HOME CONTENTS SEARCH

38

Montes, C., P. A. Restrepo-Pace, and R. D. Hatcher Jr., 2003, Three-dimensional structure and kinematics of the Piedras-Girardot fold belt: Surface expression of transpressional deformation in the northern Andes, *in* C. Bartolini, R. T. Buffler, and J. Blickwede, eds., The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir 79, p. 849–873.

Three-dimensional Structure and Kinematics of the Piedras-Girardot Fold Belt: Surface Expression of Transpressional Deformation in the Northern Andes

Camilo Montes[1]

Department of Geological Sciences, The University of Tennessee, Knoxville, TN, 37996-1410, U.S.A.

Pedro A. Restrepo-Pace[2]

600N Dairy Ashford, Houston, TX, 77079-1175, U.S.A.

Robert D. Hatcher Jr.

Department of Geological Sciences, The University of Tennessee, Knoxville, TN, 37996-1410, U.S.A.

ABSTRACT

This paper presents a new kinematic model for the structure and tectonic evolution of part of the northern Andes of Colombia based on detailed geologic mapping, strain analysis, seismic interpretation, and 3-D forward modeling. This model indicates that the oblique convergence vector imposed by the Caribbean Plate is not fully partitioned in space, but instead must be distributed in a diffuse zone of transpressional deformation spanning the Cordilleras Oriental and Central. The Piedras-Girardot fold belt, located between the two cordilleras, contains the termination of two regional scale structures of the northern Andes: the Ibagué fault and the Guaduas syncline. The Ibagué fault, with a minimum dextral displacement of 30 km, is the southern boundary of a rigid indenter that was inserted to the east-northeast, causing contrasting deformation styles in the Mesozoic sedimentary sequence to the east and to the south of it. South of the rigid indenter, a complex array of diverging north- to northeast-trending faults and folds delineate a sigmoidal stepover to the left with faults verging outwardly in opposite directions that define the Piedras-Girardot fold belt. The kinematics of deformation indicate that this fold belt is a dextral

[1]*Present affiliation*: Institute Français du Pétrole, Rueil Malmaison, 92825, France.
[2]*Present affiliation*: Ecopetrol, Cll. 37 # 8-43, Bogotá, D.C., Colombia.

transpressional system where oblique contraction is accommodated along north- and northwest-trending segments of faults, dextral strike-slip along their northeast-trending segments, and extension along the east-trending faults. This doubly vergent system has northwest-verging thrust faults with oblique displacements approximately parallel to the Ibagué fault (17-km Cambao fault; 7-km Camaito fault), as well as a southeast-verging roof thrust with approximately 8 km of oblique displacement to the east-northeast (Cotomal fault). A geometric fit constrained with a stratigraphic piercing point also requires counterclockwise rotation of the easternmost two thrust sheets by 7° and 13°. A three-dimensionally admissible and valid palinspastic restoration of this fold belt requires approximately 52% east-northeast contraction (about 32 km), which is consistent with the minimum displacement of the Ibagué fault and other estimates of shortening in the eastern margin of the Cordillera Oriental. This component of deformation had not been previously identified and quantified in the northern Andes.

INTRODUCTION

Although agreement exists that oblique convergence, not subduction, has dominated the interaction between the Caribbean and South American Plates during most of the Cenozoic (Case et al., 1971; Ladd, 1976; Pindell and Dewey, 1982; Burke et al., 1984; McCourt et al., 1984; Laubscher, 1987), very little structural evidence exists supporting this observation on the ground. In fact, numerous 2-D models ignore the contribution of strike-slip to deformation in the Cordillera Oriental and Magdalena Valley (Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995; Roeder and Chamberlain, 1995), potentially making these reconstructions incomplete. Regional paleogeographic reconstructions (Villamil, 1999) could be improved if a better understanding of the kinematics of this margin existed, particularly whether presently contiguous sedimentary facies have been telescoped perpendicular, oblique, or slid parallel along major faults.

This paper presents the results of a detailed investigation of the three-dimensional structure and evolution of the Piedras-Girardot fold belt (PGFB) in the northern Andes of Colombia (Figure 1). This fold belt is the only segment of the northern Andes where the Cordilleras Central and Oriental overlap, thus affording a unique opportunity to study the interaction between the Caribbean, South American, and Nazca plates. The PGFB also offers an excellent opportunity to study three-dimensional deformation because of its moderate size, adequate exposure, and availability of oil industry subsurface data. The study presented here includes: (1) geometric description of structures and deformation style; (2) analysis of map-scale kinematic markers to assess the direction of tectonic transport; (3) analysis of deformation in serial cross sections to evaluate shortening recorded in individual thrust sheets; (4) unfolding of individual thrust sheets in two dimensions and palinspastic restoration; (5) construction of three-dimensional models to test the validity of two-dimensional interpretations; and (6) simplified forward modeling to evaluate the validity of deformation styles and the history of deformation. These results provide an anchor point to test competing hypotheses for the kinematic development of the northern Andes. They also contribute to the development of methodologies to study deformation in three dimensions.

Geologic field mapping, collection of fabric and stratigraphic data, and analysis of field relationships constitute the foundation of this study. Field mapping concentrated on fault traces and lithologic contacts at 1:25,000 scale and collection of structural data. Changes in cutoff geometry, kinematic markers, and, in some cases, dip of fault planes were documented by tracing structures along strike, using relief to study the vertical dimension, and occasionally examining neotectonic features such as tilted terrace deposits to map fault traces. Aerial photographs and satellite imagery were useful to extrapolate contacts beyond the area traversed during field seasons, to delineate fan and alluvial deposits, and to detect neotectonic features. With the exception of the Ibagué and Cambao faults, and the Guaduas and Gualanday synclines, the nomenclature of faults and folds for the PGFB presented here is new. Even though there is no continuous trace of the Cambao fault across the Magdalena River, the westernmost fault of the PGFB was correlated with the Cambao fault because it marks the westernmost extension of faulting (Namson et al., 1994) and corresponds with the topographic front of

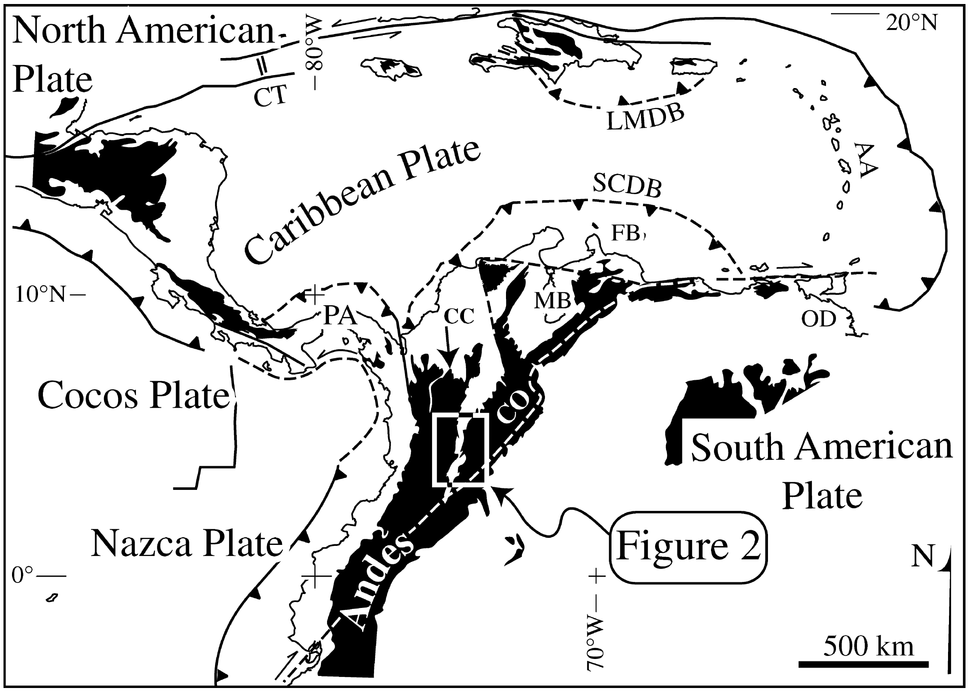


Figure 1. Tectonic map of the Caribbean region. Black indicates elevations higher than 500 m above sea level. AA = Antilles arc; CC = Cordillera Central; CO = Cordillera Oriental; CT = Cayman trough; FB = Falcón basin; LMDB = Los Muertos deformed belt; MB = Maracaibo basin; OD = Orinoco delta; PA = Panamá arc; SCDB = Southern Caribbean deformed belt.

the fold belt. Correlation to other named regional faults of the Cordillera Oriental was not attempted because the lack of detailed geologic mapping elsewhere precludes defining the exact traces and styles of faults.

To facilitate data analysis, perform geometric and kinematic modeling in two and three dimensions, and export digital data to specialized computer software, all available data were compiled into a fully digital, georeferenced, three-dimensional geologic and geographic database. This database allows complex queries as well as construction and manipulation of surfaces to be exported to Geosec2D® and 3D® software for 2-D and 3-D analysis.

CARIBBEAN PLATE BOUNDARY

Regional kinematic reconstructions indicate that the Caribbean Plate is, in many respects, an abnormal oceanic plate. This plate apparently resisted subduction because of its origin as a thick and buoyant oceanic plateau in the Pacific Plate (Malfait and Dinkelman, 1972; Pindell and Barrett, 1990; Kerr et al., 1998). Geophysical studies (Edgar et al., 1971; Zeil, 1979; Bowland and Rosencrantz, 1988; Westbrook, 1990) reveal that the Caribbean oceanic crust is abnormally thick (12 to 15 km) and 1–2 km shallower than predicted by its minimum age (Early Cretaceous). This abnormally thick, shallow plate also shows signs of internal deformation that may have resulted from its relative eastward insertion through a bottleneck (Figure 1) between the Los Muertos and the Southern Caribbean deformed belts (Burke et al., 1978).

The relative eastward drift of the buoyant Caribbean Plate with respect to the American Plates (Case et al., 1971; Ladd, 1976) requires large strike-slip components along the southern and northern Caribbean Plate margins. Indeed, the Cayman trough (Figure 1) along the sharp northern Caribbean Plate boundary contains evidence for more than 1100 km of left-lateral motion since the Eocene (Rosencrantz et al., 1988). Similarly, the eastern segment of the southern Caribbean Plate margin along northern Venezuela contains paleontologic evidence (Diaz de Gamero, 1996) that documents more than 1000 km of east-west, dextral strike-slip motions, in agreement with younging metamorphism to the east (Pindell, 1993). In contrast with these sharp strike-slip boundaries, the southwestern segment of the southern Caribbean Plate boundary is characterized by a broad and diffuse zone of oblique deformation (Kafka and Weidner, 1981; Pennington, 1981; Audemard, 2001) with the Cordillera Oriental forming its eastern border (Mann et al., 1990). The large eastward component of deformation of the Caribbean Plate (Rosencrantz et al., 1988; Pindell, 1993; Diaz de Gamero, 1996) necessarily imposes an oblique convergence vector along the northeast-trending, southwestern Caribbean Plate margin in the Andes of Colombia. Yet, structural evidence supporting oblique convergence models in the northern Andes of Colombia is missing.

