanos fold-and-thrust-belt of the Colombian Eastern Cordillera (1 in Fig. 1), roughly east of Bogotá (modified from ULLOA & RODRIGUEZ 1976). Relative location of Fig. 8 is also shown.

scarp – known as the frontal South-Andean flexure – can be followed for over 200 km in length. It extends between the cities of Barinas and Acarigua and its maximum height reaches 300 m above the rather flat topography of the Llanos plains (Fig. 2 and 3). This scarp is not continuous, only because it is dissected by large drainages, such as the Boconó and Guanare rivers (Fig. 4). That is to say that it has large river gaps (Fig. 2). Many of these large river gaps coincide with the lateral terminations of active individual ramps, as suggested by the extent of the exposed Paleogene rocks within the foothills unit (refer to the geological-structural map of Venezuela by BELLIZZIA et al. 1976). This observation has been recently confirmed by a 3-D seismic survey across the Venezuelan Llanos foothills as interpreted by DUERTO et al. (1998). The flexural scarps observed in Colombia have the same general characteristics as the Venezuelan frontal South-Andean flexure, although it is not as long due to major geometric complexities of the Llanos foothills of the eastern Cordillera of Colombia (HEBRARD 1985).

These flexural scarps have commonly been misinterpreted, both in Venezuela and in Colombia. The Venezuelan frontal south-Andean flexure used to be considered as a monoclinal structure. On the other hand, in Colombia, such scarps were considered to be the products of normal faults. As an example a ca. 50 m high SE-facing fault scarp flanking the La Florida anticline on the southeastern edge of the La Mesa de Sisigua and in an area to the north-east of it (between the Chita and Cusiana rivers; Fig. 5) was described and named the Sand Pedro-Sisigua normal fault by ROBERTSON (1989). Nevertheless, its actual geometry and origin could be observed in an abandoned gravel pit (Fig. 6a), between the Catuya and Chita rivers, where cobble beds correlative to La Corneta Formation or younger Quaternary alluvial units are perfectly flexed or warped around the clayey-silty beds of the Mio-Pliocene Caja Formation. On its own, the presence of this scarp does not prove the existence of a major fault at the surface or in the near subsurface, though it does definitely confirm Quaternary folding in the Llanos foothills of the Eastern Cordillera of Colombia. This warping is produced by thrust faulting since brittle deformation was observed at the edge of the foothills unit in: 1) the steeper southeastern forelimb of the La Florida anticline along road cuts made for the main Llanos road during early 1994, between the Catuya and Chita rivers, that expose early Pleistocene or younger, southeast-vergent, thrust faults (Fig. 6b and c); and 2) seismic profiles (Fig. 7a) where the Cusiana reverse fault has now been interpreted and is considered to be seismically active (CAZIER et al. 1995, COOPER et al. 1995).

As with the Colombian case, several localities along the Venezuelan frontal South-Andean flexure show flexing of coarse early – to middle-Pleistocene alluvial deposits, such as in the cities of Guanare and Araure-Acarigua, as well as along the banks o the Caro and Ospino rivers near the main Llanos road (FUNVISIS 1997). However, there is a clear difference between the two study areas: no major basin-vergent thrust fault crops out in association with the Venezuelan frontal flexural scarp because of the presence of a rather shallow triangular zone (Fig. 7b).

In both study areas, these flexural scarps grow at the front of active fold-and-thrust belts where deformation is dominated by thin-skinned tectonics. The thrusts are gently-dipping and form both flats and ramps (Fig. 7a and 7b). For example, the flexural scarp observed between the Cusiana and Upía rivers in Colombia results from the combination of warping of the sedimentary sequence at the shallow tip of a blind thrust (fault-pro-

