Cenozoic contractional reactivation of Mesozoic extensional structures in the Eastern Cordillera of Colombia

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[1] The Eastern Cordillera of Colombia is key to understanding the role of inherited basement anisotropies in the evolution of active noncollisional mountain belts. In particular, the Rio Blanco–Guatiquí region of the Eastern Cordillera is exemplary in displaying a variety of phenomena that document the importance of the orientation, geometry, and segmentation of preorogenic anisotropies. We document the first unambiguous evidence that extensional basement structures played an important role in determining the locus of deformation during contractional reactivation in the Eastern Cordillera. Detailed structural field mapping and analysis of industry seismic reflection profiles have helped to identify the inherited San Juanito, Naranjal, and Servitá normal faults and associated transfer faults as important structures that were inverted during the Cenozoic Andean orogeny. Apparently, the more internal faults in the former rift basin were not properly oriented for an efficient reactivation in contraction. However, these faults have a fundamental role as strain risers, as folding is concentrated west of them. In contrast, reactivated normal faults such as the more external Servitá fault are responsible for uplifting the eastern flank of the Eastern Cordillera. In addition, these structures are adjacent and intimately linked to the development of thin-skinned faults farther east. In part, the superimposed compression in this prestrained extensional region is compensated by lateral escape. The dominant presence of basement involved buckling and thrusting, and the restricted development of thin-skinned thrusting in this inversion orogen makes the Eastern Cordillera a close analog to the intraplate Atlas Mountains of Morocco and other inverted sectors of the Andean orogen farther south. Citation: Mora, A., M. Parra, M. R. Strecker, A. Kammer, C. Dimaté, and F. Rodríguez (2006), Cenozoic contractional reactivation of Mesozoic extensional structures in the Eastern Cordillera of Colombia, Tectonics, 25, TC2010, doi:10.1029/2005TC001854.

1. Introduction

[2] Contractional reactivation of preexisting extensional anisotropies in the crust is a common feature observed in many orogens and their forelands [e.g., Coward et al., 1989; Grier et al., 1991; Lowell, 1995; Teixell et al., 2003]. Fault geometry, thickness of sedimentary basin fills and the width of the former zone of extension may thus influence the style and extent of deformation and the overall configuration of an orogen [Huyghe and Mugnier, 1995; Kley et al., 1999]. In fact, in many regions the recognition of reactivated extensional structures during shortening helped to reveal the salient structural features of mountain belts. Impressive examples include the western Alps [Gillerist et al., 1987; Graciánsky et al., 1989; Coward et al., 1991], the Santa Barbara structural province of NW Argentina [Grier et al., 1991; Mon and Salfity, 1995; Kley and Monaldi, 2002] or the Atlas Mountains of Morocco [Teixell et al., 2003]. For a better understanding of the spatial and temporal evolution of orogens it is therefore important to consider their structural framework in the context of preexisting anisotropies and zones of weakness in the crust.

[3] With a length of more than 7000 km the Andes comprise distinct volcanic and morphostructural segments that appear to be correlated with changes in subduction geometry through time [Jordan et al., 1983; Kay et al., 1999; Ramos et al., 2002]. The importance of preexisting crustal architecture with respect to Cenozoic tectonics is particularly impressive in the Santa Barbara [Kley and Monaldi, 2002] and Neuquen Basin structural provinces of Argentina [Manceda and Figueroa, 1995]. In the northern Andes, the Eastern Cordillera fold and thrust belt of Colombia (Figures 1 and 2) is an extension of the Andean orogen located about 500 kilometers away from the plate boundary. Being an integral part of the Andean orogen it can be expected that plate boundary forces are transmitted to this province far from the trench similar to the case of the Santa Barbara [Kley and Monaldi, 2002] or the Atlas Mountains [Teixell et al., 2003]. Therefore a fundamental problem is determining, as to what factors exert the primary control on localizing intracontinental deformation and basin inversion. In the case of the Santa Barbara province and the Atlas Mountains, for example, the presence of ancient rift

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basins has been suggested to be an essential control determining orogenic processes.

[4] The Eastern Cordillera of Colombia spatially coincides with an extensional Neocomian depocenter that subsequently evolved into a contractional orogen, beginning in the late Mesozoic and experiencing sustained tectonic activity into the present [Colleta et al., 1990; Casero et al., 1997]. Previous studies proposed that tectonic inheritance has great importance in this mountain belt [Colleta et al., 1990; Casero et al., 1997; Sarmiento, 2001]. However, these studies were based on regional compilations that lack evidence of the Mesozoic extensional styles and modes of contractional reactivation of the ancient rift structures in this region. Therefore the precise location of Neocomian extensional structures and their role in generating varying deformation styles, different degrees of shortening, formation of hydrocarbon traps, and neotectonic activity remain speculative.