Full deformation partition between the Cordilleras Central and Oriental could be invoked to explain the lack of structural evidence for transpressional deformation in the northern Andes of Colombia.

Geologic maps show that large dextral strike-slip faults dominate the structure of the Cordillera Central (Barrero et al., 1969; Feininger, 1970; Barrero and Vesga, 1976; Schubert, 1981; Mosquera et al., 1982), whereas thrust faults accommodating northwest-southeast contraction have been interpreted to dominate in the Cordillera Oriental. Models reconstructing the predeformational geometry of the Cordillera Oriental assume plane strain and large (> 300-km wide) composite thrust sheets riding along a crustal-scale, east-verging master detachment rooted beneath the Cordillera Central, with subduction of the Caribbean Plate (or another oceanic plate) driving deformation (Kellogg and Bonini, 1982; Dengo and Covey, 1993; Freymueller et al., 1993; Taboada et al., 2000). These models, however, fail to produce acceptable solutions because (1) the aforementioned difficulty to subduct the Caribbean Plate, which more likely bends only under northwestern South America, and (2) restoration of foreland fold and thrust belts also requires displacing the metamorphic assemblages and basement overlying the internal parts of the basal detachment (Oldow et al., 1990). Normal restoration of these large composite thrust sheets along a northwest-southeast trajectory, as suggested in some of these models, would displace the metamorphic core of the Cordillera Central beyond the edge of the continental crust in the northern Andes (Case and MacDonald, 1973; Etayo Serna et al., 1986), and so sub-detachment mass would be missing. Therefore, full deformation partition is unlikely, and transpression must play a role in transferring deformation between the two orogens.

Some of the evidence cited in such models consists of earthquake hypocenters, tensor solutions (Pennington, 1981; Frohlich et al., 1995; Malavé and Suárez, 1995; Taboada et al., 2000), global positioning system (GPS) surveys (Freymueller et al., 1993), and seismic tomography (van der Hilst and Mann, 1994). All these techniques can provide clues to decipher the present structure of the crust but cannot be used to extrapolate paleotectonic configurations. Similarly, stress analysis using fault-slip data (Kammer, 1999; Taboada et al., 2000) can be used only under the assumption that all the faults sampled slipped under a stress field that remained homogeneous within the rock mass (Ramsay and Lisle, 2000). Unless precise dating of these structures can be achieved, incremental strain markers can be measured, and strain factorization is performed, they cannot be used to estimate paleostress regimes in a complexly deformed region such as the northern Andes.

The PGFB, a small element in the complex north Andean tectonic puzzle, contains the southern termination of regional structures interpreted to accommodate northwest-southeast contraction in the Cordillera Oriental (Namson et al., 1994), as well as the eastern termination of large strike-slip faults of the Cordillera Central. The pronounced curvature of structures in this fold belt, their geometric arrangement in a divergent sigmoidal pattern, and the variety of structural styles (strike-slip, normal, and thrust faulting) suggest significant amounts of transcurrent deformation. This fold belt is stylistically similar to geometries produced by analog modeling of transpressional systems (Schreurs and Colletta, 1998; Tikoff and Peterson, 1998; Casas et al., 2001; McClay and Bonora, 2001). Being at the intersection of the Cordillera Central and Oriental, it is strategically situated for testing the role of strike-slip-related deformation in a foreland system with possible oblique convergence, providing an anchor point to test regional tectonic models of the interaction between the southern Caribbean Plate boundary and the northern Andes.

THE PIEDRAS-GIRARDOT FOLD BELT

The rugged hills of the PGFB interrupt the otherwise flat and wide topographic depression of the Magdalena Valley in central Colombia. Topographic relief in this fold belt locally exceeds 500 m, with maximum elevations reaching approximately 900 m above sea level. This anomalous geomorphic province constitutes the only barrier that the Magdalena River encounters in its northward path to the Caribbean Sea and exposes critical structural (Figure 2) and stratigraphic (Figure 3) relationships between the Cordilleras Oriental and Central, which are covered elsewhere by Neogene deposits.

The study area has natural geographic boundaries to the east, in the western foothills of the Cordillera Oriental, where elevations commonly exceed 1000 m above sea level, and to the northwest, along the steep topographic front of the Cordillera Central. Quaternary volcaniclastic deposits mark the southern boundary of this fold belt. Shortening in parts of the western flank of the Cordillera Oriental has been estimated between 16 and 45 km (Namson et al., 1994; Restrepo Pace, 1999), and is accommodated mostly by low-angle, north- and northeast-trending, west-verging folds (Hubach, 1945) and faults. These faults include the Cambao and Bituima faults, regional structures that parallel the north-trending Guaduas syncline,

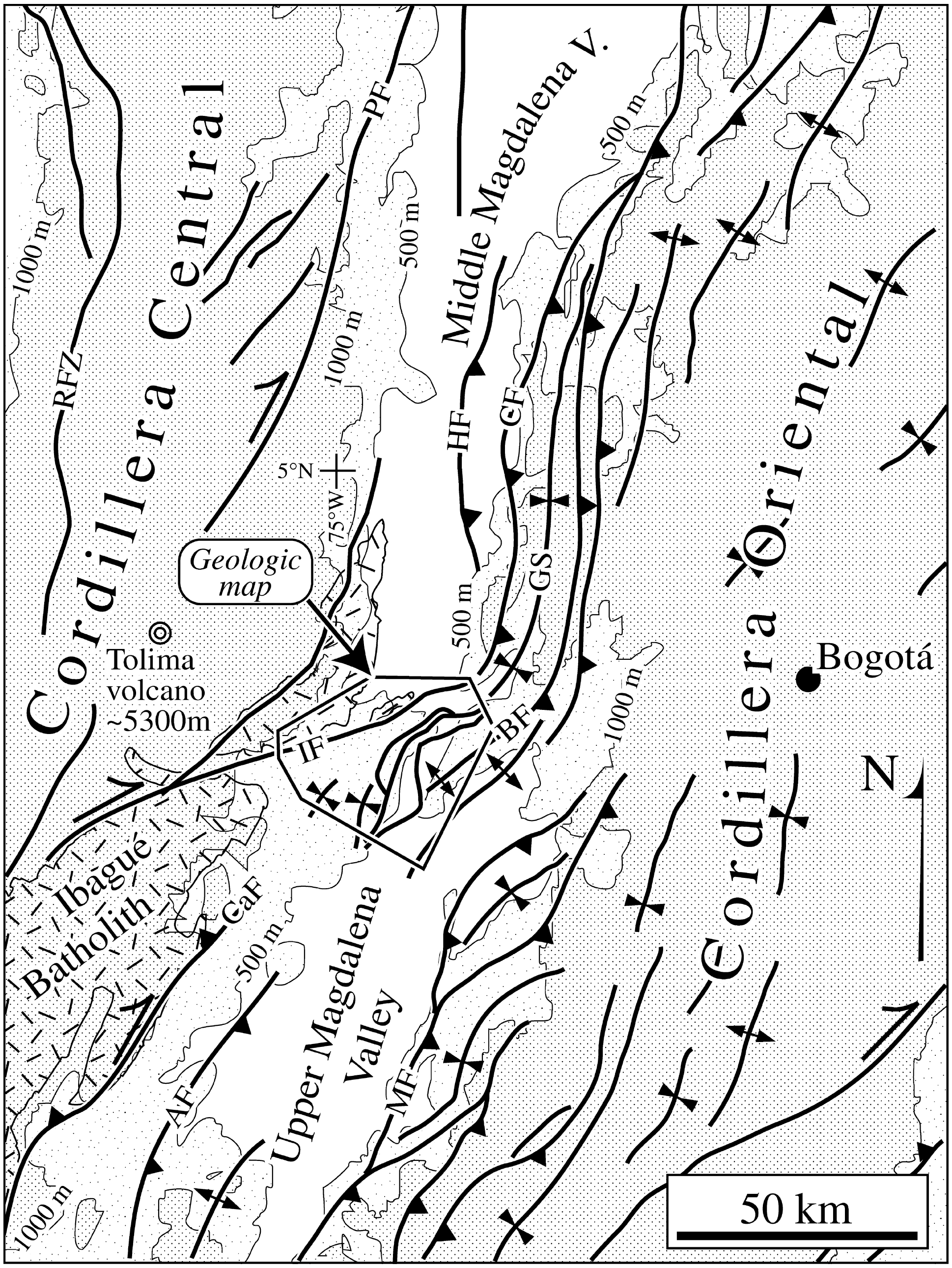


Figure 2. Tectonic map of part of the northern Andes modified after Schamel (1991) and Namson et al. (1994). Light stippled pattern indicates elevations greater than 500 m above sea level. Heavy stippled pattern indicates elevations greater than 1000 m above sea level. AF = Ataco fault; BF = Bituima fault; CaF = Calarma fault; CF = Cambao fault; GS = Guaduas syncline; HF = Honda fault; IF = Ibagué fault; MF = Magdalena fault; PF = Palestina fault; RFZ = Romeral fault zone.

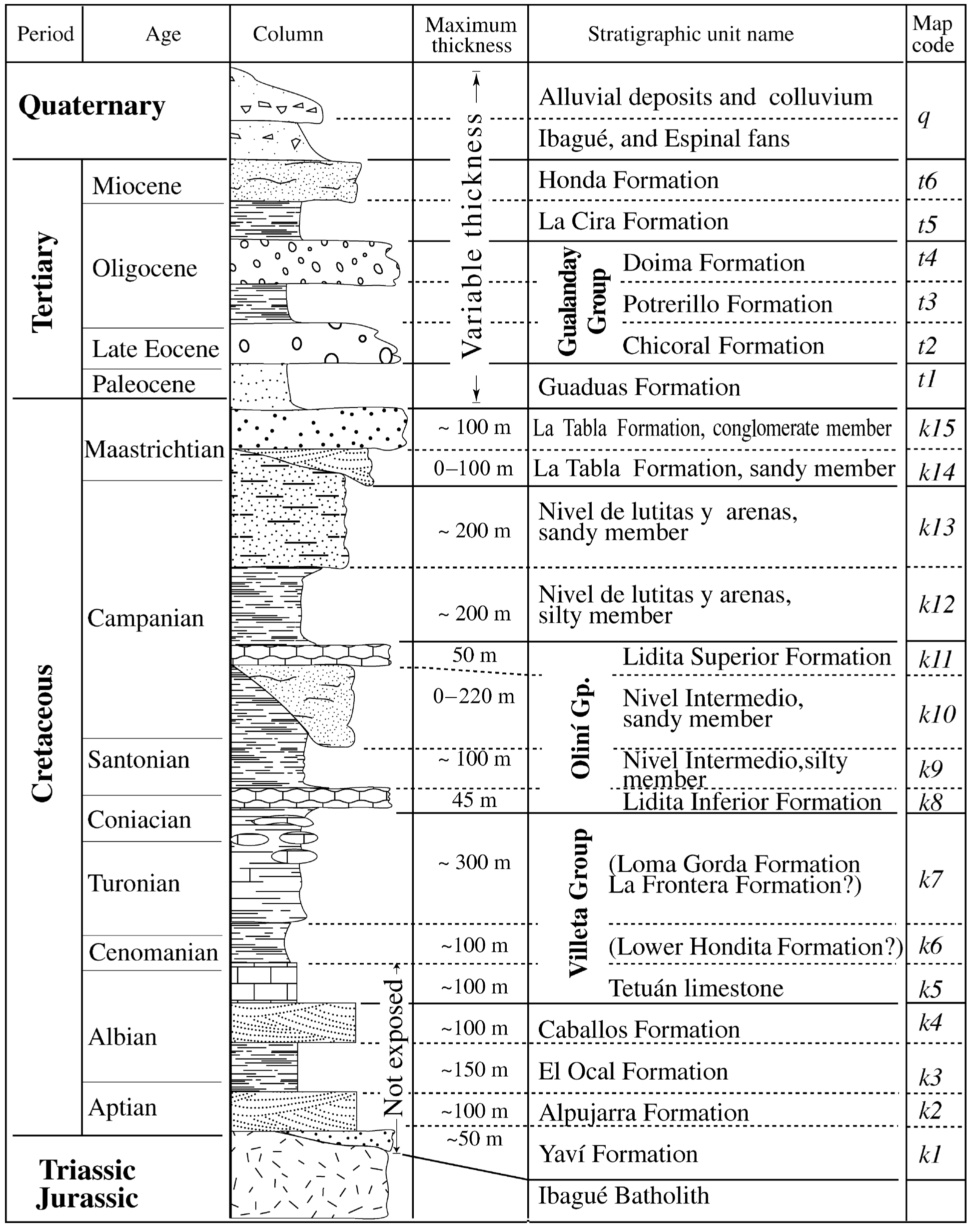
and have their southern termination in this belt (Figure 2).