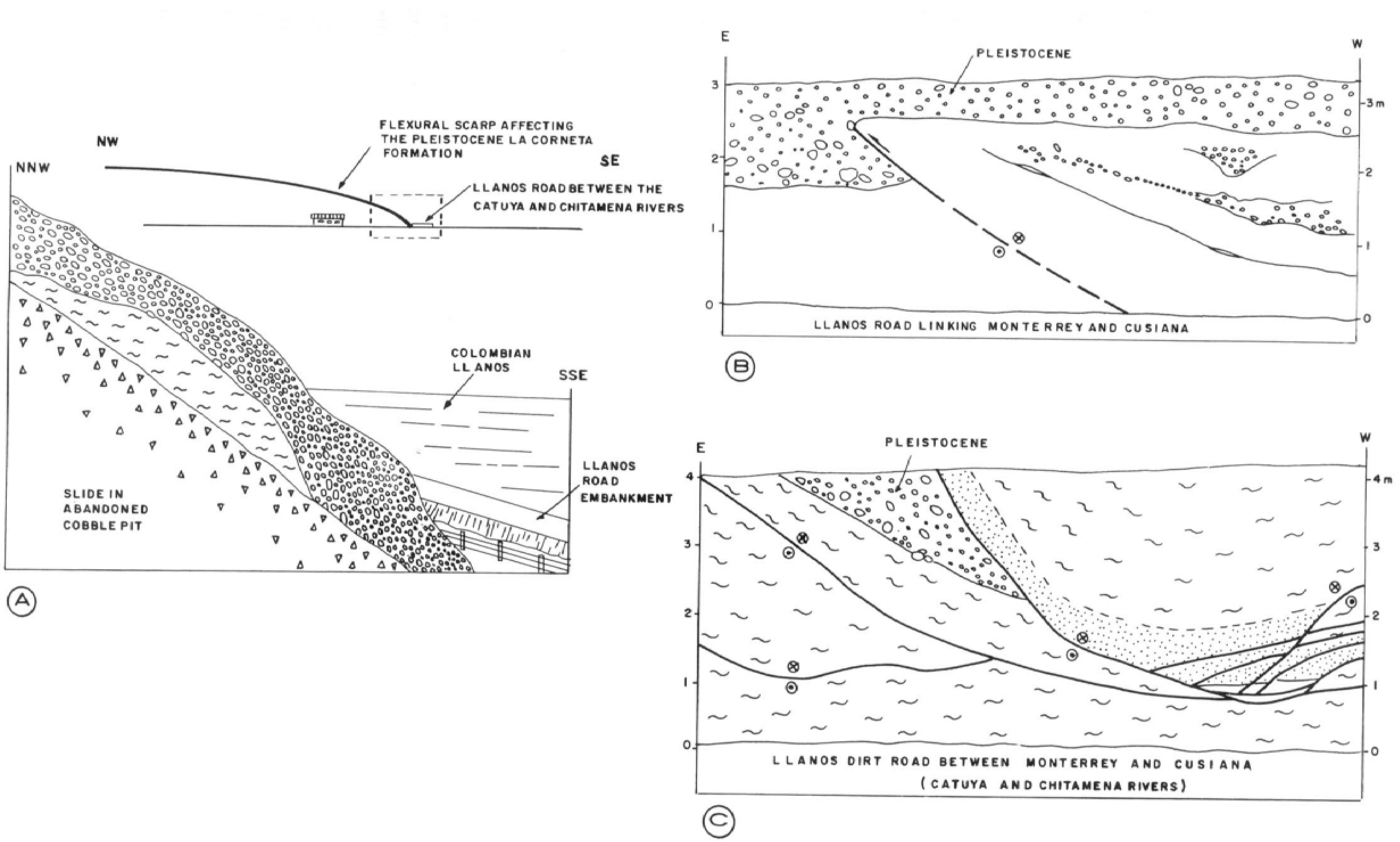

Fig. 6. (a) Flexural scarp on the southeast forelimb of the asymmetric La Florida (Cusiana) anticline, between the Catuya and Chita Rivers, affecting the Pleistocene La Corneta Formation (or younger alluvial units?); (b) and (c) Pleistocene-to-Holocene, southeast-vergent thrust faulting on the forelimb of La Florida anticline, in recently dug road cuts of the Monterrey-Cusiana Road, slightly north of the Catuya River.