[5] The Río Blanco–Guatiquía region along the eastern border of the Eastern Cordillera of Colombia is an integral part of this inverted structural province (Figure 2) and provides a wealth of exposures of various structural levels, ranging from metamorphic basement and Mesozoic-Paleogene cover sediments to poorly lithified Neogene-Quaternary molasse units (Figures 2 and 3). This region is an ideal setting to evaluate the role of preexisting structure on Cenozoic mountain building. Here we document that the inherited anisotropies in the Eastern Cordillera have a critical influence on the location of Cenozoic deformation fronts and the generation of different structural styles. This study is the result of an extensive field mapping program carried out between 2002 and 2005 and analysis of selected subsurface information made available by petroleum industry. The combination of these data sets unambiguously demonstrates for the first time detailed evidence of the character of basin inversion in this Andean province.

2. Regional Tectonic Setting

[6] The regional tectonic framework of northwestern South America is controlled by the complex interaction...
between the Caribbean, Nazca and South American plates, as well as the influence of the Baudó-Panamá block. The latter is the westernmost and last terrain to the northern Andes, and it is composed of oceanic rocks [Duque-Caro, 1990] (see Figure 1). The eastward indentation of the Baudó-Panamá block during the Late Miocene is considered to be the driving force responsible for the inversion of Mesozoic rift basins in the present Eastern Cordillera [Taboada et al., 2000]. Inversion of focal mechanism solutions [Taboada et al., 2000; Corredor, 2003; Dimate et al., 2003] and borehole breakout data [Colmenares and Zoback, 2003] suggest that the recent tectonic stress field is characterized by a 20°SE oriented $S_{H\text{max}}$ in the Eastern Cordillera. In contrast, GPS data show more W-E oriented deformation [Trenkamp et al., 2002]. Cortés et al. [2005] propose a change in the northern Andes stress field from ENE-WSW orientation of $S_{H\text{max}}$ until the Paleocene, to a NW-SE to WNW-ESE position that has prevailed to the present-day.

[7] North of 2°N the Colombian Cordillera comprises three structural branches (Figure 1). An accretionary complex of Mesozoic oceanic crust, accreted to South America during Cretaceous-Paleocene time, forms the Western Cordillera. Uplifted Precambrian and younger metamorphic rocks, locally covered by Mesozoic sedimentary units, constitute the Central Cordillera. The Eastern Cordillera comprises the external zone of the Colombian Andes and is separated from the Central Cordilla by the Magdalena Valley. This intramontane basin is bounded by east vergent thrust faults emerging from the Central Cordillera, and by west vergent thrusts from the Eastern Cordillera [Butler and Schamel, 1988; Namson et al., 1994; Gómez et al., 2003].

[8] The tectonically active Eastern Cordillera (Figure 2) is bivergent and has an up to 10-km-thick Cretaceous to
Tertiary sedimentary cover in the center, and two regional basement exposures at its northern and southern ends, respectively (Figure 2). Structurally, it comprises three segments [Kammer and Mora, 1999]. The southernmost segment is thePrecambrian Garzón basement massif (Figure 2), which is a deformed part of the Guayana Shield [Kroonenberg, 1982]. This sector of the range is fan-shaped in cross section and uplifted by dextrally oblique thrust faults that are inferred to form a regional-scale positive flower structure [Chorowicz et al., 1996; Velandía et al., 2005]. The central segment, north of about 4°N, is an axial depression characterized by a thick Cretaceous and Tertiary cover [Cooper et al., 1995, Figure 2], overlying either upper Paleozoic sedimentary rocks or low-grade pre-Devonian phyllites. The pattern of deformation consists of an internally folded belt without major imbrications and thrusting [Colleta et al., 1990; Kammer and Mora, 1999]. The exposure of pre-Cretaceous rocks in this sector is restricted to the Floresta and Quetame basement uplifts. The crystalline Santander Massif defines the northern segment (Figure 2). On the east it is bounded by the Santa Marta–Bucaramanga Fault (Figure 2), a regional strike-slip fault with paleogeographic significance during the early Cretaceous synrift phase, when it formed the western boundary of a depocenter [Toro, 1990].

3. Stratigraphic Framework

[9] Phyllites and quartzites (Quetame Group) constitute the Quetame Massif and the basement sectors of the southern portion of the central segment [Campbell and Bürgl, 1965]. These units are unconformably overlain by the Puente La Balsa Formation [Cortés and de la Espriella, 1992], shales and sandstones of Devonian (?) age, about 700 m thick. The Puente La Balsa Formation is overlain by Devonian marine to continental sandstones (Areniscas de Gutiérrez Formation) of highly variable thickness, reaching approximately 2500 m. These units are superseded by Carboniferous red beds (Capas del Valle del Guatiquía Formation), at least 2000 m thick. Both formations constitute the Farallones Group.

[10] Paleogeographic and sedimentologic studies in the Eastern Cordillera [Fabre, 1985; Hebrard, 1985; Colleta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995; Sarmiento, 2001] suggest a Late Jurassic–Early Cretaceous regional rifting event associated with a megasequence of terrestrial and marine synrift deposits that overlie basement or Paleozoic units. The southern boundary of this rift domain is approximately at 4°N, marked by the limit of deposition of Berriasian to Barremian age sediments onlapping against a paleohigh at the southern end of the study area (Figure 4).