Structural Style

The PGFB exhibits a wide variety of structures, deformation styles, and trends, a hint of its complex structural evolution. This relatively small fold belt (approximately 500 km^2), contains an array of dextral strike-slip faults, northwest- and southeast-verging thrust faults, a positive doubly vergent structure, northeast-trending tight folds, and north-dipping normal faults (Figures 4 and 5). Structural trends swing from east-west to north-south in a sigmoidal array of folds and faults that diverges southward from the southern termination of the Guaduas syncline. The structure in the vicinity of this fold belt has been previously explained as the result of fold interference patterns (Tellez and Navas, 1962) or gravity gliding tectonics (Kammer and Mojica, 1995).

From east to west, three provinces are defined by their distinctive structural styles and geomorphic signatures (Figures 4, 5, and 6). Tight, closely spaced, northeast-trending folds along the northern half of the study area east of the Cotomal fault (Figures 4 and 5) give rise to a valley- and- ridge-type topography. Map-scale folds cease to be dominant as the topography climbs westward along a gentle dip-slope (Figure 6c) into a high, relatively flat plateau (between the Santuario and Cotomal faults, Figures 4, 5, and 6b) rimmed to the northwest by a narrow ridge that is defined by northwest- and southeast-verging thrust faults and an overturned anticline (Figures 5 and 6a). Farther west (Figures 4 and 6c), the remarkably uniform La Tabla Ridge rises 600 m above the level of the Ibagué fan and marks the western edge of the PGBF.

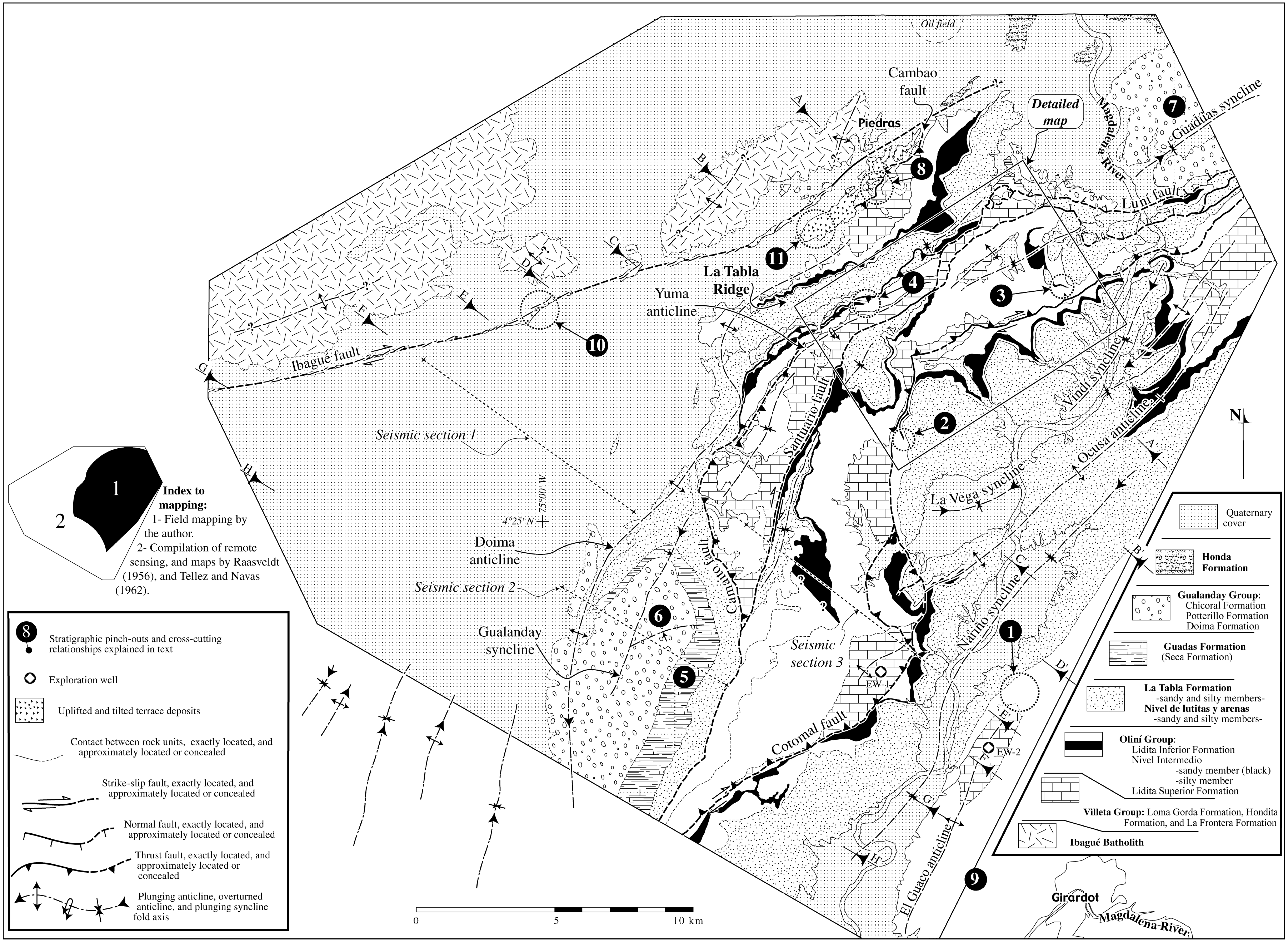
Figure 3. Stratigraphic column of the PGFB, compiled from early studies by Bürgl and Dumit (1954) and DePorta (1965) and modern regional stratigraphic work by Etayo Serna (1994), Florez and Carrillo (1994), and Gómez and Pedraza (1994), modified only to include measured thicknesses and stratigraphic pinch-outs encountered while mapping. The reference Cretaceous stratigraphic column was established along La Tabla Ridge, where good exposures and a simple structure allowed better observation of the sequence and more accurate estimation of stratigraphic thicknesses by correcting the width of the outcrop with measured dips on the map.

