Steeply Dipping Basement Faults and Associated Structures of the Santander Massif, Eastern Cordillera, Colombian Andes

ANDREAS KAMMER

Departamento de Geociencias, Universidad Nacional de Colombia, Apartado 14490, Bogotá, Colombia

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RESUMEN

El Macizo de Santander expone ampliamente el basamento andino "viejo" y está limitado hacia sus cuencas de "antepais" por fallas inversas mayores. Fallas más internas, aunque con buzamientos fuertes, pueden clasificarse como fallas normales que hundieron la cobertera sedimentaria a lo largo de semi - grábenes. El patrón de estas fallas está heredado en gran medida a partir de una tectónica jurásica de extensión. La tectónica extensiva Neógena puede integrarse a un modelo de levantamiento vertical, que por el arreglo en abanico de sus fallas indujo un componente de dilatación lateral. Este modelo está modificado para un estrecho antiforme fallado, el alto de Málaga, en donde el espacio limitado no permitió el hundimiento de su parte central, pero en donde el ajuste del bloque colgante a las fallas inversas divergentes se hizo por el colapso de sinclinales marginales.

ABSTRACT

The Santander Massif is a broad basement uplift, limited on both flanks by two major reverse faults. More internal faults, however, though very steeply dipping, are normal faults and limit sedimentary half - grabens. Much of the Neogene fault pattern is inherited from a Jurassic extensional event. The Neogene extensional deformation regime of the massif's internal parts is accounted for by a vertical uplift with an outward directed spread component, due to the fan array of its faults. This model is modified for a narrow, elongated uplift at Malaga, where the space problems created by the heave of a rock volume above downward curved faults have been overcome by the collapse of marginal synclines.

KURZFASSUNG

Das Santandermassif besteht aus einer weitläufigen Aufwölbung des andinen Grundgebirges und wird gegen seine Vorlandbecken durch steilfallende Aufschiebungen abgetrennt. An Brüchen des Massifinnern haben sich dagegen Abschiebungen vollzogen, an denen Relikte des Sedimentmantels eingekeilt wurden und sich Halbgräben bildeten. Das Bruchmuster wurde weitgehend von einer jurassischen Dehnungstektonik ererbt. Die Neogenen Abschiebungen können einer vertikalen Hebungstektonik zugeordnet werden, bei der, bedingt durch die fächerartige Anordnung der Brüche, zentrale Teile der Aufwölbung des Massivs absinken mussten. Ein leicht abgeändertes Modell wird an einem schmalen, kompressiven Grundgebirgshorst erprobt, wo, während der Hebung Randbereiche direkt über den inversen Brüchen einbrachen und sich charakteristische Synklinalen bildeten.

1. INTRODUCTION

Section modelling of the Eastern Cordillera has become increasingly popular in the past years and different attempts have been made to reconcile modern thin - skinned concepts with the well established basement involved structures, as described by Julivert (1970). Difficulties which have to be overcome when interpreting the geometry and kinematic evolution of the Eastern Cordillera concern its doubly vergent structure which rules out stacking by a simple forward breaking thrust sequence; the recognition of old Jurassic normal faults which, where inverted, supposedly give rise to high angle faults; the differentiation between anticlinal stacks and simple basement uplifts; the question of how to consume excess lengths of basement, if thin - skinned thrusting is assumed and finally, along strike integration of geologic data which may involve sudden changes in fold or fault vergence, fault displacement, etc.

With these uncertainties, restoration may become highly interpretative and gives at best guesses of possible orogenic shortening values. Things turn worse, if one recognizes that much of the Cordillera's internal deformations clearly implies horizontal extensions.

In this report the basement involved tectonics of the southern Santander Massif are analyzed. Emphasis will be put on faulted uplifts; unfaulted, basement cored structures will be treated in a later analysis. Vertical uplift models will be examined which may imply a zero orogenic shortening and represent an alternative to the thin - or thick - skinned scenarios which require as much as 150 km lateral shortening

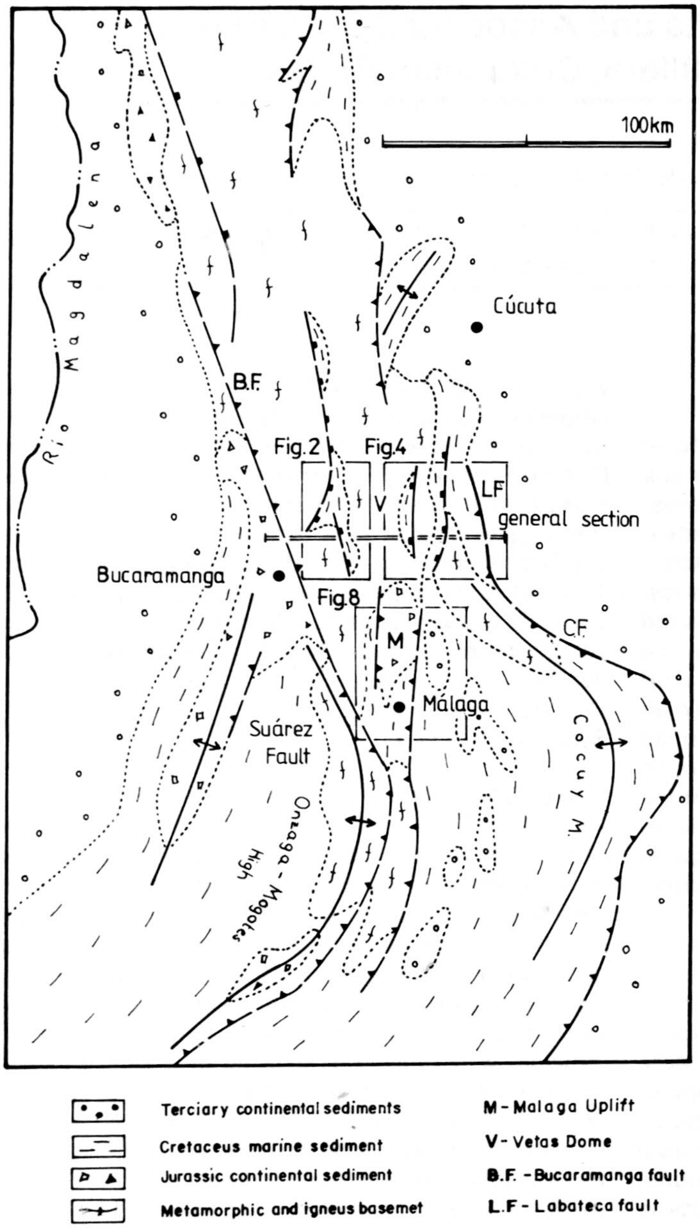

Fig. 1. Map for locations of the southern Santander Massif and southerly more tectonic units.- V: Vetas high; M: Málaga uplift; B.F.: Bucaramanga fault; L.F.: Labateca fault; C.F.: Chucarima fault.

(Dengo & Covey, 1992; Colletta *et al.*, 1990).

2. GEOLOGIC SETTING

The southern Santander Massif exposes for its most part "old" (Precambrian ?) metamorphic basement and igneous, acid to intermediate intrusive rocks, whose emplacements record Caledonian to Jurassic orogenic events (Forero, 1990; Boinet *et al.*, 1985; Dörr *et al.*, 1993). The structural grain of this basement is clearly outlined by elongated, sheet like plutons and trends N-S. It is somewhat oblique to the massif's NW oriented axis.

This basement is unconformably overlain by a fine grained clastic sequence, the Devonian Floresta formation which is overprinted by a yet little studied pre - Carboniferous low grade metamorphism (Ward *et al.*, 1973). In the southern Santander Massif this predominantly metapelitic sequence may be affected by an intense folding and an incipient slaty cleavage. In the Malaga area, these structures maintain a constant easterly vergence across the Neogene uplift and are, thus, clearly unrelated to Neogene faulting and folding.

This Devonian sequence is unconformably overlain by Carboniferous and Permian clastic to calcareous sediments (Villarroel & Mojica, 1987; Ward *et al.*, 1973; Carrillo, 1982). Due to pre - Cretaceous erosional events, these Paleozoic sequences are, however, restricted in their occurence.

Post - Paleozoic (?) sediments include the Bocas and the Jordan formations, the latter consisting of fine grained red beds. They are separated from the Jurassic red bed sequence of the Giron group by an angular disconformity which amounts up to 30° in the Bucaramanga plateaus (Cediel, 1968). This sequence reaches a minimum thickness of 4650 m west of Bucaramanga (Cediel, 1968, Ward *et al.*, 1973) and may be completely absent below the Cretaceous transgressive sediments. It records a rifting event which reactivated in the Maracaibo region a Triassic rift trend (Bartok, 1993) and affected from there on the area of the present Eastern Cordillera. Although a regional synthesis of these Jurassic tectonics remains to be done, in the Santander region some important points can be outlined:

1. In the southern continuation of the Bucaramanga plateaus, in the Aratoca region, an unreactivated half - graben with a downthrown western block is preserved (Julivert & Tellez, 1963). The minimum thickness of the graben's infill amounts to 800 m.

2. In the Surata valley of the western flank of the Santander Massif, a half - graben with an original down-to-the-W throw has been partially reactivated as a normal fault of opposed dip. This down-to-the-W polarity is displayed by another reactivated Jurassic fault, west of the town of Pamplona.

3. In the eastern flank of Santander Massif, two ancient faults with a down-to-the-E polarity have been identified which underwent dip reversal during Andean orogeny and were reactivated both as reverse and normal faults.