[11] The basal synrift sequence begins with coarse clastic units with pronounced facies and thickness changes (Buenavista Formation, Figure 3 [Dorado, 1992; Mora and Kammer, 1999]). These deposits are covered by a succession of marine shales and sandstones of highly variable thickness due to differential tectonic subsidence [Fabre, 1985] (Figure 3). In the Rio Blanco–Guatiquía region the maximum thickness of these strata reaches 4000 m. Albian to Cenomanian shallow marine sandstones (Une Formation), about 1000 m thick, cover the inferred rift troughs and adjacent regions and document the onset of postrift thermal subsidence [Fabre, 1985; Sarmiento, 2001]. The Une formation is in turn overlain by Upper Cretaceous marine black shales (Chipaque Formation) and quartz-sandstones (Guadalupe Group), about 2000 m thick. The Guadalupe Group is superseded by Cretaceous to Paleogene paralic to fluvial interbedded sandstone and shales ranging between 500 and 1500 m in thickness in the western and eastern sectors of the study area, respectively.

[12] Neogene units, restricted to the synclinal inliers within the orogen, but much more extensive in the foreland (Figures 2 and 3), comprise coarsening upward continental strata, locally 3000 m thick, inferred to be related to late Miocene uplift and unroofing of the Eastern Cordillera [Cooper et al., 1995].

4. Structural Setting

[13] The thrust faults located along the eastern and western mountain fronts (Figure 2) are typically associated with hanging wall synclines, which acted as Neogene depocenters [Cooper et al., 1995]. These basins preserve thick Tertiary sequences recording the growth history of the adjacent structures [Gómez et al., 2003], similar to wedge-top basins reported from the Bolivian Andes [e.g., Horton, 1998]. At both mountain fronts the wedge-top basins as well as the thrust faults are arranged in an en échelon pattern. Two basement highs, the Villeta Anticlinorium on the west, and the Quetame Massif (Figure 2) on the east, respectively, separate the frontal thrusts and associated synclines from a central, topographically elevated structural depression [Julivert, 1970]. This central structure is known as the Bogotá Savanna (Figure 2), where the majority of Cretaceous to Tertiary strata is preserved. The deformation style in the Bogotá Savanna, with locally periodic patterns of symmetrical box folds, partially resembles a detachment fold system [Kammer, 1997; Kammer and Mora, 1999]. However, decreasing fold amplitude with depth and an apparent homogenous flattening in the lower part of the cover (as shown by axial plane cleavage) precludes interpreting them as conventional detachment folds. Kammer and Mora [1999, Figure 4] proposed a geometric model, intermediate between detachment folding and homogenous shortening, to accommodate shortening at depth. In this geometric model the amplitudes of the folds observed at the surface are linearly reduced proportional to the distance from the surface outcrop, toward an unfolded basement-cover interface; except in those cases where field data shows that the basement is involved in folding. In our cross sections we adopt the model of Kammer and Mora [1999] to accommodate shortening at depth in the folds of the Bogotá Savanna.

[14] At the eastern mountain front (Figures 2 and 4) the subdued topographic and structural relief of marginal synclinal thrust pairs contrasts with the up to 3000-m-high internal basement uplifts of the Quetame Massif. This
Figure 4
relationship is evident where the Servita thrust fault separates the topographically elevated basement exposures from the Medina Syncline (Figure 2), which is bounded by the Guaicaramo thrust to the east. These two faults and the Yopal Fault form an en échelon relay pattern (Figure 2).

In the Río Blanco–Guatiquía region the Servita Fault (Figure 2) has the longest surface trace and is associated with the Farallones Anticline, located in its hanging wall (Figures 2 and 4). The northeastward decrease in displacement of the Servita Fault is directly proportional to the reduction of structural relief of the Farallones Anticline in the same direction. The general trend of the jagged San Juanito Fault (Figure 4) is parallel to the rectilinear Servita Fault. Finally, the Naranjal Fault is located south of the San Juanito Fault (Figure 4).

5. Reactivation of Extensional Structures

In the following sections we first demonstrate the salient characteristics of the most important Mesozoic extensional structures. Secondly, we document that the inversion styles are rather different in each case. Finally, we discuss possible factors conditioning the different contractional response of these structures and present a view of the inversion type localities in the context of the regional evolution of the Eastern Cordillera.

5.1. San Juanito Fault, a Former East Dipping Normal Fault

Footwall uplift, before the onset of local deposition of Cretaceous strata, and controlled by the San Juanito Fault, can be interpreted from the presence of different units underlying the basal Cretaceous Buenavista Formation on either side of the San Juanito Fault (Figures 4a and 5). In the western block the units underlying the basal Cretaceous rocks become progressively younger to the west (Figure 5). The lowest Cretaceous units rest on the Devonian (?) Puente La Balsa Formation, about 5 km west of the fault, whereas immediately next to the fault trace in the western block they overlie pre-Devonian phyllites (Figure 5). However, the Carboniferous strata are always below the lowermost Cretaceous rocks east of the San Juanito Fault (Figure 5).