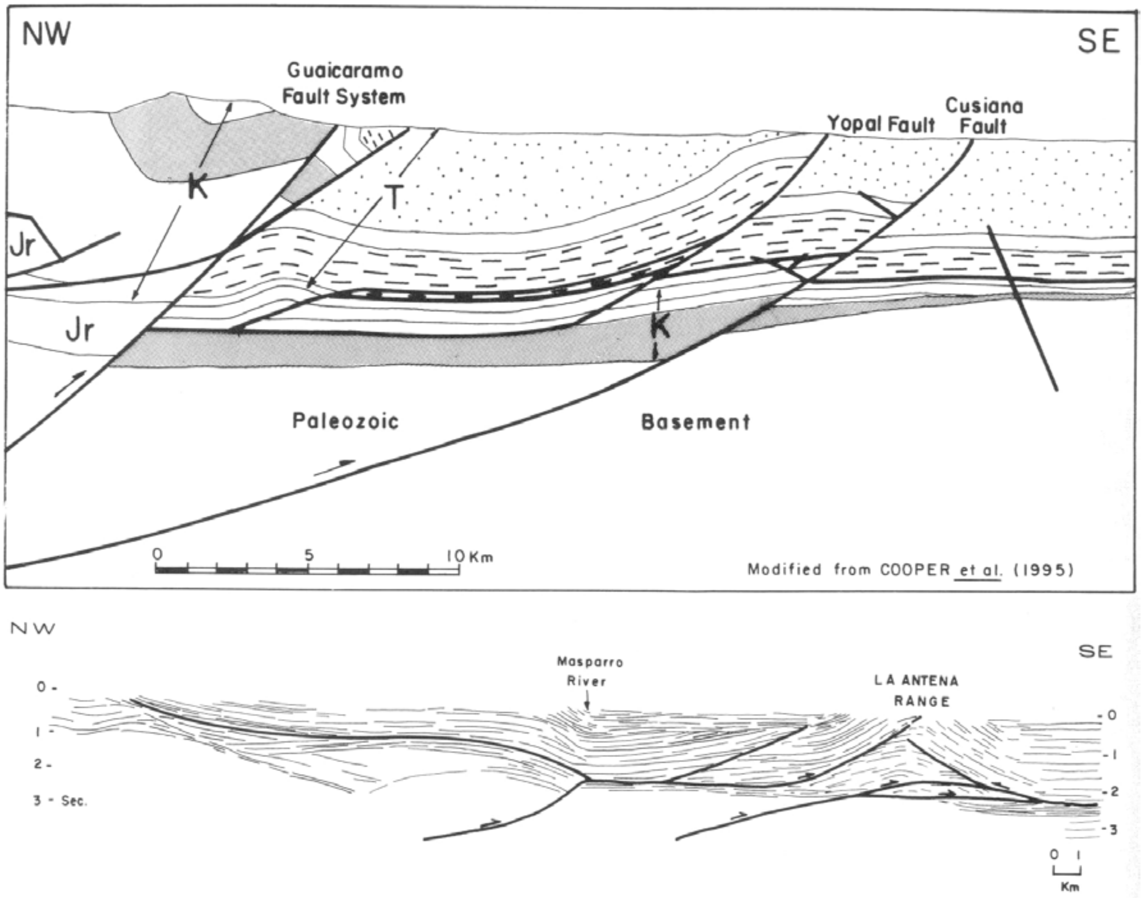

Fig. 7. (a) Subsurface geological structure of the Colombian foothills near the Cusiana River (simplified from CAZIER et al. 1995); (b) Subsurface geological structure of the Venezuelan fold-and-thrust belt close to the Masparro River (after Funvisis 1997).

pagation fold above the SE blind termination of the Yopal fault) and flexing of the steeper forelimb of a foreland- (east) vergent fault-bend fold that is associated with the most basinward fault, the Cusiana (Fig. 7a). In the Venezuelan foothills, these geomorphic features form in association with rather shallow triangular zones (Fig. 7b). The occurrence of different shortening mechanisms generates different surface responses: in Colombia, asymmetrical foreland-vergent folds form inducing local bulging, whereas the Venezuelan fotthills are all uplifted as a single unit, allowing the formation of a staircased alluvial terrace system in the hangingwall block, although piggy-back basins are forming in both areas (Fig. 7a and 7b).

Drainage patterns and anomalies

Drainage analysis may allow detection of vertical motion in a given area, as mentioned earlier. A comparative analysis is required because all rivers do not respond the same way depending on their size, although they may show similar longitudinal profiles. Generally, big rivers often cut across uplifting structures rather easily without modification of their