Evidence for an activity of the Jurassic faults during the Cretaceous depositional history has not been found so far. Instead, the red beds of the grabens are capped by an unconformity which affected part of and in some cases even the whole column of the Jurassic graben - fills and its underlying sediments. In extreme cases, the basal Cretaceous sediments overly the Devonian Floresta formation within eroded Jurassic half grabens. On the adjacent, originally elevated basement blocks, the Cordillera's metamorphic and igneous basement is directly succeeded by the Cretaceous sediments.

The marine Cretaceous and marine to continental Tertiary sediments are composed of alternating sandstones and shales or mudstones, giving rise to considerable competence contrasts within the Neogene structures. In the study area, lithological descriptions are given by Acosta (1960), Julivert (1960) and Ward *et al.* (1973).

As has been set out, the Neogene structural evolution has to be considered as a complex interplay of reactivated, inherited and newly generated, typically unfaulted structures. Among the ancestrary structures which influenced the Neogene orogeny, the Jurassic normal faults are of prime importance and their Neogene displacement and/or dip reversals are common features. Their Neogene displacements are established by the net separations of the Cretaceous formations, considering them as post - rift sequence (cf. Williams *et al.*, 1989).

3. GENERAL STRUCTURAL CHARACTERISTICS OF THE SANTANDER MASSIF

In its southern part, the Santander Massif is dominated by two distinct N-S trending highs, the Malaga uplift and the Vetas high (located in Fig. 1), which are set off slightly in a sinistral manner, according to the general NW strike of the massif.

The Malaga uplift (figs. 8 and 9) is a doubly faulted anticline, cored by Jurassic red beds and bordered on either side by two synclines which contain Cretaceous and Tertiary sediments. The limiting faults are the Baraya faults on its western, and the Servita fault on its eastern margin. These faults are reverse faults which converge toward the interior of this uplift, defining a fan - structure or a compressional horst at a minor scale. This structure has been treated in detail by Julivert (1960) and will be re - analyzed by serial sections based on a more accurate topographic and geological foundation.

The Vetas high (section B-B", Fig. 5) forms a somewhat elongated dome - structure which, morphologically, is well expressed by its radial drainage pattern. Structurally, it is delineated by two sedimentary synclines on its western and eastern flank and isolated remnants of Cretaceous cover, which partially embrace its southern termination.

The confining synclines of the Vetas high, the branched Matanza syncline (Fig. 2) on its western side and the more cylindrical sedimentary inlayers in the Mutiscua - Pamplona region (Fig. 4), share some common features: All these synclines are wedge shaped half - grabens and possess, with respect to the Vetas high, their stratigraphic contacts toward the massif's inner side and are fault - bounded against the massif's border (section B-B", Fig. 5). The faults consistently dip toward the massif's culmination, defining by their array a fan - structure at massif level. As their inner or hanging wall blocks are lowered, they can be classified as normal faults. Horizontal extensions have been computed using a simple domino model (Wernicke & Burchfield, 1982) and despite of their considerable vertical separations, values range only between 4% and 6%. The reasons for this moderate E-W lengthening are the steep attitudes of the faults planes, for which dips of 85° have been assumed.

Against its foreland regions, the massif is limited by major reverse faults which terminate the massif's fan structure.

TABLE 1. Criteria for the distinction between normal (N.F.) and reverse (R.F.) faults

Crit. 1: Deformations
R.F.: Deformations are extensional in hangingwall and compressional in footwall blocks.

Crit. 2: Cross sectional configuration of faulted blocks
R.F.: Initially horizontal datum planes dip toward footwall blocks. Faults are paralleled by synclines in their hanging wall blocks.
N.F.: Initially horizontal datum planes dip toward upthrown blocks. Faults may or may not be paralleled by synclines within the downthrown blocks.

Crit. 3: Longitudinal arching
R.F.: Within hanging blocks, regular arches pointing toward the foreland alternate with narrow re-entrants pointing toward the Cordillera's interior.
N.F.: Salients are irregular and found both within hangingwall and footwall blocks.

Crit. 4: Interaction of longitudinal arching
R.F.: Arches are transmitted across faulted blocks.
N.F.: Salients are mitigated within the sedimentary half-grabens.

The western border fault is the Bucaramanga fault, which from the Bucaramanga region on northward displays reverse displacements, affecting even the Plio- to Pleistocene alluvial fans of the Bucaramanga plateaus (Julivert, 1963). A discussion of this long - lived lineament is, however, beyond the scope of this report.

The eastern border of the massif is formed by the Labateca - Chucarima fault which further south ties to the Guaicaramo fault system (fig.1).

Note, that there is practically no difference in attitude between steeply inclined reverse and adjacent normal faults and it may be questioned if there exist at all reliable criteria which allow to distinguish between the two fault types. Doubtlessly, there exist controversial situations, as for example in the Surata syncline: Julivert (1970, Fig. 3), assumes the Surata fault to be a reverse fault and defines thus a secondary fan structure at the western border of the Santander Massif which clearly contrasts our interpretation (section B-B'', Fig. 5). In fact, the difference in attitude between normal and reverse faults amounts only to 10°. Considering the difficulty in determining accurately the dip of the major structures, additional criteria postulated to distinguish between the two fault types are presented as guide lines for the following descriptions (Table 1).

4. THE SURATA SYNCLINE

a) Map scale structures

By its forked structure, the Suratá syncline (Fig. 2) divides the surrounding massif into different blocks. On its eastern side, against the central Vetas dome, it is limited by a granodioritic stock, the Paramo Rico stock which characterizes itself in the contoured map of Fig. 2 by a broad salient which gives the syncline a striangulated appearence but does not affect the Surata fault (Crit. 4, Table 1). To the south, the basement block comprised between the two branches of the syncline is characterised by an axial plunge of 25° to 30°. The western one of the two southerly branches bounds an elongated basement high which individualizes itself at the massif's western border and forms, further N, a pronounced promontary west of the Abrego - Ocaña depression.

The syncline is limited and subdivided by a complex array of faults which tend to converge into a single strand north of Surata.

Direct observation of the attitudes of the faults could only be made at fault 1 (Fig. 2) where an easterly dip of 80° has been measured. Additionally, however, the plane slopes of the basement block which limit the syncline's eastern branch between the towns of Charta and Tona are very suggestive to represent an east dipping fault plane.

A more than 800 m thick sequence of red beds attributed mainly to the Jordan formation (Ward *et al.*, 1970), is limited by fault 2 (Fig. 2), south of Matanza. Red beds covering the eastern basement block are only 30 m thick in the section of the Rio Charta and hence, fault 2 represents an inverted normal fault (Julivert & Tellez, 1963) which, furthermore, is inferred to have undergone a dip reversal. The ancestrary Jurassic fault continues as fault 5 which, where crossing the eastern flank of the syncline has not been reactivated, as it does not displace the basal Cretaceous sediments of the syncline's eastern flank. East of Cachiri (just north of Fig. 2), the red bed sequence limited by fault 5 attains a thickness of more than 1200m.

Fault 3 opposes cherts of La Luna formation against shales of the Umir formation and is interpreted to form a rejoining splay of fault 2. The northerly continuation of fault 4 has been inferred by thickness considerations (assuming a maximum thickness of 1100 m for the lower Cretaceous) and extrapolated by morphological criteria.

b) Deformations

In the immediate vicinity of fault 4, in a quarry just north of the town of Charta, chert banks of La Luna formation have been disaggregated and rotated along normal faults (Crit. 1, Table 1).

In the transverse section of California, a general dip of 50° is well constrained for the basement cover interface. The lower Cretaceous sediments, represented by a monotonous sequence of alternating shales and sandstones, are however affected by an intense mesoscopic folding with a predominant westerly or downward vergence. The tight nature of some of these folds suggests that they formed above minor, bedding parallel detachments (Fig. 3).

5. THE PAMPLONA REGION

a) Map scale structures

In the Pamplona region N-S trending faults dissect the metamorphic basement into narrow elongated blocks, whose cover, where preserved, shows pronounced easterly dips. Fault splays are expressed by branched synclines. In cross - sectional view, it becomes apparent that the throws of the normal faults amount up to 4 km and that the basement - cover interface of the easterly most basement promontary attains a height, which is still comparable to the one inferred for the Vetas dome (Fig. 5).

West of Pamplona, a reactivated Jurassic fault (following segments 1a and 1c in Fig. 4) shows geometric relations which are quite similar to those found for the reactivated part of fault 2 in the Surata syncline (Fig. 2). North of Mutiscua, this fault crosses the sedimentary half - graben without notably displacing its western limb. Thereafter, however, it becomes again a reactivated boundary of a Cretaceous half - graben (fault segment 1c). In this branch, the erosion level of the ancestrary Jurassic wedge reaches down to the Floresta formation.

To the very south of the map shown in Fig. 4, fault segment 1a changes abruptly its trend and forms an oblique ramp with respect to the sedimentary wedge, quite similar to fault 2 south of Matanza of the Surata syncline (Fig. 2).