[18] The timing of the San Juanito Fault as a lower Cretaceous structure can be evaluated by the geometry

Figure 4. (a) Geological map of the Río Blanco–Guatiquía region depicting the cross sections shown in other figures. (b) Sketch with the Lower Cretaceous extensional structural grain in the Río Blanco Guatiquía Region.
and the character of lower Cretaceous sediments. In the eastern block of the San Juanito Fault, the marine basal shale and carbonate sequence is more than 2.5 km thick; locally, it contains megabreccias sourced from the basement rocks in the western block, whereas a thinner basal terrigenous sandstone sequence in the former footwall block onlaps the basement and pinches out (Figures 5 and 6).

5.2. Cenozoic Reactivation of the San Juanito Fault

The present-day structural style of the San Juanito Fault involves an anticline in the footwall (Chingaza Dome) which terminates as a periclinal structure to the north and south (Figures 6, 7, and 8); its hanging wall forms a west dipping monoclinal panel in the units located east of the San Juanito Fault (Figure 8). Folding affecting the Cretaceous and older rocks in the Chingaza Dome is mostly related to Cenozoic contraction, as suggested by axial planar cleavage associated with the folds. Folding thus occurred at sufficiently deep levels to generate a pressure solution planar anisotropy that not only affected the pelites but also the quartz-sandstone levels. Interestingly, the southern periclinal termination of

Figure 6. (a) Geological map of the Chingaza Dome showing different facies at each side of the San Juanito Fault. (b) Detailed cross section (see projected location in Figure 5) showing onlap relationships and facial changes in the Lower Cretaceous basal units toward the structural culmination of the ancestral footwall of the San Juanito normal fault. The sandy facies unit to the east of the Guajaro Fault probably postdates the fault.
the Chingaza Dome occurs where the San Juanito Fault ends (Figure 8). This shows that the vertical offset of the fault is much more important than the horizontal component of movement, and that Cenozoic reactivation is minor and only due to folding in the western blocks (Figure 8). In addition, Lower Cretaceous depositional and erosional patterns (Figures 5 and 6b) reveal that the presently uplifted western block was also an area of positive relief during lower Cretaceous extension. Cross sections A-A'' (Figure 5), B-B'' (Figure 7) and I-I''

Figure 7. Serial cross sections perpendicular to the San Juanito and Naranjal faults. Notice that the fault related paleohigh is in the eastern block for the Naranjal Fault and in the western block for the San Juanito Fault. Nonetheless, higher amplitude folding is concentrated west of both structures. See location in Figure 4a and text for discussion.

Lithology

- Une Fm. - (Albian-Cenomanian)
- Fómeque Fm. - (Barremian-Albian)
- Alto de CáQUEza Fm. - (Hauterivian)
- Buenavista and Macanal Fms. - (Berriasian-Valanginian)
- Capas del Guatiquía Fm. - (Carboniferous)
- Gutiérrez Fm. - (Upper Devonian)
- Puente La Balsa Fm. - (Devonian?)
- Andean Metamorphic Basement. - (Pre-Devonian)
demonstrate shorter wavelength folding restricted to the west of the San Juanito Fault, and a general westward vergence of the anticlines.

6. Naranjal Fault

6.1. Evidence of Mesozoic Activity

The bends and zigzag map patterns of the Naranjal Fault (Figure 4b) are reminiscent of segmented normal faults in extensional terrains [e.g., Morley, 1995]. The activity of the Naranjal Fault before the onset of local deposition of Cretaceous strata can be assessed by the different pre-Cretaceous rocks underlying the Lower Cretaceous unconformity at each side of the fault (Figure 4). Lowermost Cretaceous rocks are on top of the Devonian west of the Naranjal Fault, whereas they overlie Pre-Devonian rocks to the east. Thus the pattern of footwall uplift and erosion before the onset of local deposition of Cretaceous strata is opposite between the San Juanito and Naranjal faults (Figures 4 and 7). The map pattern is suggestive of a conjugate accommodation zone in the transition between both structures (Figure 4b).

A rapid east-west lateral change from a boulder conglomerate to shaly units in the basal Cretaceous strata of the western block of the Naranjal Fault indicates sediment transport from a structural high in the same direction. The lower Cretaceous Puente Quetame synthetic normal fault west of the Naranjal Fault has been deduced by extrapolating the basal Cretaceous unconformity on both sides of the inferred structure. On the basis of the surface data it is not possible for the unconformity to reach the same elevation on both sides. Therefore a normal fault that delimits an adjacent half graben depocenter and controls the maximum thickness of lower Cretaceous sediments in the investigated area is proposed (Figure 7, cross section D-D').