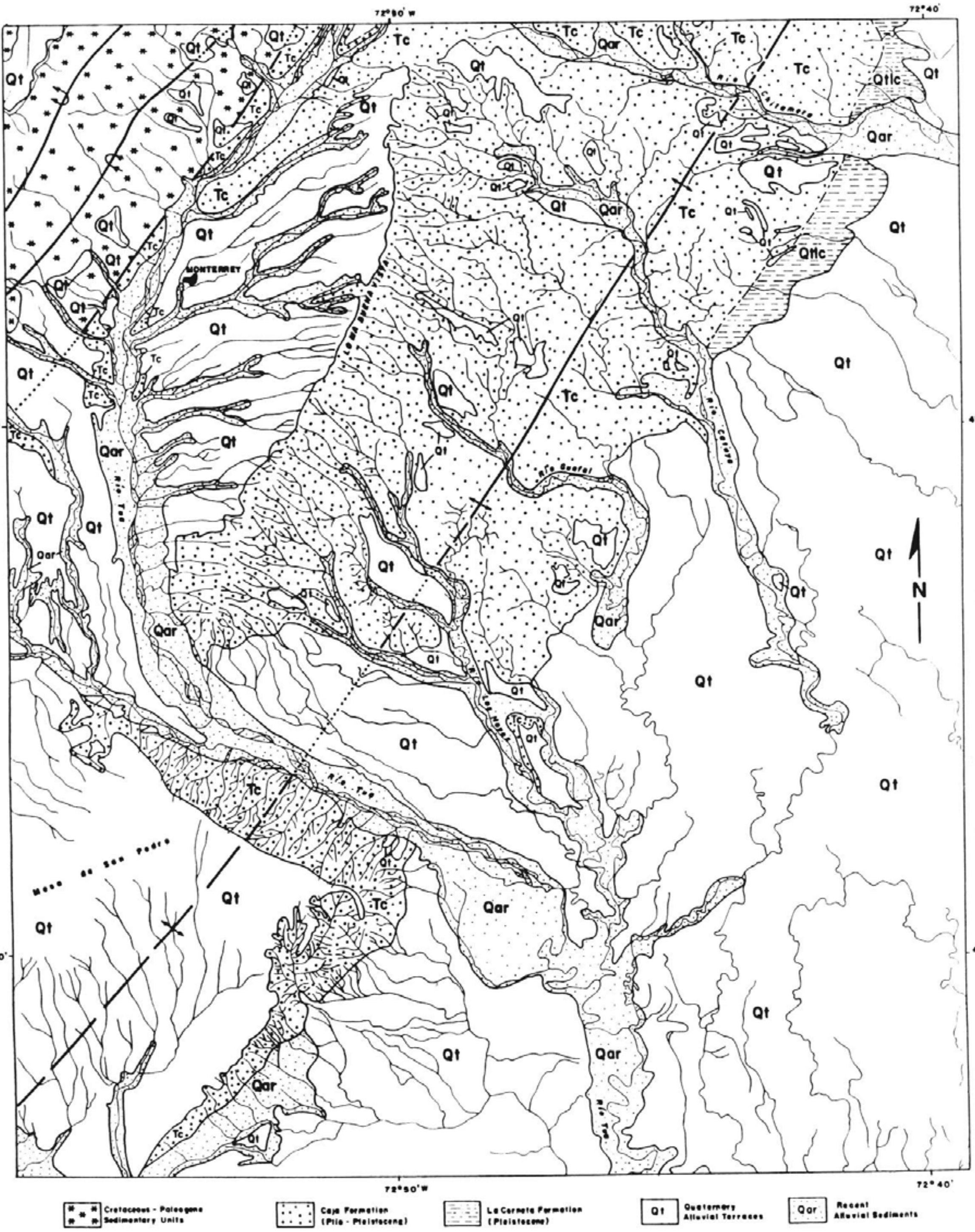

Fig. 8. Detailed geologic map of La Florida anticline, within the Llanos fold-and-thrust-belt of the Colombian Eastern Cordillera, between the Upía and Chita (or Chitamena) Rivers (for relative location, refer to Fig. 5).

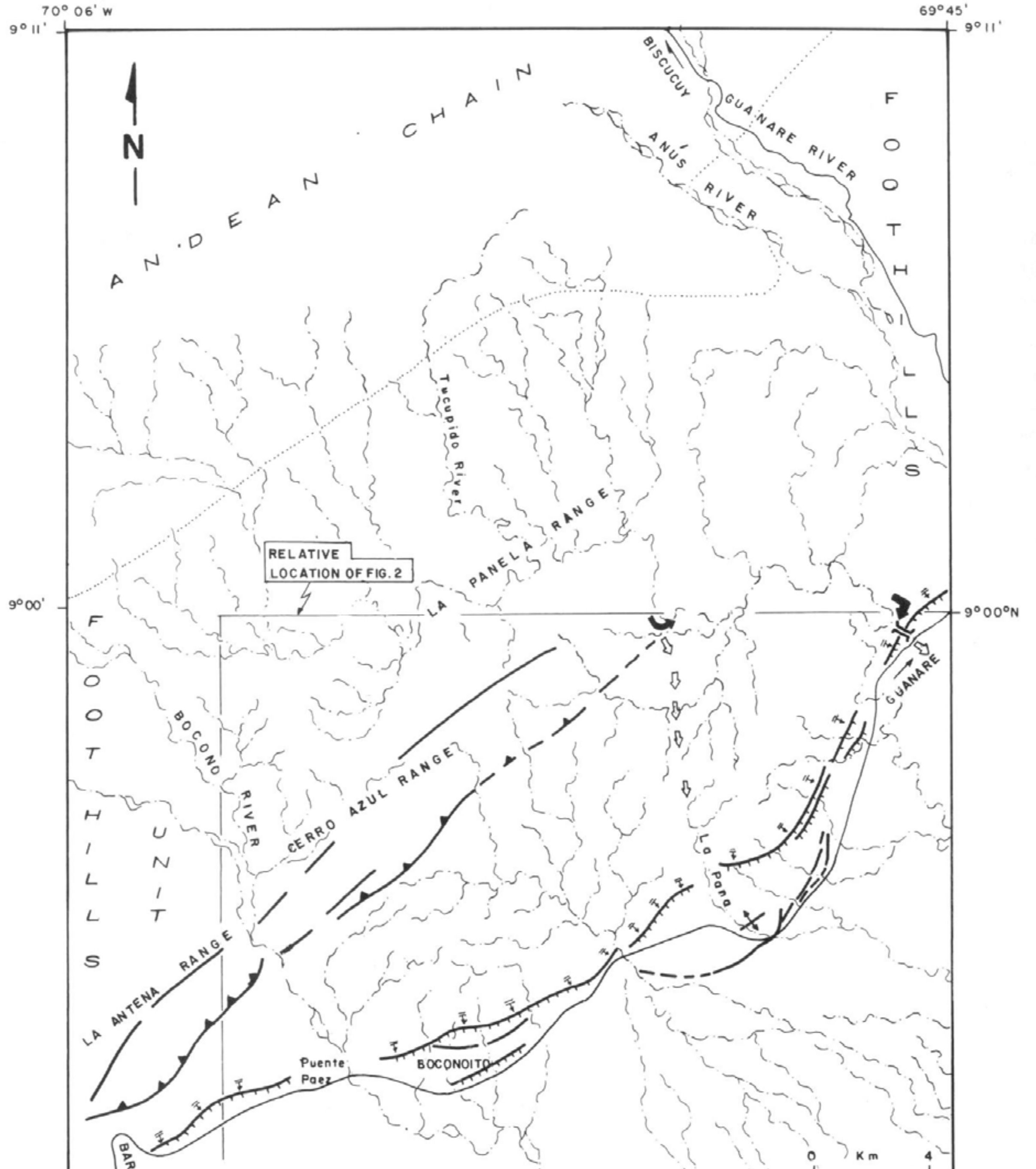

Fig. 9. Detailed drainage pattern of the Venezuelan foothills between the Boconó and Guanare Rivers, Portuguesa State. Notice the northeastward diversion of the Tucupido River behind the Venezuelan frontal South-Andean flexure. Also observe the associated wind gap (for relative location, refer to northeast corner of Fig. 2).