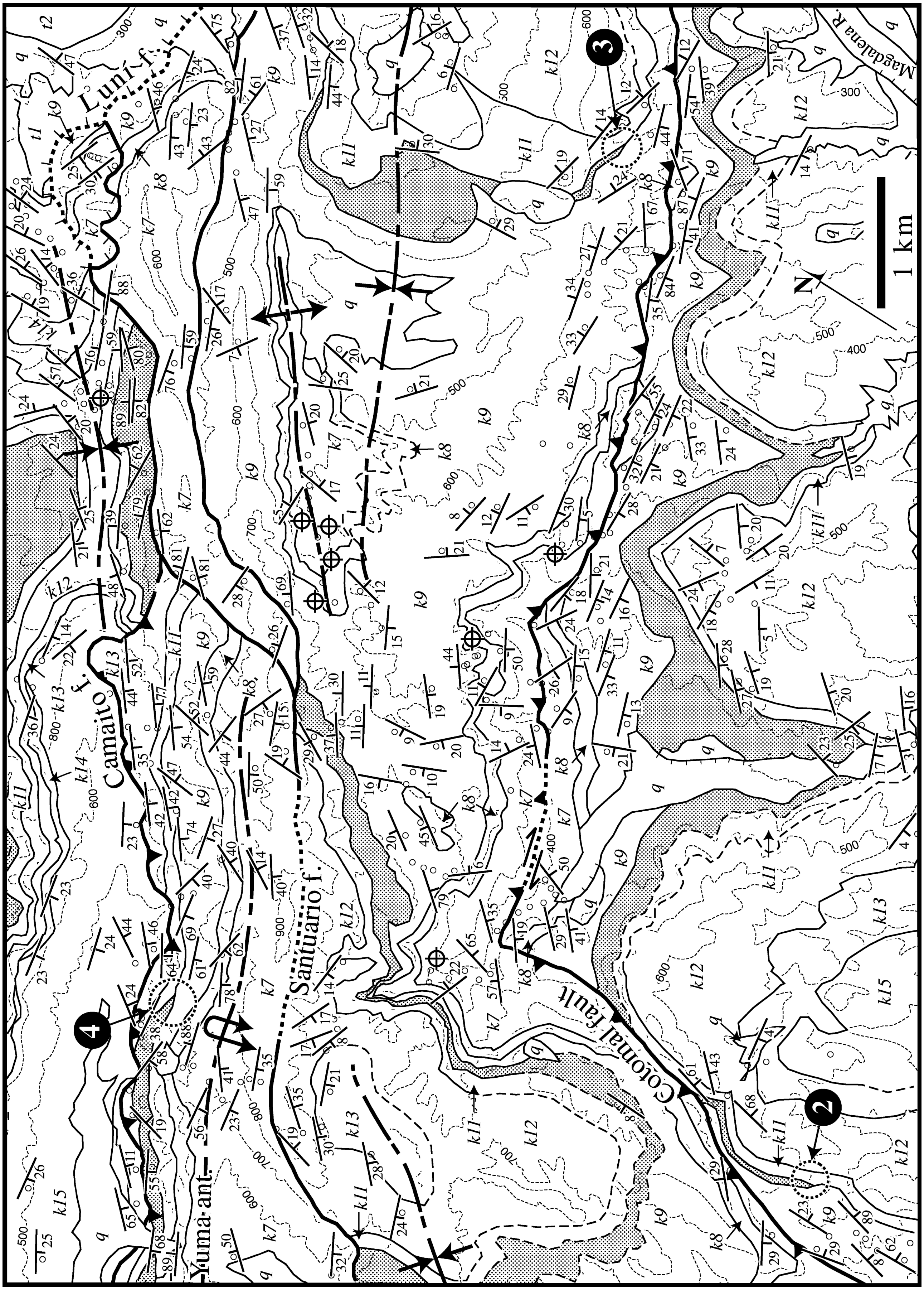


Positive Flower Structure and Camaito Fault

The PGFB culminates in a narrow, 2-km-wide, structurally and topographically high, doubly vergent positive structure bounded to the west by the west-verging Camaito fault and to the east by the east-verging Santuario fault (Figures 4 and 5). The core of this structure exposes strata as old as Turonian (Villeta Group) in the tight, northwest-verging, overturned, and locally faulted Yuma anticline (Figure 5). The northwestern limb of this anticline is overturned and emplaced by the Camaito fault onto upright, gently dipping strata of the La Tabla Formation in a footwall flat. From south to north, the trace of the Camaito fault is arcuate with trends changing from north-northeast immediately east of the Gualanday syncline, to north-northwest, to northeast along La Tabla Ridge. In the northern end of the study area, the trace turns east-west, merging with the north-dipping Luní normal fault. To the south, the trace merges with the Santuario fault as the trend changes to northeast. Observation of the dip angle of the Santuario fault was hindered by the lack of topographic relief along its trace in the plateau. This fault could be mapped only by using truncation of stratigraphic units (mostly Oliní Group) against characteristic calcareous shale and micrite of the upper part of the Villeta Group. The arcuate fault trace of the

Figure 4. Simplified geologic map of the PGFB. Black circles are markers of timing of deformation. 1 to 4 = stratigraphic pinch-out of the sandy member of the Nivel Intermedio; 5 = growth strata in Paleocene unit; 6 and 7 = folded Paleogene growth strata; 8 = post-Miocene activity along the Cambao fault; 9 = pre-Miocene fold; 10 and 11 = Quaternary deformation along the Ibagué fault.


Oil field
Cambao fault
Piedras
Detailed map
Magdalena River
Guaduas syncline
Luni fault
La Tabla Ridge
Yuma anticline
Ibagué fault
Seismic section 1
Santuario fault
Vindi syncline
Ocusa anticline
La Vega syncline
4°25' N
75°00' W
Doima anticline
Seismic section 2
Gualanday syncline
Cambao fault
Seismic section 3
Nariño syncline
EW-1
EW-2
Cotomal fault
El Guaco anticline
Girardot
Magdalena River
N
0
5
10 km
Index to mapping:
1- Field mapping by the author.
2- Compilation of remote sensing, and maps by Raasveldt (1956), and Tellez and Navas (1962).
Stratigraphic pinch-outs and cross-cutting relationships explained in text
Exploration well
Uplifted and tilted terrace deposits
Contact between rock units, exactly located, and approximately located or concealed
Strike-slip fault, exactly located, and approximately located or concealed
Normal fault, exactly located, and approximately located or concealed
Thrust fault, exactly located, and approximately located or concealed
Plunging anticline, overturned anticline, and plunging syncline fold axis
Quaternary cover
Honda Formation
Gualanday Group:
Chicoral Formation
Potterillo Formation
Doima Formation
Guadas Formation
(Seca Formation)
La Tabla Formation
-sandy and silty members-
Nivel de lutitas y arenas
-sandy and silty members-
Oliní Group:
Lidita Inferior Formation
Nivel Intermedio
-sandy member (black)
-silty member
Lidita Superior Formation
Villeta Group: Loma Gorda Formation, Hondita Formation, and La Frontera Formation
Ibagué Batholith


Luní f.
Camaito f.
Santuario f.
Cotomal fault
Yuma ant.
Magdalena R.
N
1 km

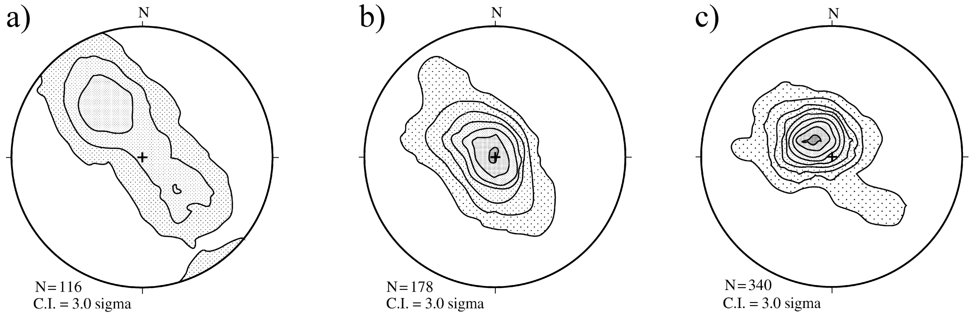


Figure 6. **Equal-area, lower-hemisphere Kamb contour diagrams of poles to bedding in the PGFB. (a) Between the Santuario and Camaito faults, bimodal pattern defines northeast-trending folding. (b) Between the Santuario and Cotomal faults, dip of bedding is very shallow. (c) East of the Cotomal fault and west of the Camaito fault, bedding shows the shallow southeast-dipping monoclines that define ramps at depth.**

Camaito fault and the combination of two outward-verging thrust faults bounding an anticline are interpreted as a positive flower structure (cf. "upthrusts" of Lowell, 1972; "positive flower structures" of Wilcox et al., 1973; "palm tree structures" of Sylvester, 1988) formed in a transpressive regime where slabs rise upward and outward.

Plateau and Cotomal Fault

Immediately east of the positive flower structure, a nearly flat and topographically high plateau (Figure 5) exposes rocks mostly assigned to the Oliní Group. The structure of this plateau is simple, with very shallow dips (Figure 6b). Open, map-scale folding is present only near its northern end, apparently in continuity with the southern termination of the northeast-plunging Guaduas syncline.

This plateau is bounded to the southeast by the east-verging Cotomal fault (Figure 7). From south to north, the trace of this fault shifts trend from northeast to north-south and again to northeast, merging at the northeast end of the study area with the Santuario, Luní, and Cotomal faults, along the southern termination of the Guaduas syncline (Figures 4 and 5). Changes in trend also are accompanied by changes in style; unlike other faults in the PGFB, the northeast-trending segment of the Cotomal fault (Figure 5) separates strata belonging to the same stratigraphic unit, commonly the Oliní Group. Detailed geologic mapping and simple outcrop analysis (Figures 5 and 7) reveal that the vertical separation along the northern, northeast-trending segment of this fault is only a few tens of meters. The north-trending segment of this fault, although less well-constrained by geologic mapping, separates older strata of the lower Villeta Group in the hanging wall from strata of the Oliní Group in the footwall, thereby defining a larger vertical separation of at least the stratigraphic thickness (~600 m). Because the hanging wall cutoff was removed by erosion in the north-trending segment of this fault, the slip along this segment remains undetermined and could be large.

Dip Slopes and Cambao Fault

Two southeast-dipping, remarkably uniform, map-scale dip slopes further characterize the PGFB. Strictly speaking, they are not monoclines because they are in both cases demonstrably only one limb of a fold. Their surface expression, geometry, and location, however, are considerably different from other map-scale structures in the area mapped.

A 10-km-long, 1-km-wide dip-slope gives rise to La Tabla Ridge, which is one of the most prominent topographic features of this fold belt, exposing the entire Cretaceous stratigraphic sequence along its northwestern flank (Figure 3). This southeast-dipping ridge (Figure 6c) is the southeastern flank of the open asymmetric Doima anticline, whose northwestern limb is poorly exposed, as it is partially buried beneath younger volcaniclastic sediments of the Ibagué fan. Unfortunately, erosion of the Ibagué fan has opened only a small inlier through which the northwestern limb of this anticline and the Cambao fault can be studied (Figure 4).

The northwest-verging Cambao fault constitutes the northwesternmost extension of thrusting in the PGFB, and it has numerous oil seeps along its exposed length. This fault places the oldest exposed stratigraphic unit of the PGFB, the lower part of the

Figure 5. **Detailed geologic map of the northern half of the PGFB. The sandy member of the Nivel Intermedio of the Oliní Group is patterned to highlight mapped pinch-outs. Note the offset between the two pinch-outs of this unit in this segment of the Cotomal fault. All symbols are as in Figure 4.**

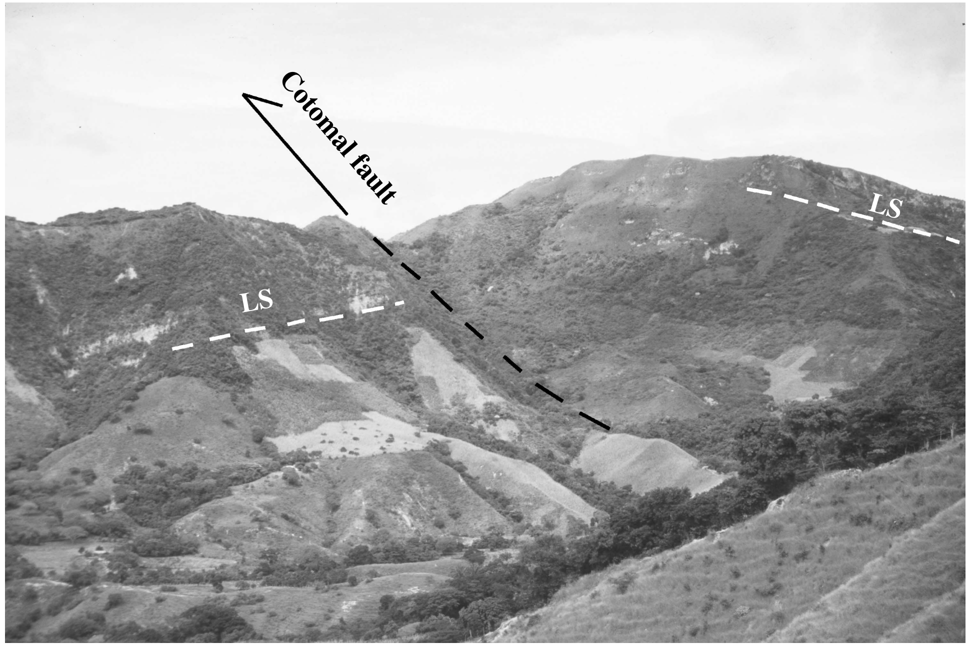


Figure 7. **Cotomal fault in the eastern edge of the plateau (right side of photo). Deep canyons along the eastern side of the plateau expose the hanging-wall and footwall cutoffs of this fault. Note that the cliff-forming unit (LS = Lidita Superior Formation) is offset against the fault in the footwall, and projections of the fault and the same unit in the hanging wall intersect. View is toward the southwest.**

Villeta Group, onto Miocene strata. Immediately south of the southern termination of La Tabla Ridge, the hinge of the anticline in the hanging wall of the Cambao fault turns southeast and then turns back to a northeastern trend over a distance of about 4 km. The southern segment of this anticline (Doima anticline), unlike its northern segment, is a tight upright fold with both limbs well exposed and strata as old as the Oliní Group in its core (Figure 4). Farther south, this fold turns to a more northerly trend.