Further structural features refer to irregular salients in the down- or upthrown blocks wich are not transmitted across the sedimentary wedges (Crit. 4, Table 1). Such a broad arched salient is outlined by fault 1a and possibly owes its

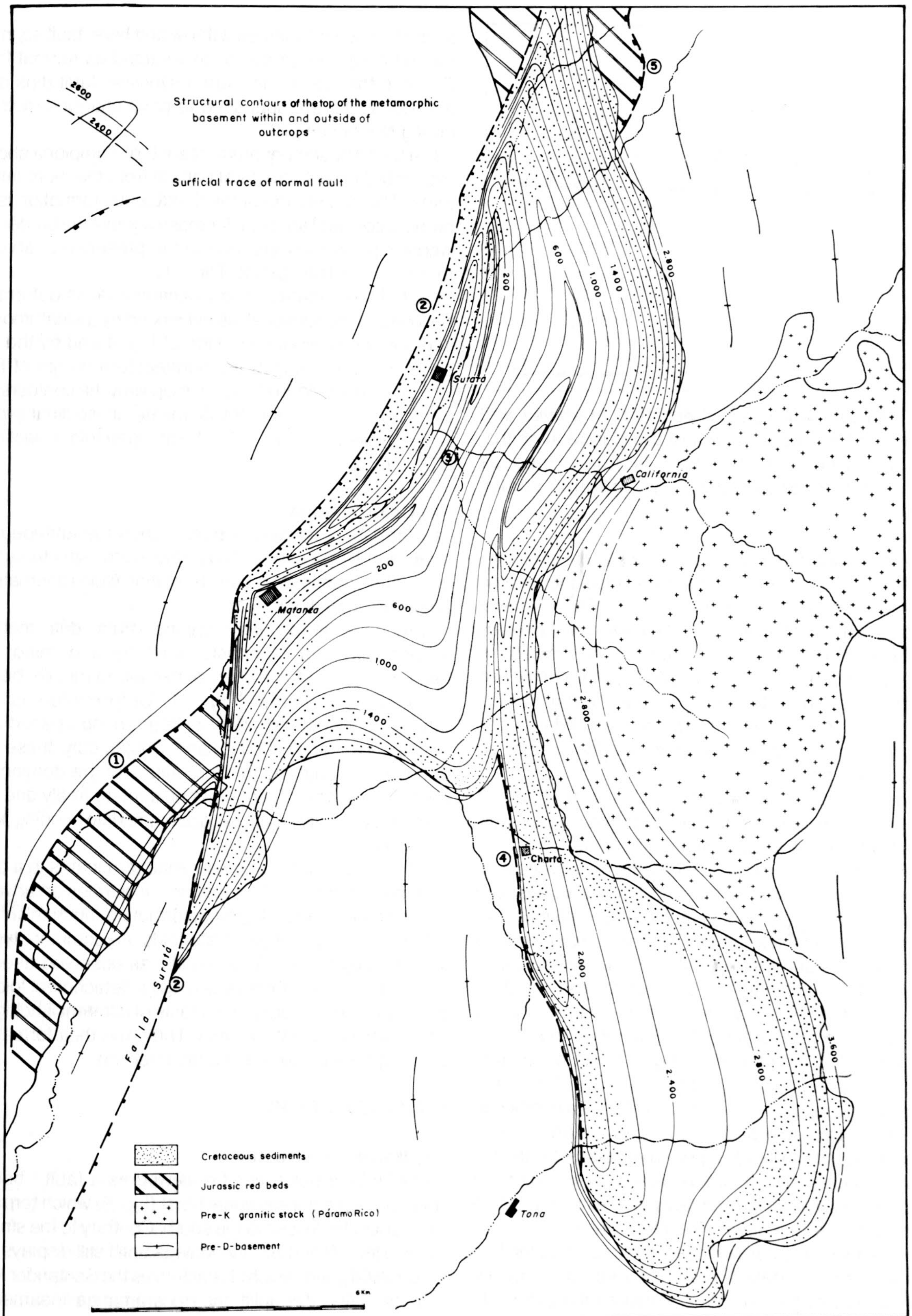

Fig. 2. Map of the Suratá syncline. The base of the Cretaceous has been contoured at intervals of 200 m in the central and eastern part. In the western branch, contour intervals indicate base of the Jurassic red beds. Sources: Maps 1:100.000 H12 and H13 (Ingeominas, 1977) and proper mapping and photogeological interpretation.

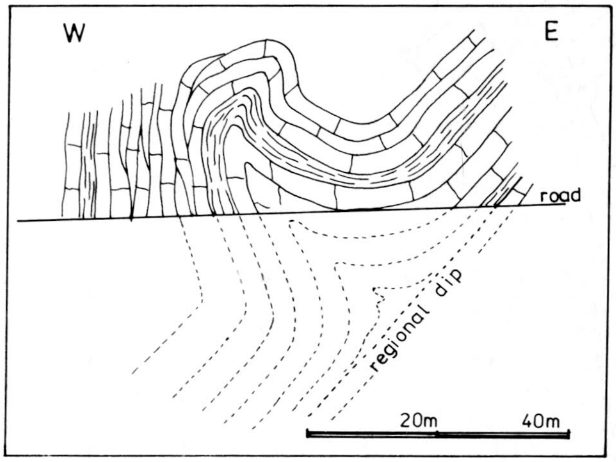

Fig. 3. Tight fold within an alternation of shales and sandstones of the eastern limb of the Surata syncline, section of California. The fold is interpreted as detachment fold above a 50° W dipping shaley intercalation.

presence to an elongated batholith to the SW of Pamplona, as was the case for the bent contour lines above the Paramo Rico stock in the Surata syncline (Fig. 2). Other smaller salients are located at the very site of the town of Pamplona and to the west of the town of Cacota. The first one is mitigated within the lower Cretaceous by its steepened strata which crop out in the canyon of the Rio Pamplonita, just east of Pamplona. Evidence for the second one has been found by constructing contour lines at the base of the Aguardiente formation.

A fault dip has been observed for fault 3 in cliffs of heights of more than 400m above the Chitaga canyon, again west of the town of Cacota. It approaches 85° west.

In the eastern part of the map of Fig. 4, the massif's eastern most promontary is subdivided and limited against the Toledo syncline by NW trending faults. At a regional scale, faults 4 and 5 link to the south of Fig. 4, at a major bend of the Toledo syncline and continue further SE as the Chucarima fault (map 1:100'000, sheet no.122, Ingeominas, 1982).

The peculiar NW trends of these faults contrasts clearly with the N-S structural grain of the Pamplona region and may be related to directional changes of the ancestrary Jurassic normal faults. These faults (fault 4 in Fig. 4 and possibly the Chitaga fault to the south of the area comprised by Fig. 4) bound red bed sequences of anomalous thicknesses (approx. 300 m), upper Paleozoic rocks and the Floresta formation on their eastern side against metamorphic basement and Cretaceous sediments on their western side and display therefore a down - to - the E polarity.

A further particular feature of these faults refers to the fact that they accommodated both reverse and normal displacements along strike: Where limiting the extensive basement promontary to the E of Pamplona against the Toledo syncline, they acted as reverse faults with throws of up to 3 km. Where penetrating this same basement high, due to their constant NW trend, displacement inverts its sense to a down-to-the-east throw and here, fault segments 5a and 4 are interpreted to have acted as normal faults. Observe that, as in the Surata syncline, fault dips of the Jurassic faults are supposed to have changed their dips during Neogene uplift.

The broad basement promontary E of Pamplona shows a distinctly different structural pattern from the more internal parts. The eastern dip of the Cretaceous formation is less pronounced, and tends to decrease against the border fault, where dip even inverts, due to the presence of an open, marginal syncline (Crit. 2, Table 1).

East of the Labateca and Chucarima faults deformation becomes compressional, as evidenced by a small imbricate sheet in the southeastern side of Fig. 4 and by the open second - order folds at the northeastern corner of Fig. 4 which parallel the fault trace (in map view the contours of La Luna Formation apparently delineate an isoclinal syncline which, however, turns out to be an open fold in section E'-E" of Fig. 5).

b) Deformations

Deformation critically depends upon the attitude of the strata and is best exemplified by the meso - structures found in the chert banks of La Luna formation which alternate with shaley intercalations.

In moderately to gently dipping strata, deformation is extensional and manifests itself by a domino - like disaggregation of the chert banks along initially bedding perpendicular joints (Fig. 6). Deformation is quite inhomogeneous and often initiated along spaced shear zones at high angles to bedding. Supposedly, these shear zones propitiated the initial rotations of the domino - like chert pieces which thereafter could rotate freely due to the surrounding shaley matrix and acommodate bedding parallel extensions.

In Fig. 6, a distributed shear zone terminates in a diffuse extensional domain. This example illustrates an advanced stage of the above inferred deformation mechanism.

Within steeply inclined strata folds are common, typically with angular hinges. These folds, as observed directly or deduced by their tightness, are again detachment folds and are found preferentially at contacts of different lithologies or above abnormally thick beds. They owe their formation to bedding parallel glide in the dip direction.

6. MALAGA UPLIFT

a) Map scale structures

The Malaga uplift may be viewed as a fault - bounded anticline or a compressional horst (Fig. 9) which terminates the Santander Massif to the south. Contrary to the structural units to its SW and SE, the Malaga uplift still displays the N-S structural grain, which characterizes the Santander Massif.