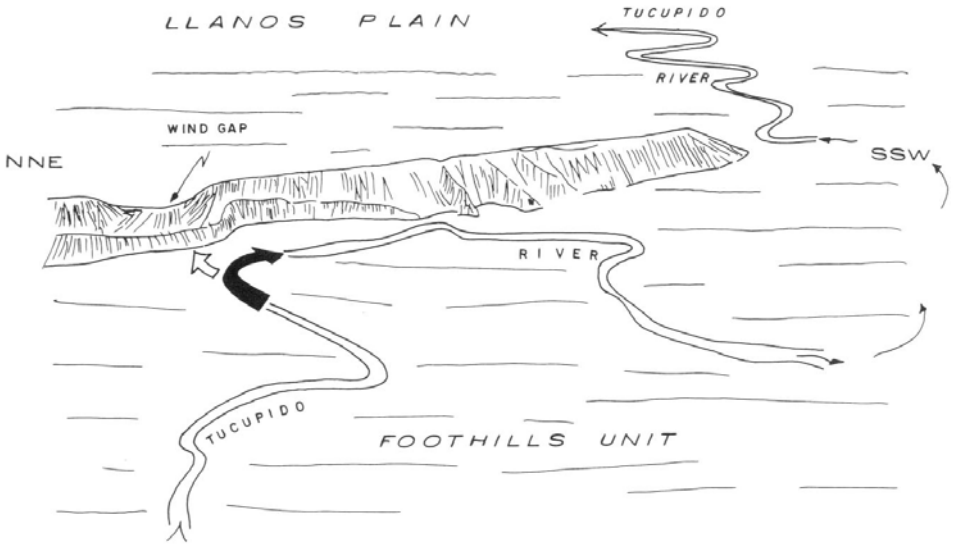

Fig. 10. Bird-eye view of the diversion of the Tucupido River behind the Venezuelan frontal South-Andean flexure. Also observe the associated wind gap (for relative location, refer to northeast corner of Fig. 2).

course. In the two study areas, small rivers reflect much more subtle topographic modifications than larger rivers in straightforward response to their respective stream power or erosional rates. Nevertheless, big rivers also bring relevant information regarding the uplift history of a region. Among the anomalous drainage behaviours detected in the Llanos foothills of Colombia and Venezuela, the following deserve mention:

(1) *Radial drainage.* This drainage pattern in fold-and-thrust belts is indicative of periclinal closure of folds. La Mesa de San Pedro in the Colombian foothills (lower left corner of Figs. 5 and 8) shows this drainage pattern, which define the southwestern periclinal closure of the La Florida anticline. This evidence had been previously reported by ROBERTSON (1989). Its significance in other tectonic settings is completely different (e.g.: domes, volcanic cones, diapirs etc.).

(2) *Densely dissected scarps.* A densely-distributed drainage pattern in an area may indicate the presence of differential uplift or tilt. The northern and eastern scarps of La Mesa de San Pedro show this type of pattern (Fig. 9), which is rather common but not singularly diagnostic of tectonic activity. However, if it accompanies one or more of the anomalies described herein, then it becomes significant. This means that the more types and frequency of anomalies are observed, the more reliable interpretations will be.

(3) *River pattern inversion.* In foothills areas where the drainage roughly flows in one single direction (from the mountain range to the lowlands), the presence of rivers or small drainage systems flowing in opposite directions (i.e., from the basin towards the range) should be considered suspicious. This pattern generally reflects tilting of the ground surface towards the range. This inversion may be due to several processes: formation of a flexural basin at the foot of the hangingwall block or range, generation of a small piggy-back basin, or increase of tilt on anticline backlimbs or syncline forelimbs. The backlimb of La Florida anticline (Figs. 5 and 8) and the forelimb of the Zapatosa

syncline (Fig. 5) show this type of anomaly, which is combined with the diversion of the Túa and Cusiana rivers, which drain those limbs respectively (Fig. 5). Small river captures are associated with these inversions.

(4) *River diversion.* Rivers may be diverted by ground surface tilting. This type of anomaly is frequently observed in association with growing anticlines or synclines (sagging areas). Diversion of small rivers is very frequent (Tucupido River in Figs. 4 and 9), but it can affect large rivers as well (Túa and Cusiana Rivers in Figs. 5 and 8). This feature suggests that diachronic and/or differential fold growth is happening and/or faster tectonic uplift (or subsidence) rates are faster than linear erosion rates (erosion by river flow). The Tucupido River shows two consecutive diversions within the foothills that reflect each of the potential causes (Figs. 4, 9 and 10): upstream, the river is affected by the differential growth of La Antena (Cerro Azul) anticline (Figs. 4, 7b and 9) and it is diverted downstream behind the frontal south-Andean flexure (Fig. 10). However, the river behaviour is mostly controlled by its low stream power when compared to other rivers of the same region. Conversely, the Túa and Cusiana Rivers, which are important rivers, are diverted to the southwest (Fig. 5) mainly because of the fast rate of vertical fold growth. This river behaviour is in agreement with the present folding evolution stages along strike of the La Florida anticline (fault-bend fold in the northeast and fault-propagation fold in the southwest), which indicates southwestward progression of fold growth. River diversion may also induce captures of smaller rivers by larger rivers. This anomaly may also generate a clear asymmetry in the cross-section profile of river beds and associated alluvial terraces since the progression of the diversion may erode the river terraces of one river bank.