Southeast of the Cotomal fault, the northwestern flanks of the La Vega–Vindí and Nariño synclines also stand out because of their uniformity and similarity to the dip slopes along La Tabla Ridge. These dip slopes, however, have gentler dips and more variable trends than La Tabla Ridge. These gently dipping slopes are only present immediately southeast of the northeast-trending segments of the Cotomal fault, in its footwall. East of the north-trending segment of the Cotomal fault, this characteristic topographic expression is lost as strata dip more steeply.

Normal Faults

The only east-west trending structures mapped in the entire area of the PGFB are north-dipping normal faults that separate Upper Cretaceous strata in the footwall from poorly exposed Paleogene strata in the hanging wall. Alluvial fans and other recent deposits commonly conceal these structures, except along the north- and northwest-facing topographic front in the northernmost part of the study area (Figures 4 and 8b) and along streams draining the plateau to the north. A conspicuous fault breccia with large (as much as 25-cm long) angular fragments of mostly chert has developed along these normal faults and locally exhibits a transition from fault breccia to pristine rock where the fault cuts Oliní Group rocks (Figure 8a). This breccia helps pinpoint the fault trace to the east, as the Cotomal, Camaito, and Santuario faults merge with the Luní fault and turn to the northeast in the southern termination of the Guaduas syncline. These normal faults not only separate the Cretaceous from the Tertiary sequence, but also split the southernmost nose of the northeast-plunging Guaduas syncline into a northern block exposing only Paleogene strata and a southernmost tip exposing only Cretaceous strata (Figures 4 and 5).

In summary, a complex array of faults and folds exists immediately southeast of the Ibagué fault: northwest- and west-verging thrust faults (Cambao and Camaito faults), north-dipping normal faults (Luní fault), southeast-verging thrust faults (Cotomal fault), and northeast-trending tight folds (Yuma anticline). A positive flower structure is delineated by opposite-verging thrust faults (Camaito and Santuario faults) at the topographic culmination of this fold belt. Changes in structural trends delineate a sigmoidal sinistral stepover, with faults verging outwardly in opposite directions.

Tectonic Transport and Piercing Points

The tectonic transport direction for structures of the PGFB simply cannot be assumed to be perpendicular to structural trends because of the dramatic changes in structural trends and because of the concern about nonplane strain. A weak-to-moderate cleavage present in the Cretaceous sequence records only a)

b)

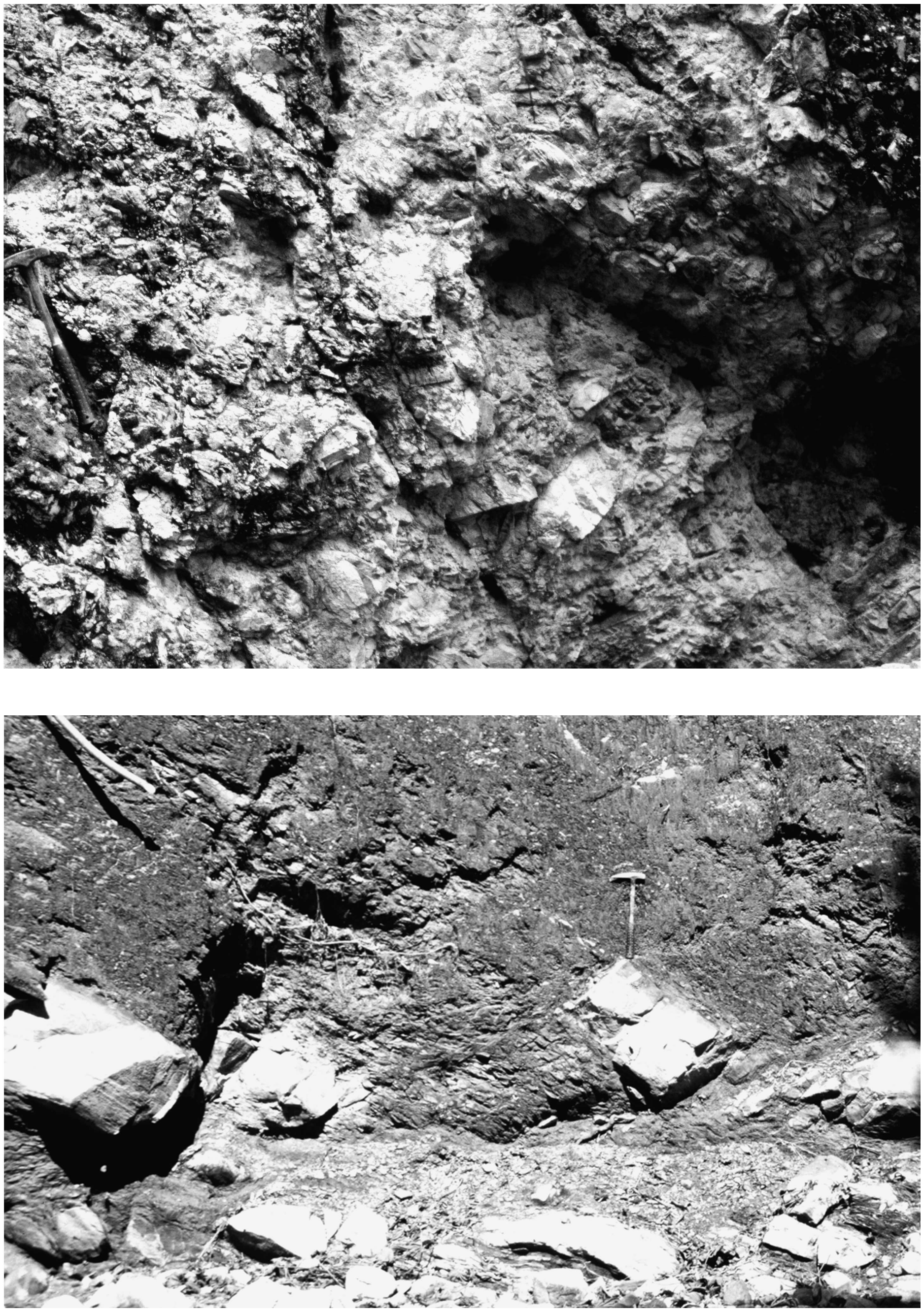


Figure 8. Normal faults in the northern PGFB. (a) Fault breccia (left side of photo) showing gradual change to highly deformed Oliní Group strata, where bedding is still recognizable (location: 74.775° W, 4.526° N). (b) Thick micrite layer offset by normal faults (location: 74.835° W, 4.517° N). Hammer is 41-cm long.

minor shortening and predates significant movement along the map-scale faults (Montes, 2001); therefore, it does not provide kinematic data that would help to decipher later thrusting.

Mild deformation during the Campanian generated gentle domes, where the accumulation of some sandy units did not occur (Montes, 2001); although this first deformation increment recorded only small amounts of strain, its stratigraphic signature provides independent evidence to constrain the two- and three-dimensional reconstructions of this fold belt. Whether these discontinuities in the accumulation of sand are the result of tectonic activity at the time of deposition (Montes, 2001) or the result of some other phenomena, they still constitute a piercing point that can be used as a strain marker. These stratigraphic pinch-outs constitute an excellent piercing point to determine the amount of strike-slip motion along faults because they define a mappable line in map view. If this line is found on both sides of a fault, the horizontal separation along the fault can be measured.

The sandy member of the Nivel Intermedio of the Oliní Group (Figure 3) pinches out across the Cotomal and Camaito faults, providing one such kinematic marker. The two pinch-outs mapped across the Cotomal fault (labeled 2 and 3 in Figures 4 and 5) are equivalent because, in both cases, this unit thins out to the south. These pinch-outs are offset 8 km across the fault, documenting the right-lateral horizontal separation that occurred since the accumulation of this unit (early Campanian).

Even though the distance measured between the two pinch-outs documents the horizontal separation, the direction and total amount of slip is not constrained because this piercing point is a line offset by a dipping fault, making the measured horizontal separation only apparent. Independent evidence for the slip direction is derived from the observation that hanging-wall and footwall cutoffs along the northern, northeast-trending segment of this fault record only small amounts of vertical separation (Figures 5 and 7). The only instance that allows a small vertical separation along a northeast-trending fault, where 8 km of horizontal separation has been documented, is if the slip direction is parallel or nearly parallel to the fault. Therefore, the direction of this 8 km of rigid-body motion must be laterally to the northeast, with very little contraction in a northwest-southeast direction.

An additional pinch-out in this unit (labeled 4 in Figure 4) helps determine the approximate extent of the area where accumulation did not take place because, unlike the other two pinch-outs, this one thins out to the north, thus defining a point along the southern boundary of the area where the accumulation of sand did not occur. Other pinch-outs in this unit could not be interpreted because of incomplete exposure.

TWO-DIMENSIONAL INTERPRETATION AND CROSS SECTION CONSTRUCTION

The structures described above were projected to depth in a suite of eight cross sections using Geosec 2D® (Figure 9). Section locations coincide with industry seismic lines in the southern half of the study area (sections E-E′ to H-H′) or with traverse parts of the map containing abundant field data in the northern half (sections A-A′ to D-D′). Three basic assumptions guided the cross-section construction process: (1) a local detachment level runs along the weak Hondita Formation shale, (2) subsurface ramps are manifested in the surface as gently southeast-dipping monoclines, and (3) the stratigraphic column (Figure 3) is a valid and uniform template with variations in thickness only in the case of syntectonic deposits.

Construction of the cross sections relied on projection of strike and dip data and stratigraphic contacts from a three-dimensional space (defined in the geologic database) into a two-dimensional space defined by the vertical plane of the cross section. Wherever conflicting data were projected into a single point or area of the cross section, a hierarchy was established to consistently give priority to data types; in order of priority: (1) exactly located contacts in the geologic map; (2) thickness of stratigraphic unit; (3) dips projected from the map and wells; (4) seismic reflectors converted to depth; and (5) approximately located or concealed geologic contacts. Additional constraints that were considered during cross-section construction include the need to keep the geometry of folds and faults consistent between sections, and the need to honor kinematic data from the analysis of pinch-outs regarding directions of tectonic transport, as well as syntectonic data regarding timing of deformation.

Seismic lines were converted to depth using migration-velocity analysis checked against two exploration wells. These reflectors were then cross-referenced between lines using strike lines and exploration wells. Subsurface information (Figure 10) was incorporated only where it was supported by the geologic map. Seismic acquisition in the mountainous regions of the Andes is notoriously difficult, often resulting in poorly imaged structures and noisy records. This problem is evident in the more rugged terrain of the PGFB, where seismic reflectors in some cases obviously contradict field mapping. Nonetheless, reflectors imaged in seismic lines in rolling hills, such as the plateau, agreed well with surface mapping. Thus, only the seismic reflectors acquired in the nearly flat Ibagué fan and in the plateau were projected into the cross sections or used to interpret deep structure.