To the SW of this uplift, the Bucaramanga lineament cuts across the N-S trending basement units and accommodates the rise of an extensive, westerly more basement elevation, the Onzaga - Mogotes high (Fig. 1) which distinguishes itself by an arched outline and a gently dipping western

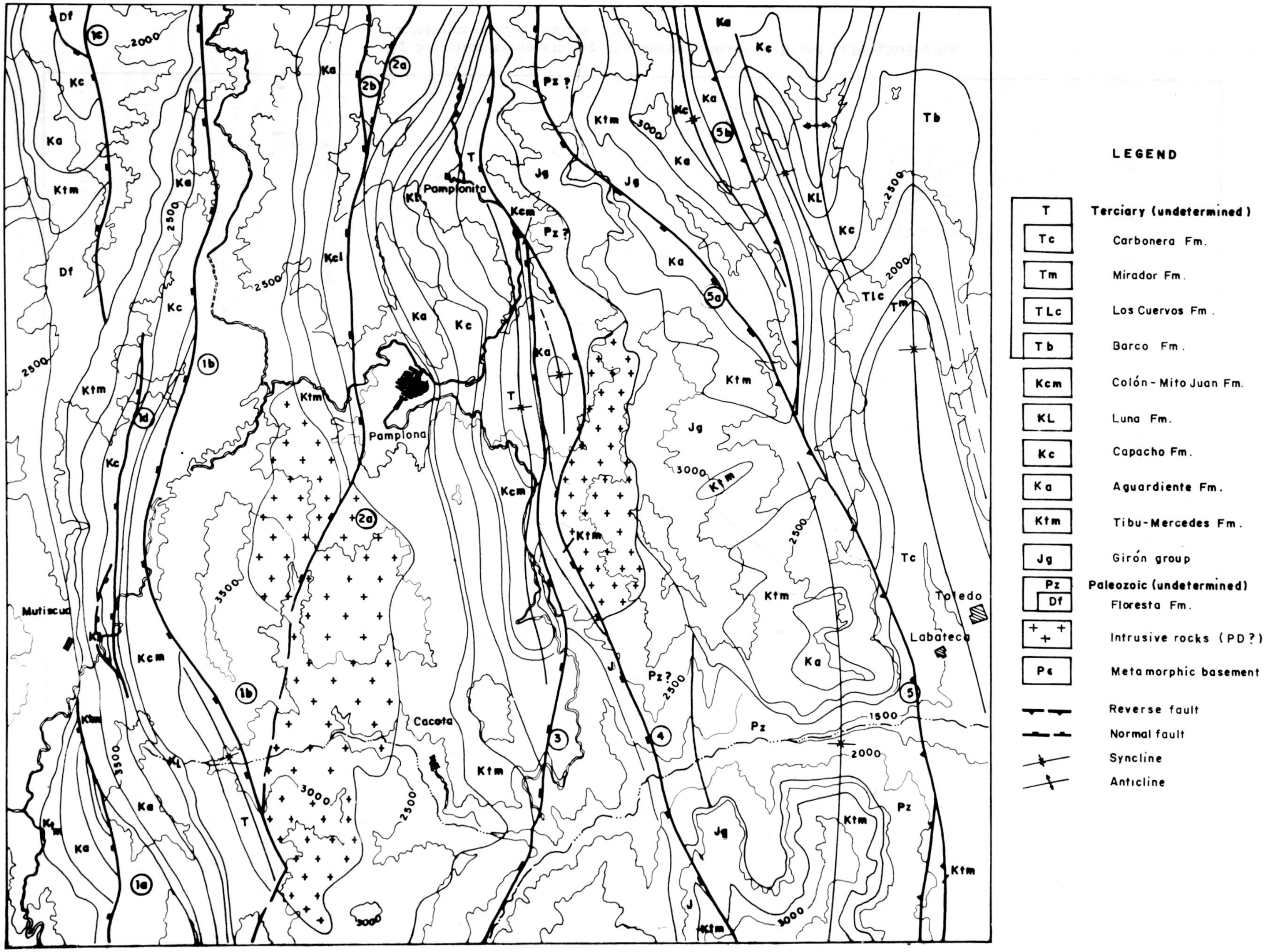

Fig. 4 Map of the Pamplona region. Sources: Maps 1: 100.000 H13 (Ingeominas, 1977) and 111 (Ingeominas, 1987) and proper photogeological interpretation.

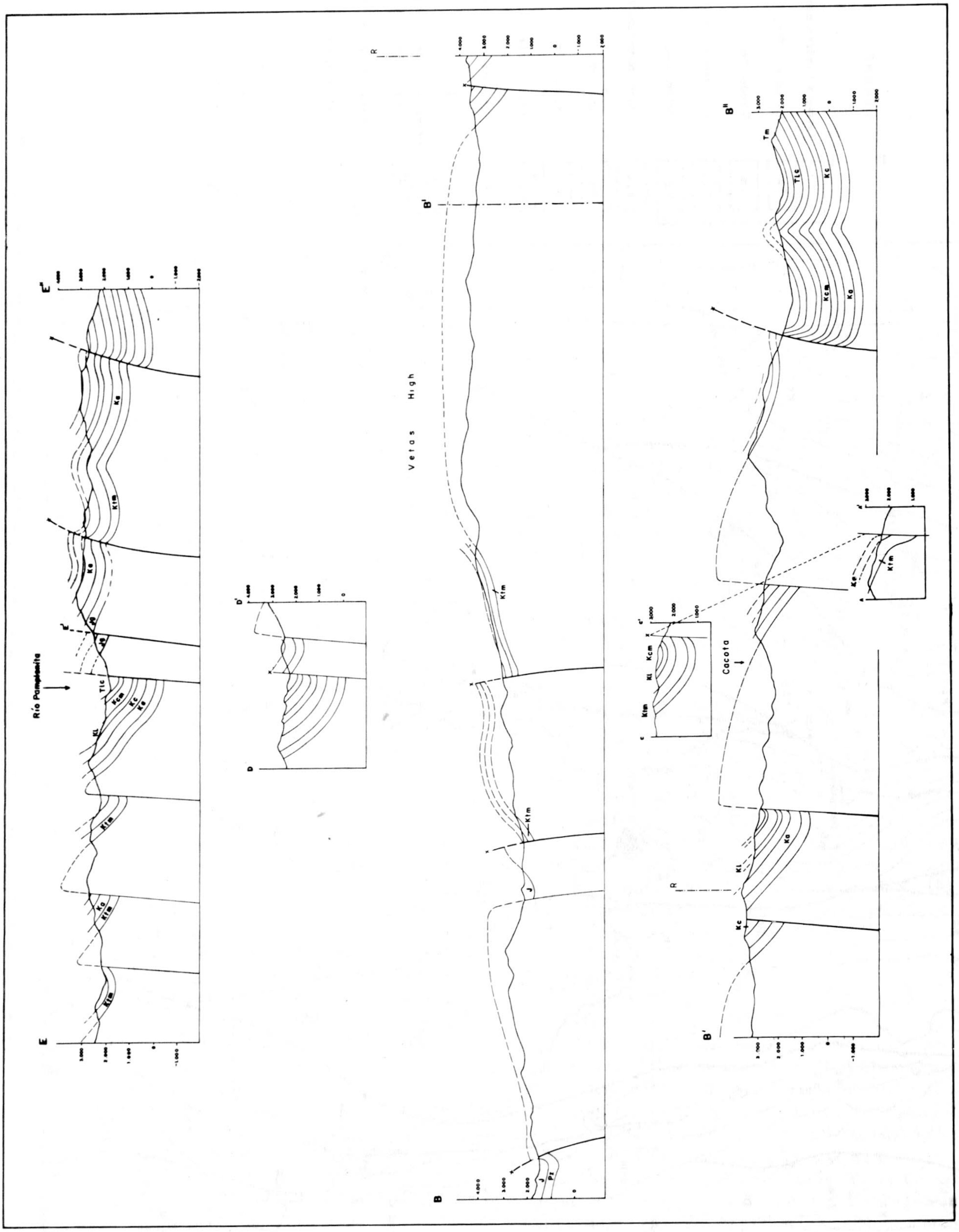

Fig. 5 Vertical sections through the Santander Massif (B-B) and the Pamplona region. For location see figs. 1 and 4.

Fig. 6. Extensional deformations in the Luna formation, road-cut Pamplona-Lejía. e: values of extension calculated by the domino model (Wernicke & Burchfield, 1982).

flank. Its folded eastern flank is bounded by the Bucaramanga fault. That is, somewhere within the Chicamocha canyon, the Bucaramanga fault inverts both dip and displacement, changing from a west vergent reverse fault in the Bucaramanga area to an east vergent one south of the Chicamocha canyon, where basement rocks of the Onzaga - Mogotes high are juxtaposed to the meta - sediments of the Floresta formation.

To the southeast of the Malaga uplift, the Chitaga fault and other related lineaments embrace the northern flank of the Cocuy massif which, as its western homologue, the Onzaga - Mogotes high, forms an asymmetric arch with a gently dipping, but this time openly folded western flank. Within the area presented in Fig. 8, this flank is composed of the Carcasi anticlinorium, a secondary basement high, cored by Carboniferous strata and the Almorzadero synclinorium further W which contains up to Tertiary units. Contrary to the Malaga uplift, these structures are not faulted and have been included in the map of Fig. 8, in order to emphasize the discontinuous structural trends of the open folds of the Carcasi anticline where they abut against the faulted Malaga uplift.

The abrupt change between the two structural trends of these highs seems to be controlled by the Servita fault at the eastern border of the Malaga uplift. This presumption is supported by the evidence that the Servita fault is a reactivated Jurassic normal fault, which contains in its hangingwall block a 500 m thick Jurassic red bed sequence. In its footwall, Jurassic red beds are supposedly absent (the Paleozoic rocks of the Carcasi anticlinorium are overlain directly by lower Cretaceous rock units). With respect to its northern continuation, represented by fault segment 1a in Fig. 4, displacement is inverted during the Neogene reactivation of the Servita fault. The two fault segments, however, count among the few ones which maintained their Jurassic dips.

Due to its northern strike, the Servita fault cuts several open folds which make up the western flank of the Carcasi anticlinorium. The cross cutting relations are especially evident between the towns of San Jose de Miranda and Malaga, where the fault strikes almost perpendicularly to the truncated syncline at its footwall. A continuation of these folds within the Malaga uplift can be discarded and therefore folding and faulting of the two highs are believed to have occurred independently and contemporaneously. An interference pattern between the two structural realms is completely missing and this absence is taken as an argument for a high angle attitude of the Servita fault.