6.2. Cenozoic Reactivation of the Naranjal Fault

The fold patterns west of the Naranjal Fault (Figure 9) clearly show fault control. The Puente La Balsa Anticline to the west has a curved axial trace that mimics the shape of the Naranjal Fault (Figure 9). The fold traces west of the Puente La Balsa Anticline are funnel shaped in plan view and converge next to the Naranjal Fault.
The dominant eastward fold vergence west of the Naranjal Fault suggests tectonic transport against the basement high in the footwall of the main fault (Figure 7). Cross section D-D₀₀ (Figure 7) shows that most of the shortening by folding is concentrated west of the Puente Quetame normal fault. As this fault loses displacement toward the south and eventually disappears, the maximum amplitude fold is shifted to the Naranjal Fault in the same way as the lower Cretaceous normal fault displacement is transferred to it (section E-E₀₀, Figure 12). A steadily increasing fold amplitude toward the basement highs (profile E-E₀₀, Figure 7) west of the Naranjal Fault contrasts with the broad Une Syncline in the westernmost sector of the study area (Figures 4 and 7). Interestingly, the down plunge-projected elevation of the lower Cretaceous unconformity in the Puente La Balsa Anticline is still lower than in the adjacent basement high east of the fault (cross section E-E₀₀, Figure 7). This indicates that the structural relief produced by Lower Cretaceous normal faulting along the Naranjal Fault was not inverted in contraction. Fold wavelengths are shorter to the west of the Naranjal Fault than to the east (Figures 4 and 7). In addition, lower Cretaceous extensional folds (Figures 7 and 10) were differentially amplified in contraction on either side of the lower Cretaceous Río Blanco Fault, a fault located west of the Naranjal Fault, which is virtually parallel to the shortening direction. This initially extensional structure therefore acted in contraction as a transverse zone separating different fold geometries (Figure 10).

7. Servitá Fault

7.1. Inherited Pre-Cretaceous and Lower Cretaceous Structures

Stratigraphic relations suggest that the hanging wall of the Servitá Fault constituted a downdropped fault block before the onset of local deposition of Cretaceous strata; it preserves up to of 5 km Upper Paleozoic sediments while this sequence is absent in the footwall to the east (Figures 4, 11, and 12). The westward thinning of Upper Paleozoic strata is interpreted to be an erosional truncation related to activity of the Servitá Fault before the onset of local deposition of Cretaceous strata (Figure 11, profile K). In addition, the Lower Cretaceous Buenavista Formation of the Buenavista Anticline consists of coarse terrigenous conglomerates [Dorado, 1992] that are absent in the outcrops of the lowest Cretaceous rocks in the hanging wall of the Servitá Fault (Figure 11 cross section K and Figure 12). In addition, the thickness of the Lower Cretaceous rocks, in the area between the San Juanito and Servitá faults, exceeds 2000 m and is thus much greater than to the east (Figure 12), where a condensed Berriasian to Barremian interval has a thickness of 1000 m. The region between the San Juanito and Servitá faults, also coincides with an area where the Paleozoic sequence is preserved, thus contrasting to structural highs to the east and to the west, where it was originally deposited but subsequently eroded (Figure 12). These observations indicate differential subsidence associated with the San Juanito and Servitá faults (Figure 12) before the onset of Lower Cretaceous deposition and also during the deposition of most of the synrift sequence, in an area that we term the Guatiquía Graben.

7.2. Inversion of the Servitá Fault and the Guatiquía Graben: Farallones Anticline and Mirador Frontal Shortcut Thrust

The Farallones Anticline appears to be controlled by the ancestral Guatiquía Graben and particularly by the inversion of the Servitá Fault. The orientation of the fold axis of the Farallones Anticline is parallel to the rectilinear Servitá Fault but also to the internal San Juanito Fault (Figures 2, 4, and 9). Thus its origin might be either completely related to inversion or an extensional rollover later amplified in contraction. It evolves from a symmetric anticline to the north coinciding with the area where it is superposed over the Guatiquía Graben (Figure 11a), to a highly asymmetric structure with a steeply dipping forelimb, coinciding with a southern half graben region.
Consequently, the degree of symmetry in the extensional Lower Cretaceous structure fundamentally conditions the geometry of the inversion structure. 

Further east, the Mirador thrust can be inferred from an exploratory well (Anaconda-1) located in the hanging wall block and documenting a basement wedge overlying Tertiary units. Its geometry is further corroborated by seismic reflection profiles [Narr and Perez, 1993]. 

The presence of coarse conglomerates in the Buena-vista Formation in the hanging wall of the Mirador Fault has been interpreted by Dorado [1992] to mark high relief conditions to the east during the Berriasian. However, in the Apiay oil field, 25 km to the east, there is a much thinner Cretaceous sequence (Figure 2). This suggests that yet another Lower Cretaceous normal fault may exist between both places. However, we do not infer a potential low angle paleo-Mirador normal fault as the boundary fault for this high relief which is responsible for the Cretaceous facial changes; instead this structure is more likely a shortcut generated by the Farallones Anticline that pushed from the rear during Cenozoic inversion. We therefore suggest that a former extensional border fault is located east of the Mirador Fault, as indicated in cross sections I, K and J (Figures 11 and 12). 

[26] When comparing the dip of the outcropping units at each side of the Servitá Fault with the rectilinear trace (Figure 11b). Consequently, the degree of symmetry in the extensional Lower Cretaceous structure fundamentally conditions the geometry of the inversion structure.