Cambao Fault and Depth to Detachment

The oldest stratigraphic unit exposed in the PGFB is the shaly lower part of the Villeta Group (Lower Hondita Formation, Figure 3). This unit commonly is exposed near the base of fully exposed thrust sheets, such as in the hanging wall of the Cambao fault near Piedras (Figure 4, and cross section A-A′ in Figure 9). The stratigraphic unit immediately below is the Caballos Formation, a thick, massive quartz sandstone exposed south of the PGFB (Raasveldt, 1956) resting in angular unconformity on Triassic–Jurassic volcaniclastic rocks. The total absence of this sandy unit in the study area has been previously interpreted to reflect the northernmost progradation of sands during the Albian relative sea-level drop (Schamel, 1991; Etayo Serna, 1994). Alternatively, a detachment level may utilize the weak shale along the base of the Villeta Group, thus concealing the presence of the Caballos Formation (or its lateral equivalent) in the PGFB. If the reason for the absence of the Caballos Formation in the study area is purely stratigraphic, basement should be exposed in the hanging wall of faults with large throws, such as the Cotomal fault (approximately 8 km). Basement is not exposed in such hanging walls; thus, Cretaceous and

Tertiary strata must be detached at this weak level, concealing older stratigraphic units. In addition, the black shale of the Hondita Formation and equivalent units of the lower part of the Villeta Group constitute the lowest continuous weak unit in the stratigraphic sequence of this part of the Magdalena Valley. Weak units stratigraphically below the Hondita Formation (Figure 3), such as the Ocal Formation, are characteristically discontinuous (Florez and Carrillo, 1994) and probably would not constitute an efficient detachment level. The facies and thickness of these concealed units is unknown, and for the purpose of cross-section construction (Figure 9), they were simply extrapolated from stratigraphic studies of these units farther south (Florez and Carrillo, 1994).

The thickness of the Cambao thrust sheet above the Hondita Formation detachment could be measured only where the Cambao fault reaches the surface near Piedras (Figure 4, and cross section A-A′ in Figure 9). If the detachment remains at the same stratigraphic level to the south, the depth and location of the Cambao fault can be extrapolated from the mapped contacts in the surface and the measured thickness of the thrust sheet near Piedras. Thus, dipping strata along La Tabla Ridge can be used to ''hang'' the dip and location of the footwall ramp in cross sections B-B′ to D-D′ (Figure 9). Although the La Tabla Ridge as a topographic feature is absent in the southern half of the study area, the eastern limb of the Doima anticline still was used to extrapolate the location of the footwall ramp in cross sections G-G′ and H-H′ (Figure 9), while including the stratigraphic thickness changes of the Guaduas Formation and Gualanday Group (Figure 10b). The presence of deep seismic reflectors (>1 sec., approximately 3000 m, Figure 10a) in the western halves of sections E-E′ to H-H′, suggests that repetition of Cretaceous strata occurs in continuity with the Cambao fault to the north. So, although this fault is not exposed, its presence in the subsurface of the PGFB is confirmed by deep seismic reflectors and by syntectonic strata (Gualanday syncline), folded and transported by an intra-Cretaceous detachment, most likely the Cambao fault.

A Deeper Detachment

This interpretation of the geometry of the Cambao thrust sheet indicates that it consists exclusively of Cretaceous cover rocks in the northern and middle parts of the fold belt (cross sections A-A′ to E-E′ in Figure 9), whereas it involves lower parts of the stratigraphic sequence, possibly Triassic–Jurassic volcaniclastic rocks (Saldaña Formation), in the southern end of the fold belt (cross sections F-F′ to H-H′ in Figure 9). Older stratigraphic units in the southernmost sections are involved because seismic lines (Figure 10a and 10b) show a relatively silent zone at shallow levels (approximately 0.5 secs) below the Cretaceous strata in the eastern limb of the Gualanday syncline. This relatively silent zone was interpreted to correspond to Triassic–Jurassic volcaniclastic rocks in the hanging wall of the Cambao fault because Cretaceous and Tertiary reflectors in contrast are characteristically continuous and strong.

Although the Triassic–Jurassic volcaniclastic sequence may contain sporadic shale layers (Cediel et al., 1981; Bayona et al., 1994), it traditionally has been interpreted as a relatively strong sequence considered part of the mechanical basement for Cenozoic deformation (the Andean phase of deformation). However, the presence of basement-cored folds indicates that the upper part (approximately 1000 m) of the Triassic–Jurassic volcaniclastic sequence is detached. A similar behavior was proposed farther south to explain asymmetric paired synclines and basement-cored anticlines (Schamel, 1991), although the detachment proposed in that model was much deeper, at middle crustal levels.

In the PGFB, not only the Cambao thrust sheet contains the upper part of the Triassic–Jurassic volcaniclastic sequence, but also the Camaito thrust sheet carries this part of the sequence (e.g., wells EW1 and EW2 in cross sections E-E′, and F-F′ in Figure 9). The thickness of the Camaito thrust sheet was calculated by projecting to depth the western limbs of the La Vega–Vindí and Nariño synclines until they intersected the Cambao fault. The projection of this thrust sheet underneath the axis of the synclines defines the depth to this detachment that cuts across the remaining Cretaceous sedimentary sequence (Caballos Formation) into the upper part of the Triassic–Jurassic volcaniclastic sequence. Thus, the footwall of the Cambao fault defines a ramp-flat-ramp geometry that cuts across the upper part of the Cretaceous sequence, remains parallel to the base of the Hondita Formation along the local detachment, then dips across the remaining Cretaceous sequence into a flat in Triassic–Jurassic basement.

Delamination and the Cotomal Fault

The weak shale of the Hondita Formation near the base of the Villeta Group also is used as a detachment by the Cotomal fault. A piercing point along the northern, northeast-trending segment of the

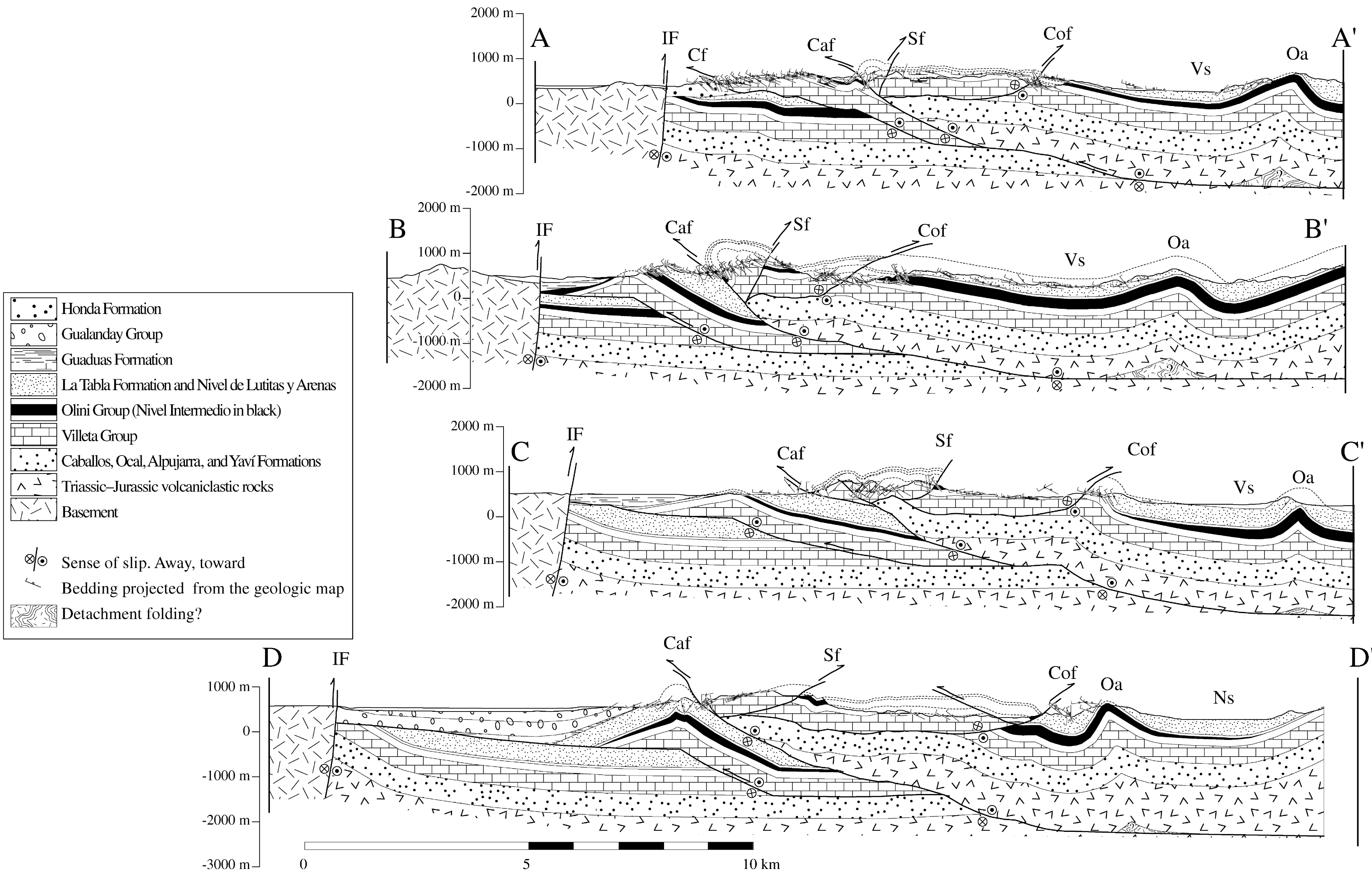


Figure 9. Serial cross sections of the PGFB. See text for discussion and Figure 4 for location. Caf = Camaito fault; Cf = Cambao fault; Cof = Cotomal fault; Da = Doima anticline; Gs = Gualanday syncline; IF = Ibagué fault; Ns = Nariño syncline; Oa = Ocusa anticline; Sf = Santuario fault; Vs = Vindí syncline.