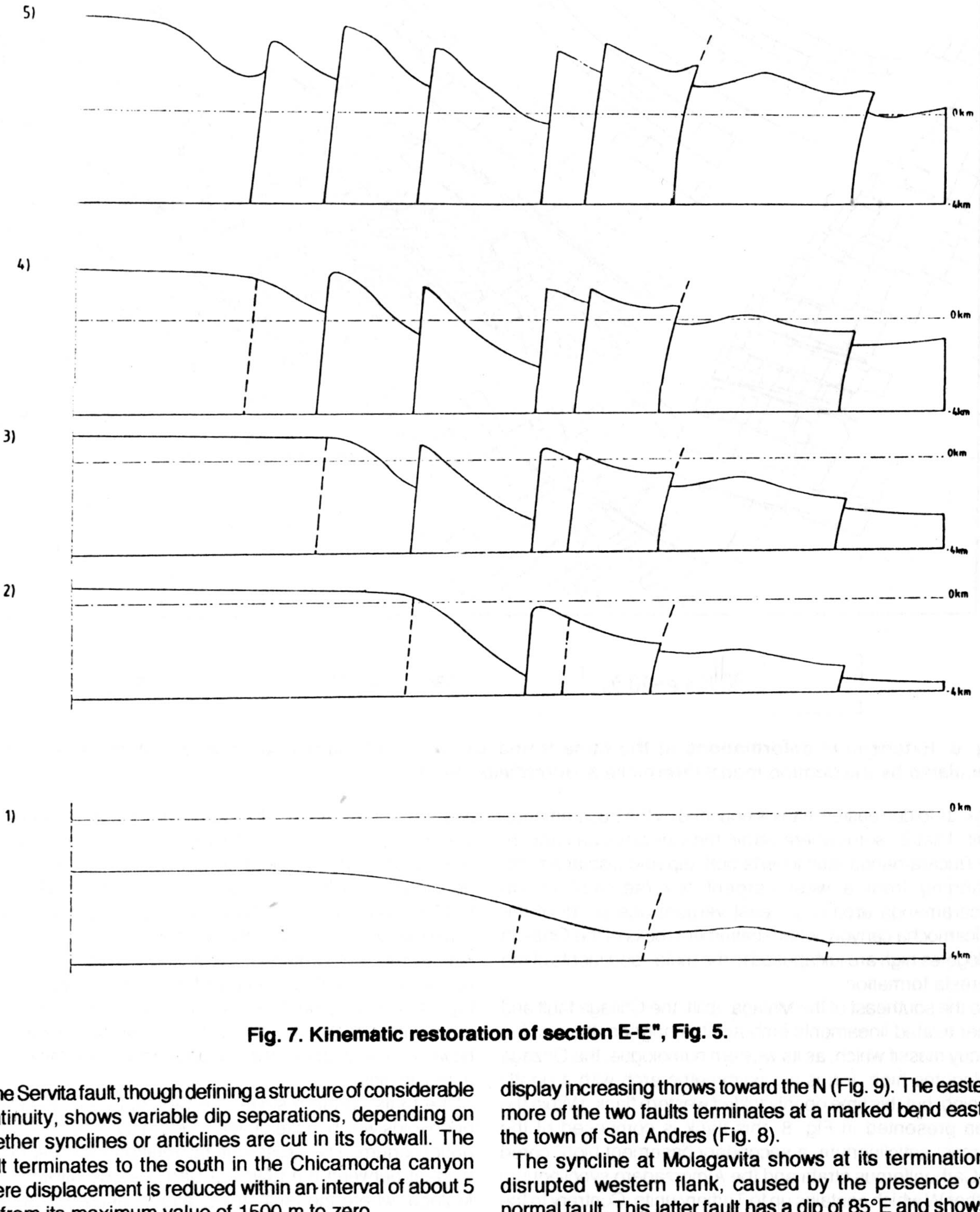

Fig. 7. Kinematic restoration of section E-E", Fig. 5.

The Servita fault, though defining a structure of considerable continuity, shows variable dip separations, depending on whether synclines or anticlines are cut in its footwall. The fault terminates to the south in the Chicamocha canyon where displacement is reduced within an interval of about 5 km from its maximum value of 1500 m to zero.

In the region depicted by Fig. 8, the Baraya faults consist of two strands which limit the Malaga uplift against the western more parts of the Santander Massif. They oppose Jurassic or lower Cretaceous rocks in their hanging wall against upper Cretaceous rocks in their footwall. They evolve near the town of Molagavita out of the eastern flank of a major syncline which borders the Malaga uplift and display increasing throws toward the N (Fig. 9). The easterly more of the two faults terminates at a marked bend east of the town of San Andres (Fig. 8).

The syncline at Molagavita shows at its termination a disrupted western flank, caused by the presence of a normal fault. This latter fault has a dip of 85°E and shows a similar attitude to the one inferred for the Baraya faults. By their parallelism these faults are not conjugate, but what will be referred to as "transcurrent" faults. Incipiently, this structure resembles the doubly faulted synclines of the Central Cordillera which divide its basement antiforms (see Kammer, "Las Fallas de Romeral y sus relaciones con la tectónica de la Cordillera Central", this volume).

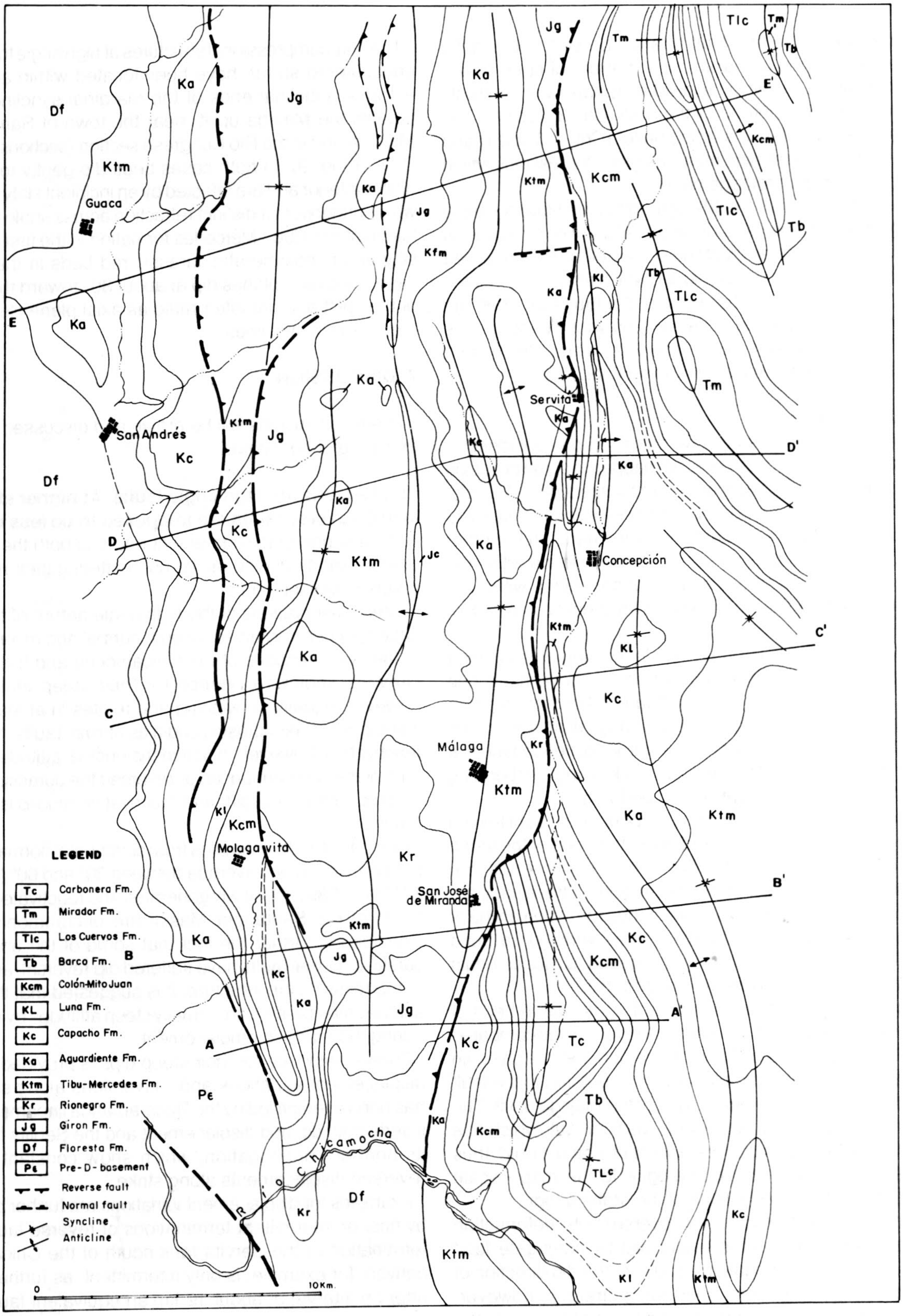

Fig. 8. Map of the Malaga region. Sources: Maps 1:100.000 H13 (Ingeominas, 1977) and 136 (Ingeominas, 1977) and proper mapping and photointerpretation.

In map view, the two fault strands prove to be slightly arched, displaying a characteristic pattern of open bends directed toward the syncline, divided by narrow re - entrants pointing toward the interior of the uplift (Crit. 3, Table1). The arches of the two faults are "in phase" (Crit. 4, Table1) and its re - entrants determine morphological depressions which configure today's drainage pattern.

The central parts of the Malaga uplift constitute a simple antiform, which exposes Jurassic and lower Cretaceous rocks. The well defined crest line of this antiform is paralleled by two marginal synclines (Fig. 8), which are closely related to the reverse faults: Where one of the faults dies out, the accompanying syncline in its hanging wall disappears as well. This point will be referred to when discussing emplacement mechanisms in the next section.

b) Deformation

The vertical sections are characterized by considerable thickness changes which could be mapped to some precision in the slopes of the Chicamocha canyon (section A-A' in Fig. 9). In this area, the steep limbs of the synclines adjacent to the Malaga uplift are conspicuously thinned. On the other hand, a locally overthickened part has been found within the shaley Capacho formation at a secondary hinge within the eastern hillside of the Molagavita valley (section A-A' in Fig. 9).