[27] The presence of coarse conglomerates in the Buena-vista Formation in the hanging wall of the Mirador Fault has been interpreted by Dorado [1992] to mark high relief conditions to the east during the Berriasian. However, in the Apiay oil field, 25 km to the east, there is a much thinner Cretaceous sequence (Figure 2). This suggests that yet another Lower Cretaceous normal fault may exist between both places. However, we do not infer a potential low angle paleo-Mirador normal fault as the boundary fault for this high relief which is responsible for the Cretaceous facial changes; instead this structure is more likely a shortcut generated by the Farallones Anticline that pushed from the rear during Cenozoic inversion. We therefore suggest that a former extensional border fault is located east of the Mirador Fault, as indicated in cross sections I, K and J (Figures 11 and 12).
of the fault itself, it is evident that the fault is dipping steeper than the units, resulting in a ramp over ramp geometry (Figures 4 and 8). Nonetheless, a steeply dipping fault plane of the Servita Fault is not favorable for a forward breaking relationship with the Mirador shortcut and a shallower, more frontal horizontal detachment on top of the Cretaceous sequence (cross section I, Figure 11). We therefore assume that the fault flattens out at depth.

In addition, a gently dipping western panel of the Farallones Anticline, only disrupted by the San Juanito Fault, can be explained in terms of a long backlimb produced by displacement along the listric fault plane at depth of the Servita Fault (cross section I, Figure 11). These observations and the presence of an inferred lower Cretaceous rift related roll-over anticline (Figure 12) west of the Servita Fault are best explained by a deep listric segment of the Servita Fault that reactivates a former extensional detachment (Figures 11 and 12).

8. Along-Strike Inversion Examples

The Guacaramo thrust fault, a relay of the Servita Fault, has evolved as a more eastern frontal thrust between 4° and 4°50'N (Figure 2). It can be interpreted as an inverted west dipping normal fault as it has Lower Cretaceous rocks in its hanging wall that are absent in the footwall foreland block, where only post-Albian rocks occur (Figures 13–15). There are remarkably different styles of deformation and folding in the hanging wall of the Guacaramo Fault. A southern segment comprises open folds with gentle limbs, but north of about 4°45’ the style changes to tight folds with upright limbs (Figures 13b, 14, and 15). This segmentation coincides with the segmentation of the basement highs.
inferred from gravimetry (Figure 13). This view is also supported by neotectonic structures [Dimaté et al., 2003] and seismicity (see Figure 13b).

[31] As already pointed out by Rowan and Linares [2000] based on evidence from seismic information [see Rowan and Linares, 2000, Figures 15 and 16], we suggest that the Guaiacarao Fault south of about 4°45’N appears to be a detachment shortcut fault, conditioned by an underlying undisturbed pre-Cretaceous normal fault (Figure 14), whose presence is supported by a gravity anomaly below the Guavio Anticline (Figure 13). In contrast, north of 4°45’N the Guaiacarao Fault appears to have a steeply dipping fault plane as shown by earthquake aftershocks [Dimaté et al., 2003, Figure 15]. The hanging wall of this fault apparently overlies an area where the basement is structurally in a lower position as suggested by gravity and density modeling [Velasquez, 2002]. The tight short wavelength folding restricted to the hanging wall at the northern...

Figure 12. Regional cross section (location in Figure 4a), showing a Lower Cretaceous graben (the Guatiquia Graben) defined by normal faults dipping in opposite senses. The Lower Cretaceous timing of the different faults is defined by the facies and thickness changes in each faulted block (see the stratigraphic profiles above). The graben is transported by the only reactivated fault, the Servita Fault, which generates a compressional shortcut to the east (Mirador shortcut thrust). The Servita Fault at depth is interpreted based on the presence of a zone of seismicity and the depth inferred when restoring the original position of the Lower Cretaceous unconformity before its movement over the hanging wall of the Servita and Mirador faults.
Figure 13
segment, reveals that here the fault may have primarily acted as a buttress like the Naranjal and San Juanito faults (Figures 13 and compare Figure 15 with cross section E in Figure 7), although with a lesser degree of reactivation when compared to the Servita Fault/Mirador shortcut. Therefore the Guaicaramo Fault appears to reflect the reactivation of different segments of a former basin bounding normal fault array; each segment probably having different Lower Cretaceous stratigraphic sequences (Figures 14 and 15). The boundary between both segments is inferred to be a transverse NNW-SSE striking blind ancestral fault, an interpretation supported by the presence of aligned periclinal terminations along the inferred trace of this zone (Figure 13). In addition the aftershocks of the 1997 $M_w = 6.5$ Tauramena earthquake [Dimet et al., 2003] were concentrated along the NW prolongation of this transverse discontinuity (Figure 13).

When viewed in cross section (Figures 14 and 15), the northern segment appears to accommodate less shortening than the southern ramp anticline segment. As a consequence the low angle decollement ramp thin-skinned style of deformation appears to be transferred from the southern segment of the Guaicaramo Fault to the more frontal Cusiana and Yopal faults (see Figure 13 and Cazier et al. [1995] and Cooper et al. [1995]).