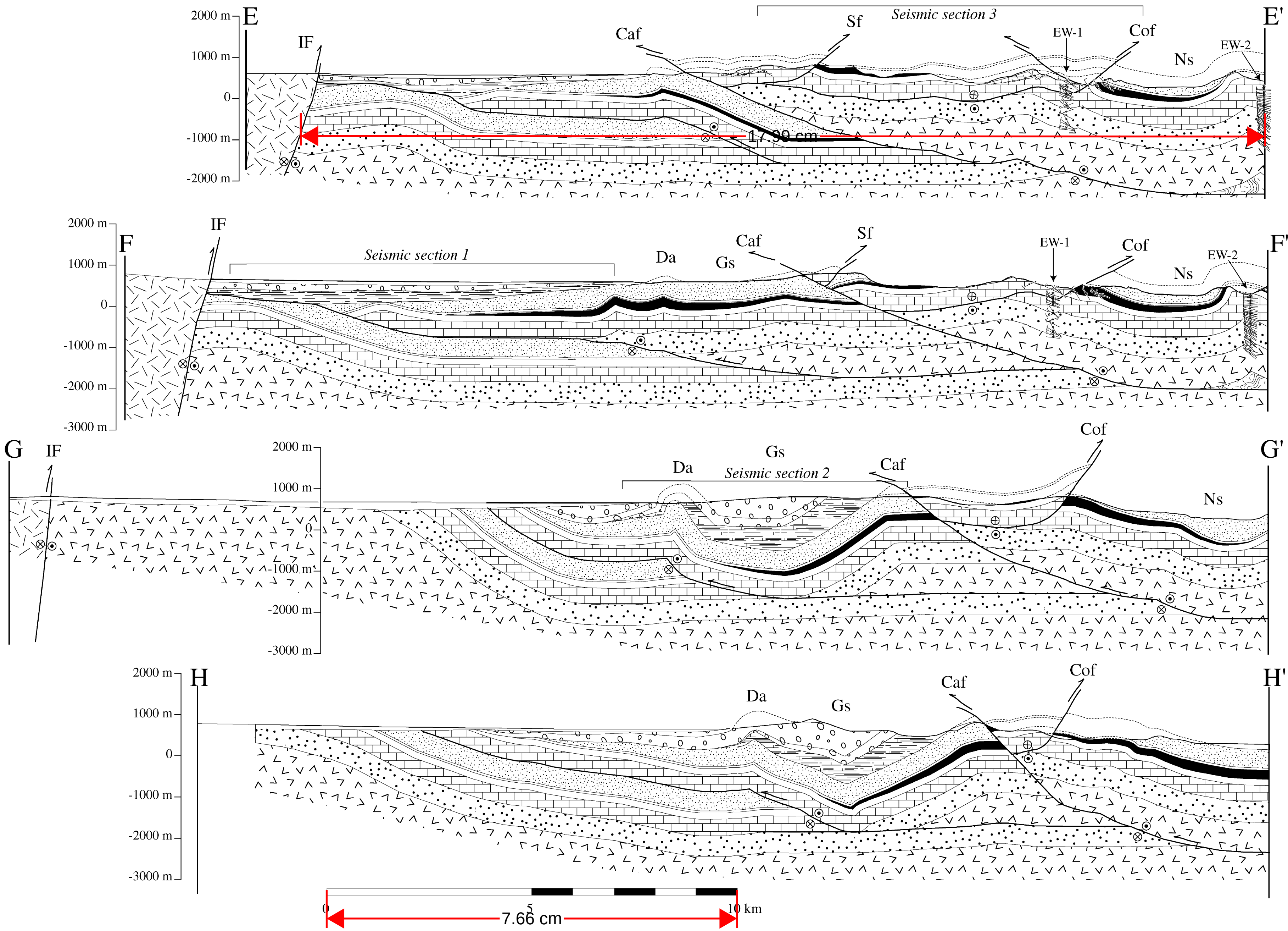


Figure 9. (cont.).

HOME
CONTENTS
SEARCH

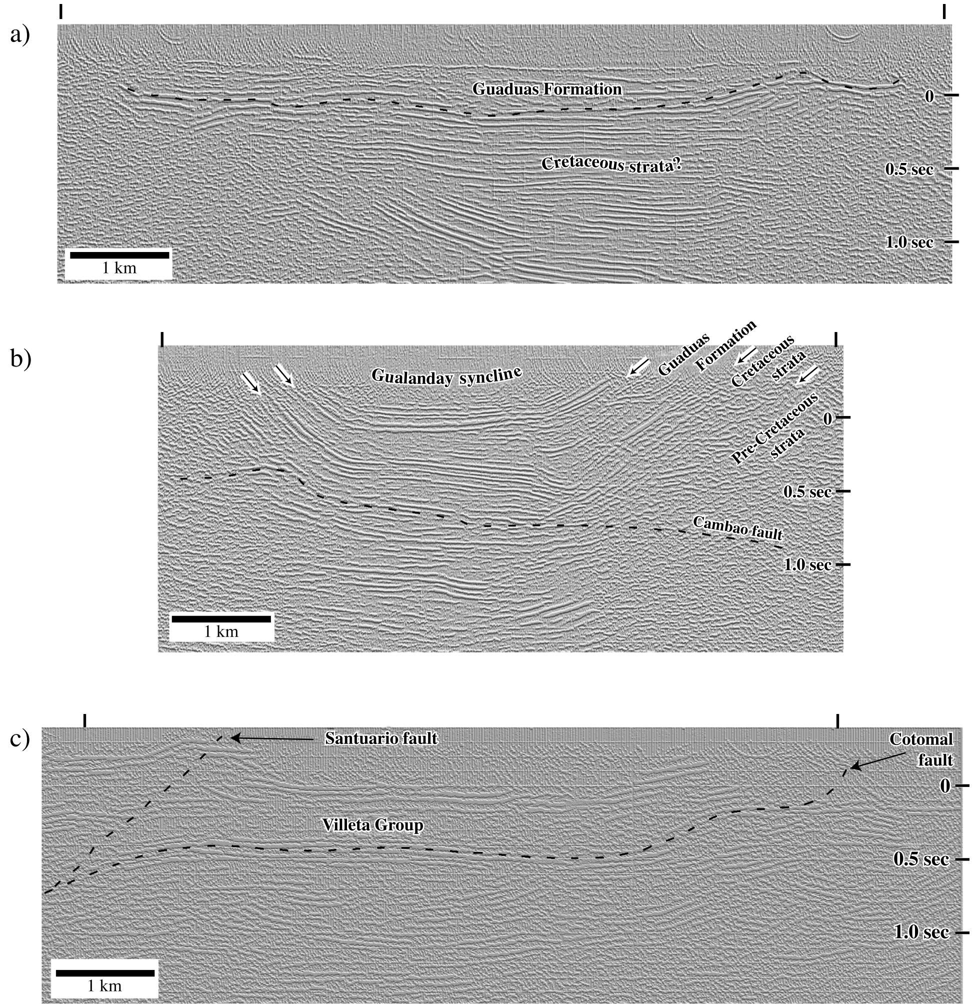


Figure 10. Seismic lines across the southwestern part of the PGFB. See Figure 4 for location. (a) Seismic section 1: Cretaceous strata offset along the base of the Guaduas Formation. Compare with the western half of cross section F-F′. Note the deep reflectors imaged in this section, probably corresponding to a repetition of the Cretaceous sequence below the Cambao fault. (b) Seismic section 2: Growth strata in the core of the Gualanday syncline. Note the dramatic thickness changes in the Guaduas Formation. Hanging wall of Cambao fault brings up pre-Cretaceous strata, more likely the Jurassic Saldaña Formation. Compare with cross section G-G′. (c) Seismic section 3: Across the southern part of the plateau, the Villeta Group apparently is detached along the east-verging Cotomal fault. All these sections correspond to the GT-90 seismic program; section 1 is part of line 1672, section 2 is part of line 1625, and section 3 is part of line 1695.

Cotomal fault documents 8 km of right-lateral northeast-southwest displacement, with a small vertical component. The middle segment of this fault, however, trends to the north, and would be expected to have a much larger dip-slip displacement for the same northeast-trending slip vector. Although this north-trending segment necessarily accommodates 8 km of northeast-southwest convergence, it exposes only the lower part of the Villeta Group in the hanging wall (cross sections C-C′, D-D′, E-E′ in Figure 9). If the Cotomal fault did not root at the weak shale of the base of the Villeta Group, the 8 km of northeast-southwest contraction should necessarily bring the basement to the surface. The geologic map (Figure 4) shows that this is not the case. Therefore, the Cotomal fault is interpreted to root at the base of the Villeta Group, separating the Villeta Group and younger units in the hanging wall from the Caballos Formation and older units in the footwall. The Cretaceous sequence below the Caballos Formation and the upper part of the mechanical basement thus define a tectonic wedge bounded above and below by thrust faults of opposite vergence (tectonic delamination, Price 1986). Delamination also is supported by seismic reflectors that allow tracing of the Cotomal fault beneath the plateau along the base of the Villeta Group (Figure 10c).

Given the interpretation of the Cotomal fault as a roof to the tectonic wedge above the Camaito fault, and the fact that the Cotomal fault has significant dextral offset, it seems appropriate to test whether restoration of the cross sections by removing simple convergence is viable (e.g., Elliot, 1983). Three cross sections were selected to attempt this plane-strain restoration (Figures 9 and 11). Examining the equal-area restorations, large area deficiencies below the lower part of the Villeta Group are evident and cannot be solved by honoring available data and performing a plane-strain restoration.

In summary, the northwest-verging Camaito thrust sheet obliquely transported the entire Cretaceous sequence and a portion of basement to the southwest

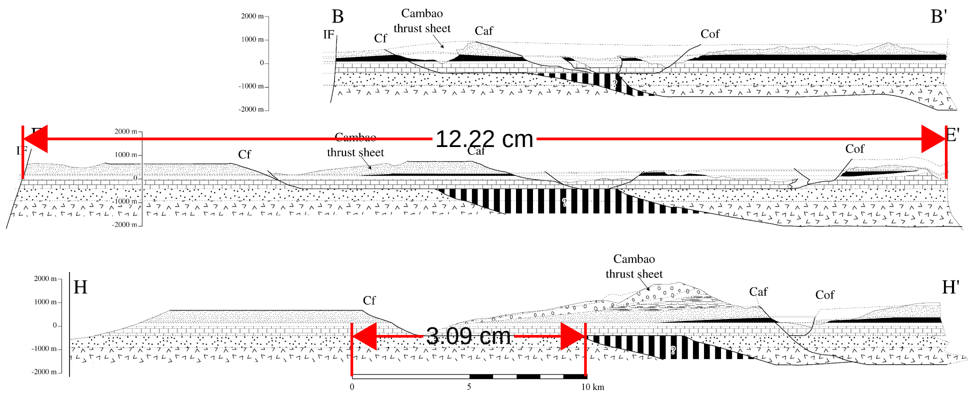


Figure 11. Failed restoration attempt of three of the cross sections in the PGFB. Note the significant deficiency of subdetachment area in all cross sections (vertical pattern). All symbols and patterns are as in Figure 9.

over an irregularly shaped ramp-flat-ramp surface of the Cambao fault. The emplacement of the Camaito thrust sheet was accommodated by two elements: tectonic wedging with the southeast-verging Cotomal fault as a roof thrust that has significant dextral offset; and development of a positive flower structure between the Camaito and Santuario faults at the tip of the wedge (Figure 9).