Structures which illustrate possible thinning or thickening mechanisms and which are pertinent to the above mentioned sites, are shown in Fig. 10. Fig. 10a is taken from a steep segment of the eastern limb of the Malaga uplift and shows a sand lens embedded within a shaley sequence which is sheared off at a fault. The fault forms a low angle to bedding and is extensional with respect to bedding.

The converse situation is brought about by the tight folding of in part strongly extended and disrupted beds of the same Capacho formation (Fig. 10b). The chaotic folds are reminiscent of synsedimentary slump folds. These folds are absent in the underlying Tibu - Mercedes formation and lack an equivalent in the chert beds of the overlying La Luna formation. This local thickening is believed to owe its origin to gravity - driven, downward directed glide.

Extensional deformation is present again within beds of low to intermediate dips, though less intense, when compared to the chert beds of the Pamplona region. Fig. 11 gives an example of a slightly disrupted fold encountered in the fault bounded block at the western flank of the Malaga uplift. The fold is displaced by a major sub - vertical fault which has about the attitude of the Baraya faults and could thus represent a meso - scopic analogue to the map - scale structures of the western flank of the Malaga high.

In the immediate footwall of the reverse faults, deformation may be cataclastic and is evidenced by conjugate fault zones, causing an elongation parallel to the dip direction of the faults. This horizontal shortening strain is, however, restricted to a narrow zone, as has been observed in the footwall block of the Servita fault, where an anticline adjacent to the fault displays extensional faulting at its hinge zone (section C-C' in Fig. 9).

The only compressional structures at high angle to bedding, encountered so far, have been located within and at the extreme anticlinal ends of the marginal synclines which parallel the Malaga uplift, near the town of San Jose de Miranda and in the Rio Congreso section (sections B-B' and D-D' of Fig. 9). In both cases beds dip gently toward the uplift's interior and are affected by an incipient slaty cleavage which underwent a distinct refraction across shale and sand layers of the Tibu - Mercedes formation in the first case and silty and conglomeratic Jurassic red beds in the second case. Cleavage planes dip at about 80° toward the interior of the uplift and are interpreted as axial plane cleavage of the marginal synclines.

7. DISCUSSION

Three conclusions will be drawn and discussed from the foregoing observations.

I. The faults are high angle faults. At higher structural levels, reverse faults are supposed to be less inclined.

The first part of this statement refers to both the massif's internal and bounding faults, not mattering their normal or reverse displacements.

Direct observations of the high angle nature of the faults have only been obtained for both normal and reverse faults in the deep sections of the Chicamocha and the Chitaga canyons. Indirect evidence for their steep attitudes is, however, equally convincing and relates in at least some instances to their Jurassic origin as normal faults. Neogene reactivation, however, modified the original attitude of these fault planes and enhanced or reversed the Jurassic throws. A compilation of the different reactivation modes is given in Table 2.

Compared to dip estimates from continental normal faulting earthquakes, which average between 30° and 60° (Jackson & White, 1989), the newly generated and reactivated normal faults of the Santander Massif are uncommonly steep. Considering further the fact that some of the ancestrary Jurassic normal faults have suffered dip reversal, according to the massif's fan structure, it is suggested that the faults attained their present abnormally steep attitudes by rotations during the massif's emplacement.

Further evidence for their steep dips is provided by their displacement variations and - inversions along strike, as has been exemplified by the Bucaramanga lineament which inverts both dip and displacement and the Servita fault and its northern prolongation, which show constant dip but reversed displacements along strike.

Examples for displacement variations are further provided by final or intermittent terminations of reverse faults. The termination of the Servita fault south of the Chicamocha canyon, for example, is only intermittent, as further south, after an interval of about 12 km an equivalent fault at the same structural position sets in (geologic map 1:100'000, sheet no.136, Ingeominas, 1984).

Thus, the well corroborated postulate of displacement conservation within foreland fold and thrust belts (Dahlstrom,

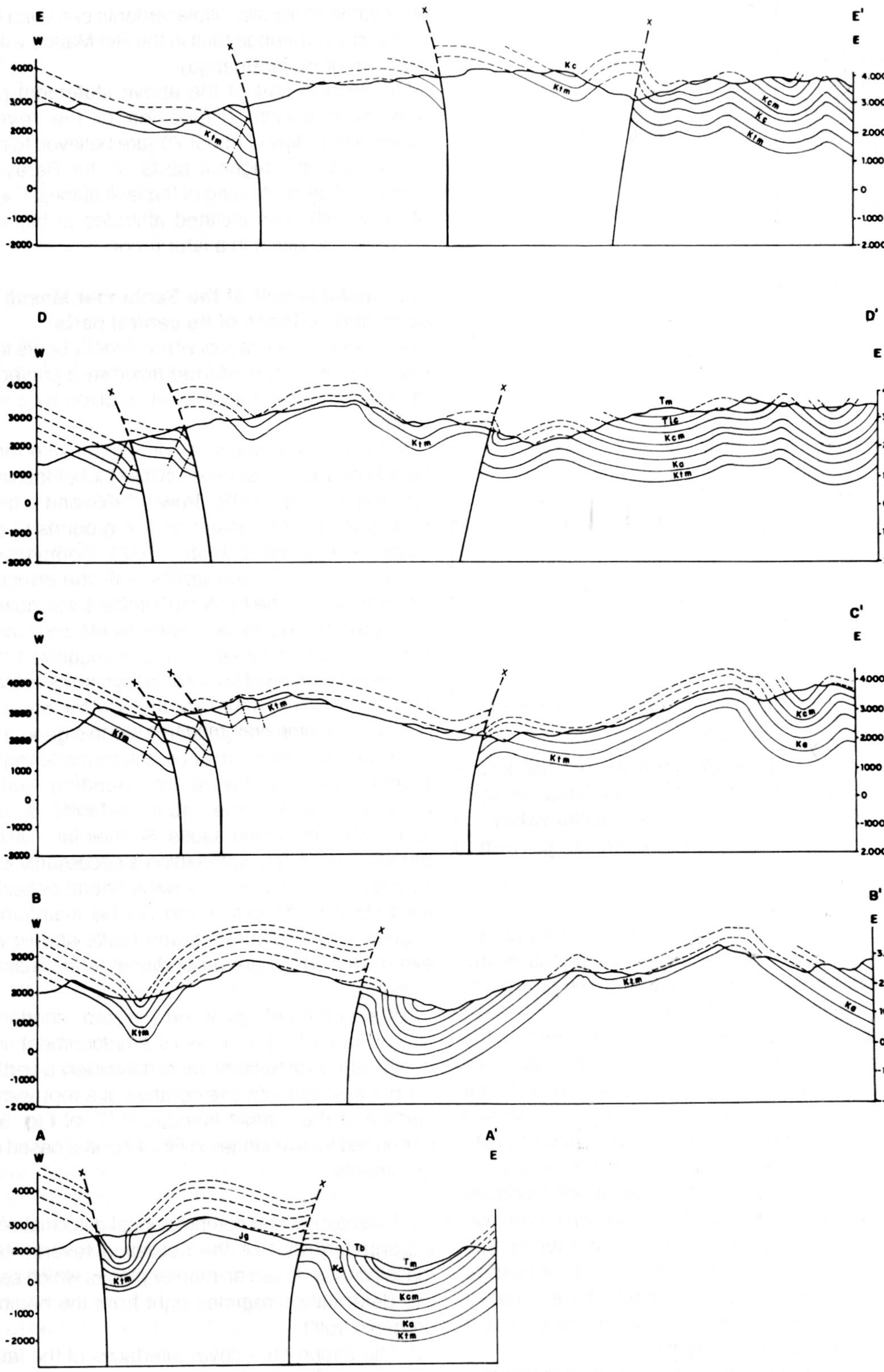

Fig. 9. Serial sections across the Malaga uplift. For location see Fig. 8.

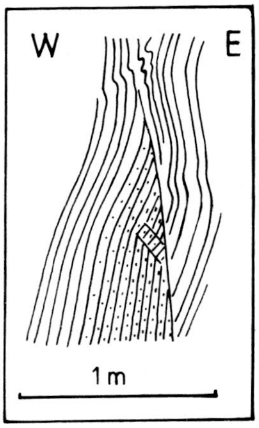

Fig. 10a

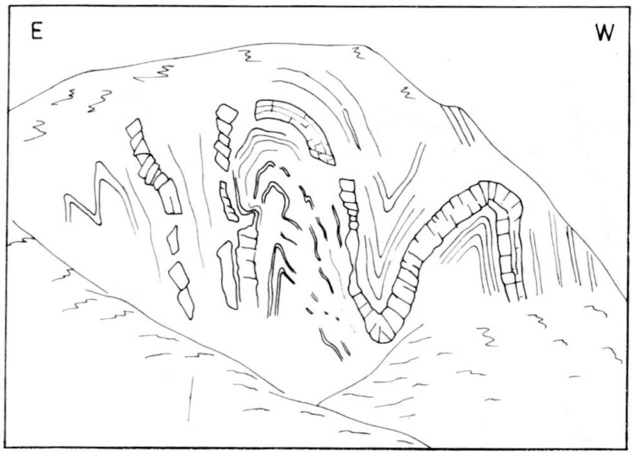

Fig. 10b

Fig. 10. Deformations which account for thickness changes of the Capacho formation. a) Sheared sand layer, south of San José de Miranda (Servita valley); b) Disrupted and folded strata, south of El Junco (Mogalavita valley).

1969), is invalidated for the internal parts of the Eastern Cordillera. Furthermore, displacement variations of the extents, as shown above, are kinematically unconsistent for moderately to little inclined fault systems.