About 36 km west of the Guaicaramo Fault, the normal Esmeralda Fault strikes parallel to the San Juanito Fault (Figures 2 and 14), and probably depicts a change in polarity with respect to it. It has also been interpreted as a lower Cretaceous normal fault [Rowan and Linares, 2000; Branquet et al., 2002] but evidence collected during our field work and investigations by others [Branquet et al., 2002; Rowan and Linares, 2000] do not point toward a significant reactivation, but rather suggest that the fault acted as a buttress. The latter point is suggested by the fact that analogous to the Naranjal and San Juanito faults the Esmeralda Fault separates a shorter wavelength folding domain from the wide basement culmination of the Farallones Anticline (Figure 14).

9. Discussion

We have presented evidence that structures generated during lower Cretaceous rifting were important in configuring and conditioning contractional structures and their...
protracted tectonic activity into the present. Reactivation of preexisting structures is dependent on several factors that will be further assessed below.

9.1. Orientation of Preexisting Structure and Long-Term Cenozoic Strain Patterns

The mechanics of contractional fault reactivation has been analyzed in various studies, based on the Navier-Coulomb criteria for brittle failure [Sibson, 1985; Gillcrist et al., 1987; Sibson, 1995; Turner and Williams, 2004]. From these investigations it can be concluded that the main factor conditioning reactivation is the interaction between the superimposed compressional stresses and the geometry and dip of any preexisting anisotropy.

The most important structural relief in the central segment of the Eastern Cordillera is associated with the inversion of the Servitá normal fault, whereas the less pronounced Naranjal and San Juanito faults are passively uplifted in the hanging wall of the Servitá Fault, preserving an inherited pattern of extensional structural relief (Figures 11 and 12). Apparently, these faults have acted as buttresses separating a western structural domain where tight folding is dominant from an eastern area with open folds and basement thrusts (Figures 7 and 11). These observations underscore that the Mesozoic basement highs have served as rigid backstops where Cenozoic shortening was absorbed, similar to structures described in the Appalachian Blue Ridge province [e.g., Bailey et al., 2002] or in the Devonian basins of northern Scotland [cf. Coward et al., 1989, Figure 11]. In these case studies the conventional use of basement buttressing assumes a rheologic contrast between a rigid basement and layered rocks. However, in the area investigated by us “basement” units appear to be involved in buckling in the hanging wall of the inherited normal faults against the structural highs. We note that the low degree of metamorphism and the preserved sedimentary texture of the exposed basement allow it to fold together with the overlying cover. Conversely, adjacent footwall uplifts are cored by crystalline basement units, therefore favoring the presence of a rheologic contrast. Increasing bedding dip toward the west in the eastern block of the San Juanito Fault together with concentrated penetrative deformation in the steeper dip domain is a remarkable west vergent contractional feature possibly related to back folding and buttressing of the San Juanito Fault, analogous to

Figure 15. Cross section through the folded belt to the west of the northern segment of the Guacaramo Fault. The Guacaramo Fault angle was inferred with the aftershocks of the Tauramena earthquake [Dimaté et al., 2003]. The star shows the main shock. Those aftershocks, defining a roughly eastward dipping pattern, are inferred to be the prolongation of the transverse zone separating the two folding domains. For location, see Figures 2 and 13.
the Bourg-d’Oisans half graben as described by Gillcrist et al. [1987] and Graciansky et al. [1989].

[37] A primary controlling factor for this differential behavior of extensional structures appears to be fault geometry. The Servitá Fault is rectilinear and has a listric profile, compared to the more segmented and vertical Naranjal and San Juanito faults (Figures 9 and 11). This may have resulted in a reactivation and the formation of a shortcut in the former and locking of the latter.

[38] The second important aspect in reactivation is the long-term Andean strain pattern superimposed on Lower Cretaceous structures. There are no published paleostress studies for the study area. However, the variable structural trends in the Eastern Cordillera (Figure 2) pose major questions. Can the Cenozoic paleostress orientations obtained in other locations in the orogen [e.g., Corte´s et al., 2005] be inferred to influence this region? Or are the variable structural trends a response to local variations in the tectonic stress field? An additional complication in answering these questions is that the timing of the major contractional structures in the study area remains unknown due to the lack of datable growth strata. Given these limitations, we assume for our purposes a local shortening direction, perpendicular to the major fold axes. We furthermore assume that this direction is roughly parallel to the dominant compressional stresses that acted on this part of the orogen at the time of contractional deformation. The major fold orientations west of the Naranjal and San Juanito faults and to the south of the study area are N-S (Figure 9). This character prevails westward in the synclines of the axial zone of the Eastern Cordillera between 3.5° and 4.5°N (Figure 2). In contrast, the orientation of the Farallones Anticline, preconditioned by the Guatiquia Graben, is NNE-SSW (Figure 9). This suggests a deviation of the orientation of the lower Cretaceous structures and the shortening direction (see also the fold traces terminating obliquely against the Servitá Fault in its hanging and footwall blocks, Figure 9). We therefore suggest that such an oblique pattern would favor a transpressional reactivation of the Servitá Fault. Conversely, the Naranjal Fault strikes approximately parallel to the N-S folds to the west. The San Juanito Fault is also oblique at a smaller scale, exemplified by the orientation of the folds immediately to the west compared to the orientation of the fault itself (Figures 8 and 9). In this case, however, an east dipping fault plane would not be favorably oriented as the dominant vergence of the Cenozoic contractional folds and faults is toward the east (Figure 11). These two factors could have generated the final contractional pattern of minor uplift by buckling in the western blocks of the internal half grabens; in this case the half grabens would have been mainly passively uplifted by the external Servitá Fault. Thus underthrusting in contraction along a listric Servitá Fault would be the main mechanism that had uplifted the entire eastern mountain front and the internal preexistent half grabens. This behavior is reminiscent of the “interior ramp supported uplifts” described by Schmitt and Steidmann [1990] in northwestern Wyoming.