(5) *Tectonic "gutters".* At the thrust front, small rivers may flow parallel and close to the front on the down-thrown block, which suggests tectonic loading due to foreland-vergent thrusting. Mostly, these gutters trend normal to the main drainage. In Fig. 8, the Guafal River acts partly as a tectonic gutter at either the geographical or geological unit boundary. This latter example can also be interpreted as a river diversion due to sagging.

(6) *Beheaded rivers or creeks.* Rather quick uplift may disconnect a segment of a river course from its headwaters. Most times, it implies that tectonic uplift rates are faster than erosion rates (stream power) of drainages. The Venezuelan South-Andean frontal flexure exhibits areas where beheaded river channels are nicely preserved (Fig. 3). La Pana Creek in the Venezuelan foothills can be considered as a beheaded creek with respect to the Tucupido River that was diverted to the northeast by the progressive and relatively-fast growth of La Antena (Cerro Azul) anticline (Figs. 2 and 9).

(7) *Change of incision depth and river gradient along river courses.* The analysis of longitudinal river profiles may reveal the presence of vertical motion. Also, the change of river patterns (from anastomosing to meandering) can indicate the occurrence of uplift or sagging. For instance, Mederos Creek, which crosses the eastern sector of the city of Guanare (in the Venezuelan foothills), shows a steeper river gradient (very small rapids are present) where it crosses the frontal South-Andean flexure, implying that the ground surface has been tilted locally in the Holocene. Longitudinal profiles of small rivers are more sensitive than big river ones, because the evidence of tilting takes more time to be erased and longitudinal profile to be smoothed as a straightforward response to their respective stream power.

(8) *Dammed channels and rivers.* In some cases, rivers may be emponded behind active structures, implying that erosion by river flow is much less important than current tectonic uplift. It would more easily affect very small rivers or ephemeral creeks, but this evidence has not been observed in these foothills.

(9) *Wind gaps.* Wind gaps are former river gaps across an active structure (anticline, flexure, etc.) but no river is draining it at present time, because the river could not keep up with vertical uplift of the active structure. This feature is very common and frequently accompanies dammed or diverted rivers on the upstream side of active structures (Fig. 10) and/or abandoned alluvial fans on the downstream side of active structures (Fig. 2). Many beheaded rivers on the Venezuelan South-Andean frontal flexural scarp may evolve wind gaps.

(10) *Disproportionate size between present river flow and gap.* In some cases, the size or width of river gap does not match with river width or current stream power, suggesting that the present river is not responsible for the gap. Two possible explanations can be given: the present river has inherited a gap previously eroded by a different (more powerful) river, or the river flow has diminished with time, but the explanation has to be found upstream. this kind of feature may become a wind gap or it may occur jointly with a beheaded river or creek. La Pana Creek is a nice example of this type of anomaly (Figs. 2 and 9).

(11) *Abandoned alluvial fans downstream of uplifting structures.* Downstream of wind gaps, it is common to see abandoned alluvial fans. Nice examples have been observed at the foot of the Venezuelan frontal South-Andean flexure in association with wind gaps in the city of Guanare and at the foot of the basinward slope of the Buenos Aires Range (between the Tucupido and Boconó Rivers; Fig. 2).

(12) *Staircased alluvial terrace systems.* This feature has been used for almost a century to prove the presence of regional uplift and it is not exclusive to fold-and-thrust belts. In areas where very gently-dipping flat-and-ramp thrusts are affecting the subsurface (such as in the Venezuelan foothills), the ground surface of the hangingwall block may raise almost horizontally, allowing rivers to cut deeper and leave their alluvial terraces aside and on higher ground. It is necessary then that rivers keep cutting through the area under uplift, implying that they have strong stream power. In the Venezuelan foothills, four Quaternary alluvial terraces are widespread: the oldest and highest terrace, which erodes and truncates the Pliocene molassic deposits (Río Yuca Formation) is the one that forms the ground surface of the Venezuelan frontal South-Andean flexure; the three other terraces crop out behind the flexure. The younger the terrace is, the lower and smaller it is. Most main rivers, such as the Boconó and Guanare, show four well-developed staircased alluvial terraces exclusively within the foothills. As soon as rivers cross the frontal flexure, they enter the almost perfectly flat (depositional) Llanos plains. Locally, up to eight staircased terraces have been preliminarly identified in association with the Morador anticline (i.e., in Chiguire, close to the village of Ospino in the Venezuelan foothills), but no detailed geomorphic and chronologic studies have been performed yet.