Finally and not least importantly, we should mention the fact that high angle faults of a similar attitude may accommodate displacements of opposed senses both at a regional and at a very local scale. In analogy to positive and negative flower structures (Harding, 1985), pairs of faults which gave rise to uplifts can be assigned to a positive transcurrent shear. Conversely, fault couples which produced doubly faulted, synclinal depressions would have given rise to a negative transcurrent shear. The massif itself and its secondary faulted uplifts have been emplaced by a positive transcurrent shear. An incomplete example for a negative transcurrent shear would be represented at the southern termination of the Molagavita syncline.

The dip and displacement variations can, to our knowledge, only be reconciled by wrench tectonics or a vertical uplift model. Among these two alternatives, the first one is excluded, as strike slip displacements have not been detected in and along the borders of the Santander Massif (Mappable strike slip displacements can even be excluded for the Bucaramanga fault in the Rio Manco valley, south of the town of Bucaramanga)

The second part of the above statement postulates a downward curved disposition of the reverse faults. Intermediate dips of about 70° are believed to prevail along the structurally highest parts of the Baraya faults, as evidenced by contouring of the fault planes. Clear evidence of faults with less inclined attitudes at higher structural levels will be given in a later report.

II. Emplacement of the Santander Massif by vertical uplift and collapse of its central parts:

An emplacement model which directly bears to the steeply dipping faults, their inferred downward curved shape and their fan array at massif level, is given by a vertical uplift mechanism.

Vertical uplift models in connection with forced folding have been widely discussed in the Rocky Mountains foreland (see e.g. Stearns, 1978; Brown, 1988) and subsequently, at least partially, dismissed on the grounds of geophysical evidence (Smithson *et al.*, 1978). Comparison of these large - scale foreland uplifts with the structures of the internal parts of the Eastern Cordillera will, however, not be attempted as the tectonic environments are in many respects opposite to one another. It is rather suggested, that a key for the understanding of the internal dynamics of the Santander Massif is its fan structure and that any comparison with other mountain chains should start from this general feature.

A most straightforward approach for modelling the massif's emplacement, is taking its bounding faults, i.e. the Bucaramanga and the Labateca faults, as transcurrent reverse, or "extrusion" faults. By their fan - disposition, i.e. by their inward dips, upthrusting is necessarily accompanied by lateral extensions; otherwise lateral cohesion with the inert foreland blocks would not be maintained. In fact, slightly inward dipping, plane faults should induce bulk extensions which are proportional to the massif's vertical heave.

In the sections of figs. 9 and 5, a zero - shortening solution is advocated for the massif's emplacement, in which the downward curving faults reach ultimately a vertical attitude.

A putative kinematic restoration of a representative half - section of the massif (section E-E" of Fig. 5) has been performed for five stages in Fig. 12 and is based on two main arguments:

1. Extensional and compressional deformations are never superposed; that is, the bounding reverse faults of the massif can be taken as marker planes which separated the two deformation regimes right from the beginning of the orogenic uplift.

2. The basement - cover interfaces of the faulted blocks are steeply E - dipping. It is assumed that, prior to being affected by faulting, they formed the flank of the ancestrary Vetas dome and acquired their upwarped attitude in that

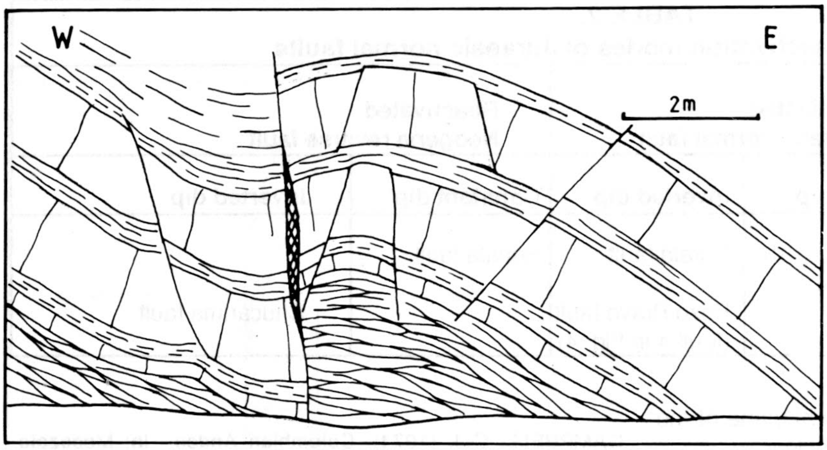

Fig. 11. Faulted fold. Rio Congreso, south of San Andres.

position.

These two criteria allow us to establish a backward breaking deformation sequence for four extensional stages (according to the 4 major normal faults) which are initially triggered near a marginal reverse fault. During each stage, a more internal fault is initiated which lowered the central Vetas dome with regard to its detached marginal blocks. This sequence could be a mirror image to an outward migrating or forward breaking, slightly compressional deformation front, east of the main bounding fault.

III. Varied model for uplifts of reduced widths:

Within minor basement highs of the dimensions of the Malaga uplift, it seems that there was not enough space available for the development of central collapse structures, as typified by the Vetas dome. Instead, faulting seems to have been relieved by the folding, which manifests itself by the synclines in the immediate hanging wall parts of the reverse faults. In what follows, it is suggested that these marginal synclines compensated the uplift's outward spread, acting as collapse structures. This idea will now be examined by a simple geometric model.

In figs. 12a and b, the geometry which results from the heave of a rigid block is compared to one which allows for an internal deformation of the upthrust block and its adjustment to the confining walls of the inert foreland block. In order to find a simple relation between the collapse structures and the shape of the confining faults, the fault traces are being analyzed in terms of circular and vertical segments.

In Fig. 12a, the area of a gap is defined which results from the heave of a rigid block above a circular fault segment, which, in Fig.12b, is subsequently closed by a partial collapse of the upthrust block. Equating the area of the intersticial gap with the one formed by the foundered hanging wall syncline, knowing the vertical heave and assuming an appropiate estimate for the surficial fault dip, it is possible to calculate the radius of the circular fault segment (Fig. 12b).

In this calculation, estimates for the surficial dips of the reverse faults have to be constrained by field experience. Theoretically, they could be derived from the hangingwall strata immediately above the fault plane, if a rigid body rotation is assumed for that part of the upthrust block (Erslev, 1986). This approach has, however, not been followed, due to the paucity of reliable dip data in the vicinity of the faults.

When calculating the fault shapes for various surficial dip angles, it turns out furthermore, that the fault shape is not critically dependent upon a particular angle, as the circular segments which correspond to constant heaves and collapsed areas, join at a same vertical line (Fig. 12c).

This method has served as a guide in estimating the shapes of the reverse faults in figs. 5 and 9. A comparison of similar structures of other basement highs and a more thorough discussion of the application and limitation of this method will be given in a special report.

8. CONCLUDING REMARKS

The advocated model relies upon a perhaps unusual supposition, a zero - shortening emplacement of the Santander Massif. In this model, uplift is exclusively related to mass additions at the roots of the mountain range at an undeterminate lower crustal level. Besides the geometrical properties, dealt with in this paper, this model should clearly be corroborated by other evidence, like gravity anomalies, elevated geothermal gradients and a fixed reference frame with respect to older structures, to name just a few criteria. So far, the steeply dipping faults and the extensional deformation justify this hypothesis most accurately. Extensions could, however, not be quantified sufficiently in coherent sections to obtain an independent constraint for the massif's geometric evolution. Works in regions of better exposure and easier access are being extended to pursue this question.

A compressional emplacement model could easily account for the massif's fan structure and more specifically, for the dip reversals of the Jurassic normal faults. Pop - up structures above lower crustal detachments, as modeled by Malavielle (1984) and discussed by Butler (1989; cf. his fig. 1), would easily explain rotations of these marker planes. In the proposed model, rotations can be called for by a) curved movement paths of the rising basement blocks according to the downward curved faults and b) increasing uplift rates from external to internal parts which would establish a vertical shear gradient across a half-section of the massif.

An apparently contradicting (at least not predicted) feature of the proposed model, is the presence of the incipient cleavage found in the anticlinal terminations at the external parts of the

TABLE 2.
Examples of reactivation modes of Jurassic normal faults

Polarity of original Jurassic normal fault	Reactivated Neogene normal fault		Reactivated Neogene reverse fault	
	Constant dip	Inverted dip	Constant dip	Inverted dip
Down-to-the-W polarity	Faults 1a and 1b (Fig. 4)	Surata fault	Servita fault	
Down-to-the-E polarity	-	Pozo Bravo fault (fault 4 in Fig. 4)	-	Chucarima fault

marginal synclines which parallels the axial plane of the synclines and whose significance is still unclear.

Mesoscopic folding of incompetent or distinctly layered rock units, which is found in the otherwise little folded half-grabens is, if tight, related to minor detachments at lithological changes and seems to have originated by local gravity-driven gliding, as it is restricted to moderate to steeply inclined strata. Buckle folds indicative of a compressional deformation regime have not been identified.

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REFERENCES

ACOSTA, C.E. (1960): Estratigrafía de García Rovira.- Bol. Geol. Univ. Industrial de Santander, no.5, 33-40, Bucaramanga.

BARTOK, P. (1993): Pre - breakup geology of the Gulf of Mexico - Caribbean: its relation to Triassic and Jurassic rift systems of the region.- Abstract AAPG/SVG Intern. Congress and Exhibition, Caracas.

BROWN, W.G. (1988): Basement involved tectonics, foreland areas.- AAPG Continuing Education Course Note Series no.26, 92p., Tulsa.

BOINET, Th., BOURGOIS, J., BELLON, H. & TOUSSAINT, J.F. (1985): Age et métamorphisme du magmatisme Prémésozoïque des Andes de Colombie.- C.R. Acad. Sc. Paris, t. 300 Série II, no.10, 445-450.