[39] The angular pattern between Cenozoic fold orientations and lower Cretaceous extensional structures is not evident along the eastern mountain front, north of about 4°40’N (Figure 2). Instead, the principal orientation of the Cenozoic folds in the axial zone of the Eastern Cordillera turns parallel to distal thrusts generally striking NNE-SSW. This structural pattern is compatible with a recent ESE-WNW orientation of Shmax inferred from borehole breakout data [Colmenares and Zoback, 2003; Corredor, 2003; Dimaté et al., 2003]. Thus the inherited anisotropies along the eastern section of the fold belt north of 4°40’N are in principle not suitable for a reactivation in contraction. For instance, the northern segment of the Guacarumo Fault (Figures 2 and 13) is parallel to the Andean fold orientations and perpendicular to the compressional patterns. Dimaté et al. [2003] argue that a reactivation in such a case might be caused by either high fluid pressure or low friction conditions [e.g., Sibson, 1995]. Assuming a similar dip angle in comparison to other faults, like the Esmeralda and Naranjal faults, it is likely that this particular case of reactivation might be aided by fluid overpressure [Sibson, 1995].

9.2. Periclinal Terminations and Lateral Escape in Contraction

[40] An important aspect of the reactivation of structures in the Cordillera Oriental is the close association of periclinal terminations of Cenozoic anticlines and the segmentation of inherited normal faults. For example, the southern periclinal termination of the Chingaza Dome is located at the termination of the San Juanito Fault, while the northern termination coincides with a significant reduction in displacement of this fault (Figure 8). In addition, the northern periclinal termination of the Puente La Balsa Anticline coincides with the termination of the Naranjal Fault (Figure 8). In this context the overturned southern termination of the Farallones Anticline against a segment of the Naranjal Fault is remarkable (see Figure 4), suggesting that all of these cases are related to some degree of nonplain strain deformation. Also folding parallel to the Río Blanco Fault (see cross section in Figure 10) is explainable with lateral escape of material. The backstop effect of the Naranjal Fault prompts a N-S extrusion that encounters a new obstacle in the Río Blanco Fault, analogous to observations reported from the Alps (Figures 4b and 10) [e.g., Coward et al., 1991].

[41] In the case of the Guacarumo Fault, the boundary between the segments north and south of 4°45’N is depicted by the change in the style of folding, where the tight folds of the northern segment end as periclinals (compare Figures 8 and 13b). These periclinal terminations may also be interpreted as the result of lateral escape, similar to the location of periclinal terminations controlled by ancestral faults discussed above. In this case, the inferred transverse blind fault separating the southern and northern segments of the Guacarumo Fault may have acted as a lateral buttress in contraction (Figure 13).
9.3. Regional Implications and Analogs

[42] Our assessment of the reactivation of inherited extensional structures during Cenozoic contraction contrasts with previous investigations evaluating the evolution of the Eastern Cordillera. For example, Roeder and Chamberlain [1995] argue for a typical thin-skinned thrust belt deformation in this region independent of Neocomian graben structures. In addition, they suggest that low angle thrusting also characterizes the central structure of the Bogotá Savannah. Alternatively, Dengó and Covey [1993] proposed initial Miocene age thin-skinned thrusting overprinted by Plio-Pleistocene out-of-sequence uplift and reactivation of ancestral normal faults. They suggest that the Miocene thin-skinned structural style also applies to the interior of the orogen. Finally, Colletta et al. [1990] pointed out the importance of inversion tectonics but they did not unequivocally document the presence of ancestral normal faults bounding Jurassic to Lower Cretaceous depocenters.

[45] Our compilation and structural analysis of previously unmapped areas clearly supports a model of fault inversion for the Eastern Cordillera of Colombia. Our data document the presence of different structural styles in close proximity to each other; from a central folded belt to an external thick-skinned thrust belt that has ultimately evolved into a thin-skinned style of deformation toward the foreland. 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Colmenares, L., and M. D. Zoback (2003), Stress field and seismotectonics of northern South America, Geology, 31, 721–724.


Cortés, R., and R. de la Espriella (1992), Apuntes sobre la tectónica del Valle del Río Negro al oriente de los Alpes Cordobeses, Geol. Colombiana (Colombia), 24, 137–147.