(13) *Progressive unconformities.* The frontal flexure functions as a hinge zone that simultaneously allows the development of staircased alluvial terraces on the uplifting foothills (corresponding to the hangingwall block) and rapid alluvial sedimentation in the subsiding Llanos basin. This mechanism requires the formation of progressive unconfir-

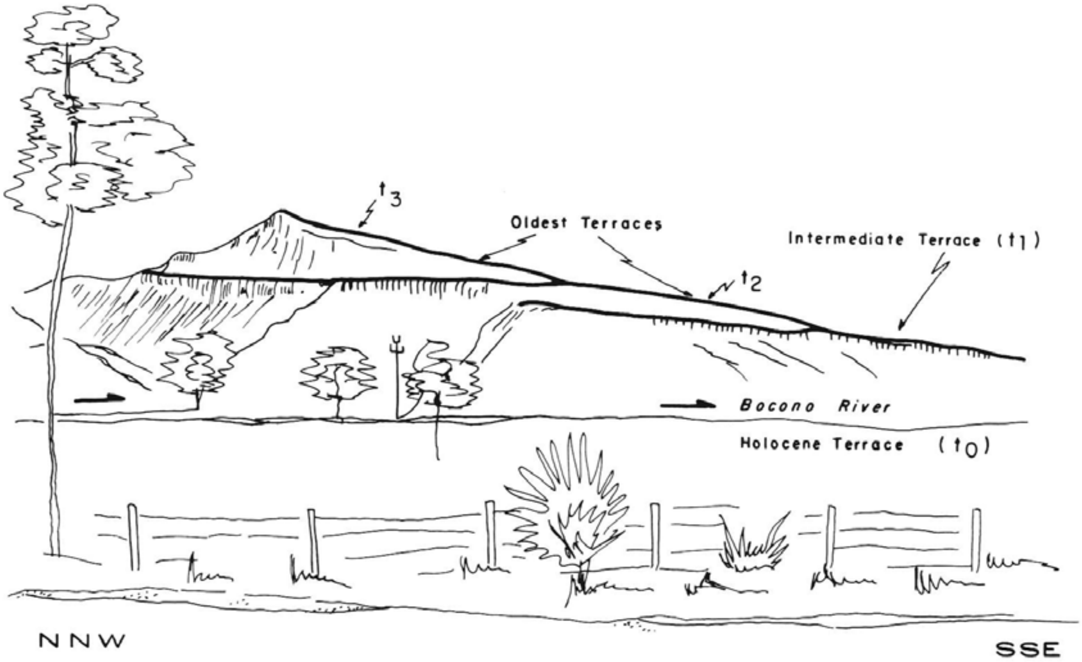

Fig. 11. Progressive tilting of the four major Quaternary alluvial terraces of the Boconó River at the Venezuelan frontal flexure at Puente Páez (after Funvisi 1997), close to Boconoíto (for relative location, refer to lower left corner of Fig. 2). Terrace relative age increases with subindex.

mities close to the flexure that are reflected in an increase of tilt of the surface of Quaternary alluvial terraces with increasing age. it can also be detected in stratigraphic dip of older underlying geological formations. Across the Venezuelan frontal South-Andean flexure, this configuration is only clearly exhibited at Puente Páez on the Boconó River (Fig. 2) where the four alluvial terraces are well exposed t_0 to t_3, Fig. 11). The development of progressive unconformities is also common in the fold limbs.

(14) *"Broom-shaped" river patterns.* At the external edge of these foothills and within the Llanos basin, it is common to observe several rivers, that leave the foothills unit in an orthogonal manner, gather in a bigger single river downstream, showing a "broom-shaped" pattern. This pattern reflects sagging close to the foothills edge owing to tectonic loading of the Llanos basin due to foreland-vergent thrusting. This type of feature may be associated with any main thrust of the fold-and-thrust belt that is capable of either down-loading its footwall compartment or counter-tilting the hanginwall block (formation of piggy-back basins may be then induced). This pattern has been observed both in Colombia (Figs. 4 and 8) and Venezuela (Fig. 12), although the Venezuelan Llanos foothills do not develop this pattern because there is no exposed basinward-vergent thrust associated with the frontal South-Andean flexure (Fig. 7b). The Venezuelan example shown in Fig. 12 corresponds to a short part of the Coast Range front of northwestern Venezuela, west of San Carlos (upper left corner of Fig. 12). In the rainy season, this area is subject to flooding. In this case, if ground surface tilting had been more important, the observed feature would have corresponded to dam rivers instead of "broom-shaped" pattern. Up to now, there has been no way of elucidating the mechanism responsible for