BROWN, W.G. (1988): Basement involved tectonics, foreland ares.- Continuing Education Course Note Series 26, AAPG, Tulsa, 92p.

BUTLER, R. W. H. (1989): The influence of pre - existing basin structure on thrust system evolution in the Western Alps.- In: Cooper, M.A. & Williams, G.D. (eds), Inversion Tectonics, Geol. Soc. Spec. Publ. 44, London, 105-122.

CAMPBELL, C.J. (1974): Colombian Andes.- In: Mesozoic-Cenozoic Orogenic Belts, Geol. Soc. London Spec. Publ.4, 705-725.

CARRILLO L.,V. (1982): La quebrada Confines, una nueva localidad fosilífera del Palezoico superior en la Cordillera Oriental de Colombia.- Geología Norandina 1982, 34-38, Bogotá.

CEDIEL, F. (1968): El Grupo Girón, una molasa mesozoica de la Cordillera Oriental.- Bol. Geológico XVI, 5-96, Ingeominas, Bogotá.

COLLETTA, B., HEBRARD, F., LETOUZEY, J., WERNER, P., RUDKIEWICZ, J.-L. (1990): Tectonic style and crustal structure of the Eastern Cordillera (Colombia) from a balanced cross - section.- In: Letouzey, J. (ed.), Petroleum and Tectonics in Mobile Belts, Ed. Technips, Paris, 81-100.

DAHLSTROM, D.C.A. (1969): Balanced cross sections.- Canad. J. Earth Sci. 6, 743-757.

DENGO, C.A. & COVEY, M.C. (1991): Structure of the Eastern Cordillera of Colombia: A tectonic model of the Colombian Andes.- Abstract in: IV Simposio Bolivariano sobre la exploración petrolera en las Cuencas Subandinas, Bogota, march 1991.

DÖRR, W., GRÖSSER, J., RODRIGUEZ, G. & KRAMM, U. (1993): Edad de la intrusión de la granodiorita-tonalita de Páramo Rico, Macizo de Santander (Cordillera Oriental) y su significado geotectónico.- Resúmenes VI Congreso Colombiano de Geología, p. 153, Univ. EAFIT, Medellín.

ERSLEV, E.A.(1986): Basement balancing of Rocky Mountain foreland uplifts.- Geology 14, 259-262.

FORERO S., A. (1990): The basement of the Eastern Cordillera, Colombia: An allochthonous terrane in northwestern South America.- J. South Am. Earth Sci. 3,141-151.

HARDING, T. P. (1985): Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion.- Bulletin AAPG 69, 582-600.

JACKSON, J.A. & WHITE, N.J. (1989): Normal faulting in the upper continental crust: observations from regions of active extension.- J. Struct. Geology 11, no.1/2, 15-36.

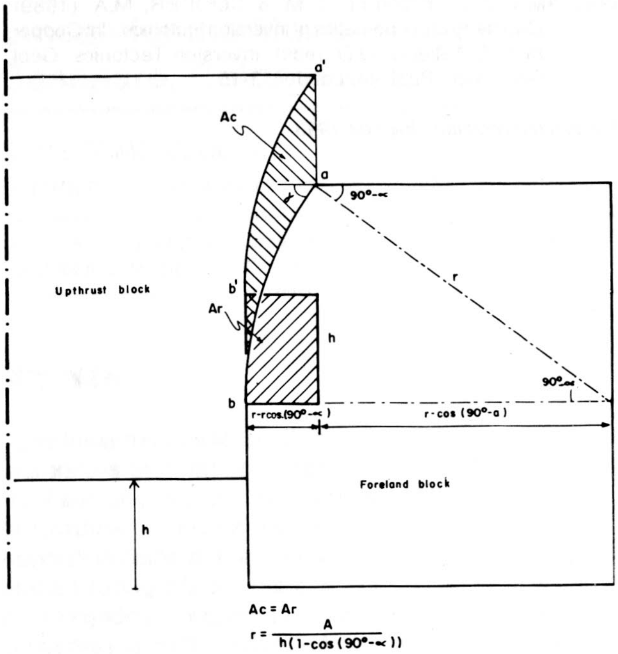

Fig. 12a

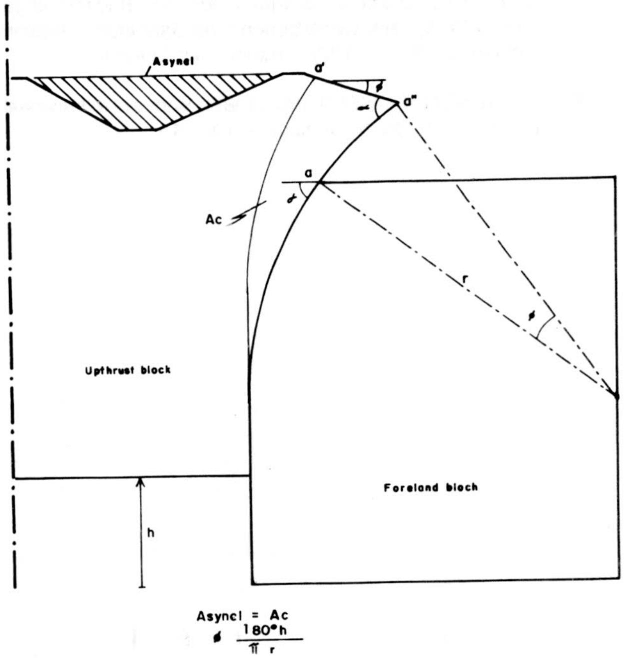

Fig. 12b

Fig. 12. Uplift model applied to narrow basement highs.

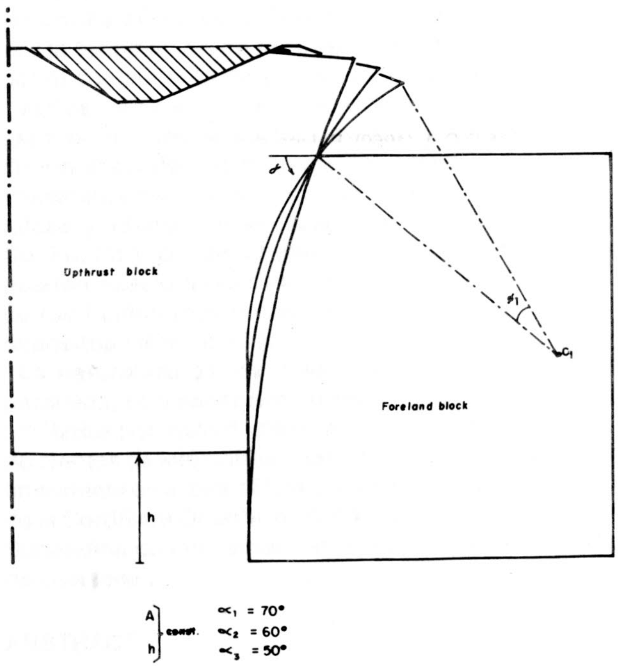

Fig. 12c

JULIVERT, M. (1960): Geología de la región occidental de García Rovira (Cordillera Oriental, Colombia).- Bol. Geol. Univ. Industrial de Santander, no.5, 5-32, Bucaramanga.

JULIVERT, M. (1963): Nuevas observaciones sobre la estratigrafía y tectónica del Cuaternario de los alrededores de Bucaramanga.- Bol. Geol. Univ. Industrial de Santander, no.15, 41-59, Bucaramanga.

JULIVERT, M. (1970): Cover and basement tectonics in the Cordillera Oriental of Colombia, South America, and a comparison with some other folded chains.- Geol. Soc. Am. Bull. 81, 3623-3646.

JULIVERT, M. & TELLEZ, N. (1963): Sobre la presencia de fallas de edad pre-Cretácea y post-Girón (Jura-Triásico) en el flanco W del Macizo de Santander (Cordillera Oriental, Colombia).- Bol. Geol. Univ. Industrial de Santander, no.12, 5-17, Bucaramanga.

MALAVIELLE, J. (1984): Modélisation expérimentale des chevauchements imbriquées: application aux chaînes de montagnes.- Bull. Soc. Géol. France 7, XXVI/1, 129-138.

SMITHSON, S.B., BREWER, J., KAUFMAN, S., OLIVER, J. & HURICH, C. (1978): Nature of the Wind River Thrust, Wyoming, from COCORP deep reflection data and gravity data.- Geology 6/11, 648-652.

STEARNS, D.W., (1978): Faulting and folding in the Rocky Mountains foreland.- In: V.Matthews,III (ed.), Laramide folding associated with basement block faulting in the western U.S., Mem. Geol. Soc. of America 151.

VILLARROEL, C.& MOJICA, J. (1987): El Paleozoico Superior (Carbonífero-Pérmico) sedimentario de Colombia. Afloramientos conocidos y características generales.- Geología Colombiana 16, 81-87, Universidad Nacional, Bogotá.

WARD, D.E., GOLDSMITH, R., CRUZ B., J. & RESTREPO, H.

(1973): Geologia de los cuadrangulos H-12 Bucaramanga y H-13 Pamplona, Departamento de Santander.- Boletin Geologico XXI/1-3, 132p., Ingeominas, Bogota.

WERNICKE, B. & BURCHFIELD, B.C. (1982): Modes of extensional tectonics.- J. Struct. Geology 4, 105-115.

WILLIAMS, G.D., POWELL, C.M. & COOPER, M.A. (1989): Geometry and kinematics of inversion tectonics.- In: Cooper, M.A. & Williams, G.D. (eds), Inversion Tectonics, Geol. Soc. Spec. Publ. 44, London, 3-15.

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