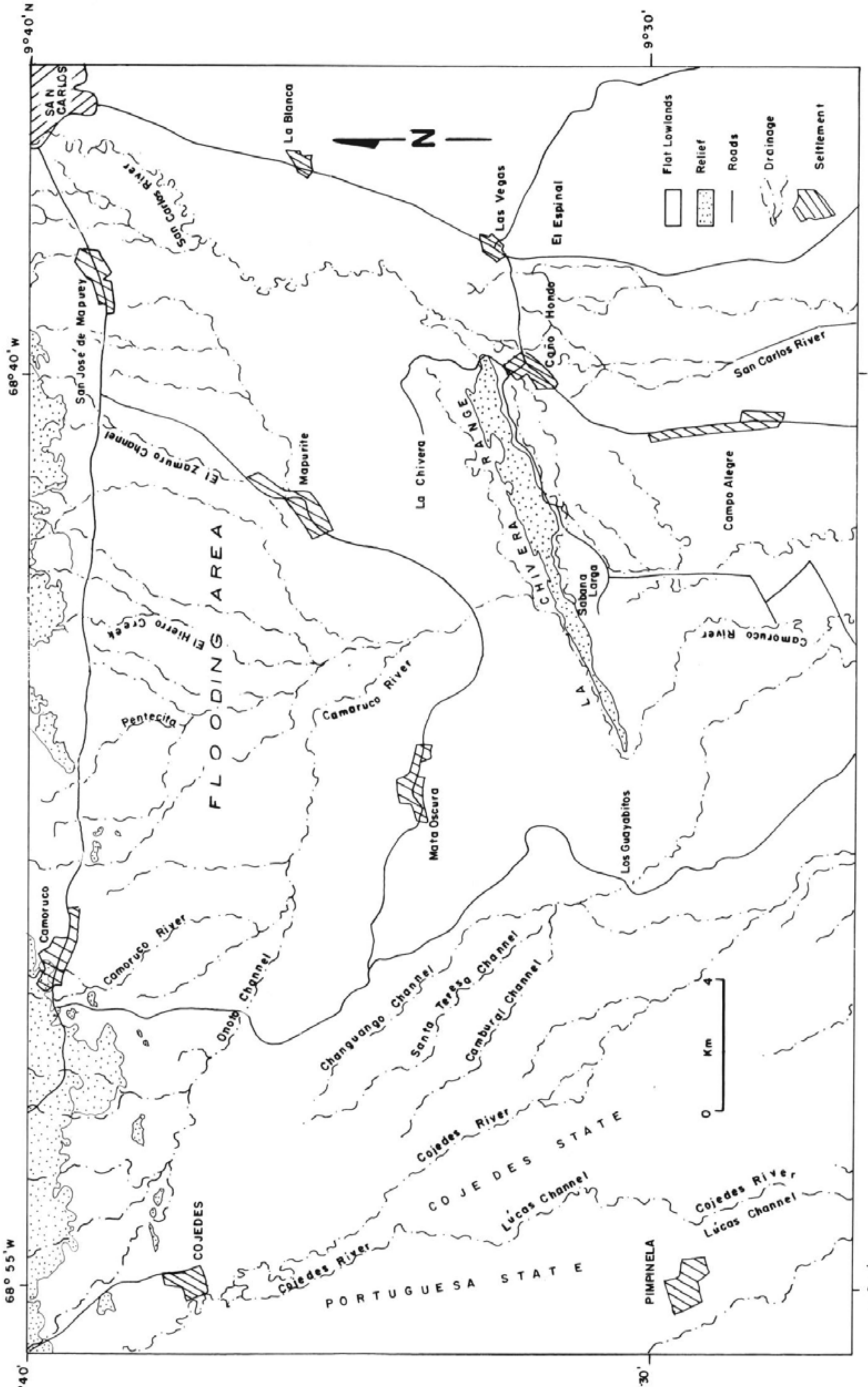

Fig. 12. "Broom-shaped" river pattern associated with the frontal thrust sheets of the Coast Range of northern Venezuela, west of San Carlos (capital of Cojedes State). Also notice the associated area of flooding.

the formation of such a pattern since we have had no access to the seismic data. It could be associated to either tectonic loading of an inner thrust sheet, counter-tilting of the outermost thrust sheet or a combination of both mechanisms. Nevertheless, the existence of this feature actually demands the re-evaluation of the frontal area of the Coast Range because it has been commonly considered to be a tectonically inactive region.

Conclusions

The most conspicuous and persistent surface evidence of ongoing compressional shortening in these foothills areas is the formation of a frontal flexural scarp that can be followed laterally for over few hundreds of kilometers. However, the assessment of drainage patterns and anomalies is a more powerful tool in the recognition of either vertical motion or warping produced by thrust faults due to both its high sensitivity to vertical perturbations of ground surface and its high frequency of occurrence along these tectonically active areas.

All rivers do not reflect vertical perturbations introduced by active underlying structures in these foothill areas. If rivers happen to be wide and highly erosive, they simply flow across hidden structures most of the times (they are very rarely affected; the Cusiana and Túa rivers in Colombia seem to be exceptions to the rule). Conversely, smaller rivers and ephemeral channels are much more perturbed and they record much better any deformation occurring in the active fold-and-thrust belt. In other words, those rivers whose erosion rates are slower than the vertical tectonic rates are able to record any ongoing deformation and they definitely confirm the current tectonic activity of a given structure or region.

Before making conclusions regarding the activity of a certain structure, we recommend that investigators analyze thoroughly the associated drainage patterns and determine as many anomalies as possible. Such persistent and consistent drainage anomalies should help to elucidate the present activity and the recent tectonic evolution of an active structure or an entire fold-and-thrust belt.

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