PALINSPASTIC RESTORATION, MAPPING CUTOFFS

Cross sections can be balanced where the condition of plane strain applies so that bed lengths in hanging-wall and footwall blocks match before and after deformation. In the PGFB, however, material moves in and out of the plane of the section as a result of displacements oblique or parallel to the structural trend (Figure 11). Nonetheless, the cross sections presented in this paper (Figure 9) contain a wealth of information regarding the three-dimensional structure of this fold belt— particularly the location of hanging wall and footwall cutoffs. This sets the foundation of a simple method to attempt the construction of a three-dimensionally viable model for the PGFB (Figure 12). This method consists of unfolding each thrust sheet on each cross section to obtain a map view of its undeformed shape and extent. This simple technique yields quantitative palinspastic restorations only where the hanging-wall and footwall cutoffs can be mapped (Figure 13) and little internal distortion has taken place during transport (Montes, 2001). Once the shape and extent of each thrust sheet has been established, kinematic markers can be used to restore the blocks to their initial configuration.

Hanging-wall and footwall cutoffs were used to quantify the original shapes of individual thrust sheets by restoring the top of the Villeta Group to a horizontal position in all cross sections. Separate unfolding of each thrust sheet (Figures 13a to 13d) reveals the initial shape of each sheet. The resulting thrust sheets can be transported along the strike to achieve a geometric fit, like the pieces of a puzzle, in agreement with the observation of nonplane strain. In fact, two of the pieces of this puzzle contain a stratigraphic piercing point (Figures 4 and 5) that constrains their initial positions relative to each other (blocks III and IV in Figure 13e) and documents the local direction and amount of tectonic transport (8 km, east-northeast–west-southwest).

The direction and amount of displacement documented by the piercing point was used to propose a consistent kinematic scheme in which individual thrust sheets can be displaced along east-northeast trends, nearly parallel to the Ibagué fault until the restored top of the Villeta Group achieves a geometric fit with neighboring blocks (Figure 13e). This kinematic scenario also is consistent with the observations regarding structural style in outcrop and

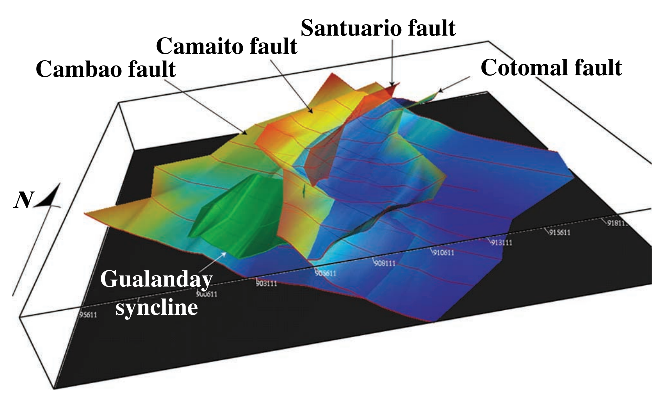


Figure 12. Perspective view of the three-dimensional model showing only the major faults of the PGFB. This visualization was used to test the three-dimensional validity of the two-dimensional cross sections; e.g., no surfaces should intersect. Color shading represents elevation for each surface, and it was added only for clarity.

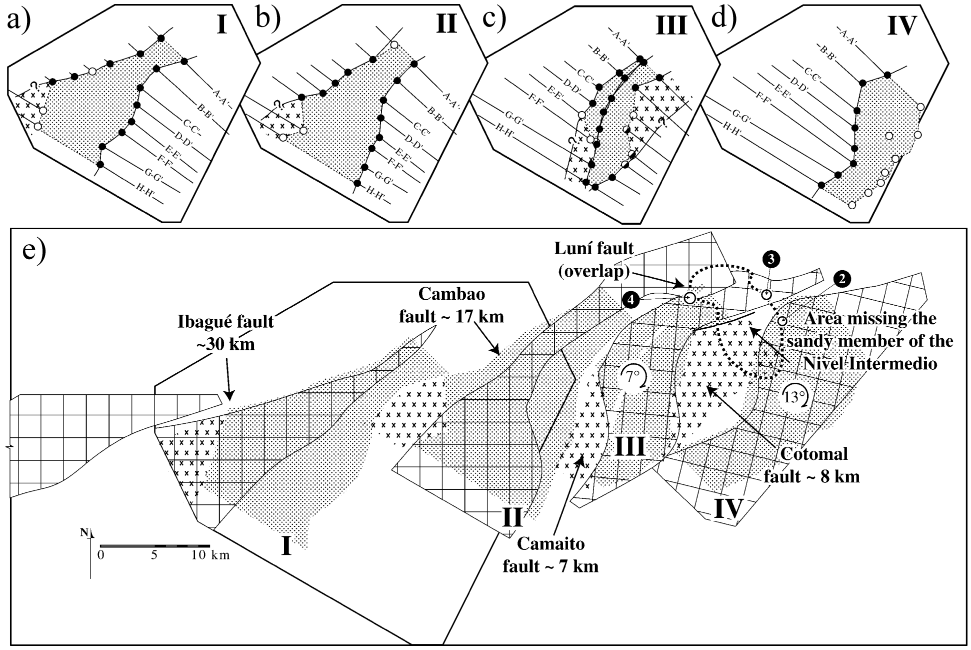


Figure 13. **Palinspastic reconstruction of the top of the Villeta Group (pattern) in the PGFB. Black dots along cross-section lines represent mapped or interpreted location of hanging-wall cutoffs. White dot or half-white dot represents a cutoff removed either by erosion or uncertain. Areas filled with a pattern of crosses indicate the likely areal extent of top of the Villeta. (a) Restored lengths in the footwall of the Cambao fault. Ibagué fault was used as the pin line. (b) Restored lengths in the Cambao thrust sheet. An arbitrary pin line was chosen. (c) Restored lengths in the plateau (Camaito and Cotomal hanging walls). (d) Restored lengths in the footwall of the Cotomal fault. Hinge of the La Vega–Vindí and Nariño synclines was used as pin line. (e) Geometrically acceptable fit of the thrust sheets in the PGFB.**

map scale and with the regional geologic setting. The resulting palinspastic restoration documents approximately 52% east-northeast contraction, not including the Ibagué fault. The best geometric fit is obtained if blocks III and IV are rotated clockwise 7° and 13°, respectively. The kinematics and geometry of deformation show that the PGFB is a classic example of a dextral transpressional system with a stepover to the left (Figure 14a). This fold belt accommodates contraction along north- and northwest-trending segments of the Cotomal and Camaito faults, dextral strike-slip along their northeast-trending segments, and extension along the north-trending Luní fault. In total, approximately 32 km of east-northeast–west-southwest contraction are recorded in this fold belt, 17 km are accommodated to the west-southwest in the Cambao fault, approximately 7 km in the Camaito fault, and approximately 8 km to the east-northeast in the Cotomal fault. The Cambao fault represents the master fault in this fold belt, transporting the entire Mesozoic sequence and basement along a winding ramp-flat-ramp geometry. Syntectonic sedimentation dates large-scale propagation of these thrust sheets to the early Paleogene, with further activity during the Neogene (Montes, 2001). This structural style had not been reported previously in the northern Andes, although the term "transpressional" was used liberally to name a tectonic transport direction nearly perpendicular to the structural trend of the Cordillera Oriental (Kammer, 1999).

FORWARD MODELING

A partial three-dimensional forward model was run in Geosec-3D® to qualitatively test the kinematic viability of some of the first-order structures shown in the geologic map. This model was built by applying the constraints from the palinspastic reconstruction (Figure 14a) to set the geometric and kinematic boundary conditions. The initial undeformed model consists of a restored and simplified version of the geometry of the Cambao fault and two surfaces representing the top of the Cretaceous strata (at 0 m) and the top of the Villeta Group (at −1200 m) (Figure 14b). The total thickness of the sequence above the detachment was set at 2100 m. The sinuous surface with a flat-ramp-flat geometry representing the Cambao fault was obtained by unfolding the footwall of this fault and removing the remaining tilt by using the top of the Cretaceous as a datum. These initial surfaces were defined by an triangular irregular network (TIN) with cell sizes of approximately 300 m. Deformation was modeled in two steps: the first one simulates 7 km of west-southwest motion on the Camaito thrust sheet, and the second one simulates the motion of both the Cambao thrust sheet and the

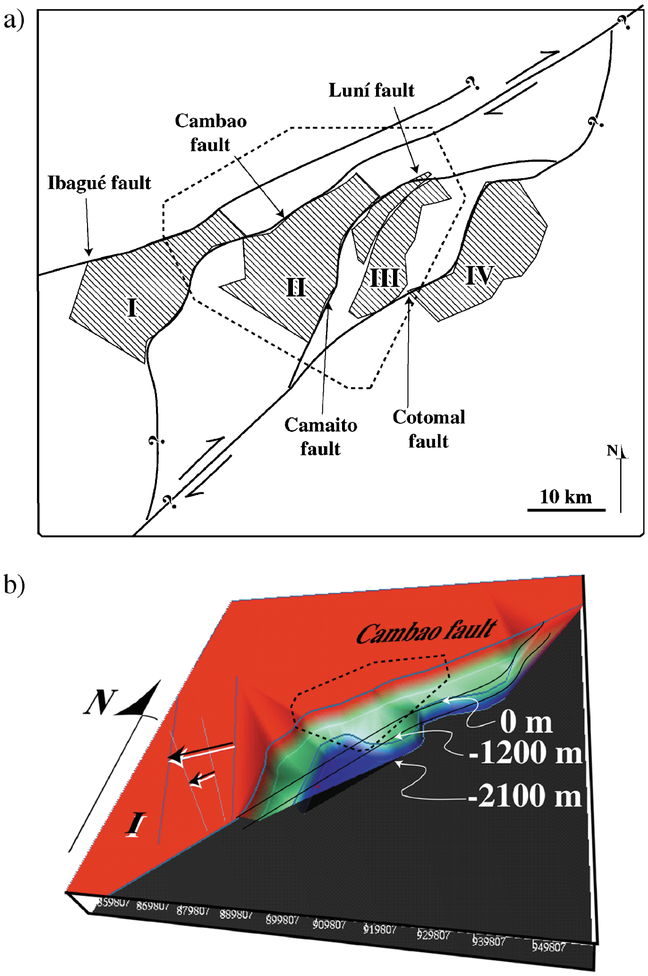


Figure 14. **Simplified palinspastic geometry of the PGFB used to construct the initial state of the forward model. (a) Map view of this dextral strike-slip shear zone stepping over to the left, defining a zone of transpressional deformation. (b) Initial geometry of the three-dimensional model based on the simplified geometry of the palinspastic reconstruction. For simplicity, only the northwestern half of the PGFB was modeled (blocks I, II, and III).**

Camaito thrust sheet transported in piggyback 17 km to the west-southwest (Figure 15).

This synthetic forward model successfully reproduces some of the first-order structures in the northwestern PGFB: the location, shape, and orientation of the La Tabla Ridge; the location of structurally and topographically low regions of the La Vega syncline; and the location and migration of the Gualanday syncline in the back of the Cambao thrust sheet (Figure 15). It also predicts the elevation differences between the plateau and surrounding regions, as well as the stratigraphic levels exposed to erosion. On the other hand, this model cannot reproduce the more complex structural features of the PGFB such as delamination and doubly-vergent structures because of the oversimplified boundary conditions imposed at the beginning, which are related to technological barriers.

This model demonstrates that the surfaces and kinematics of deformation obtained by palinspastic restoration of a three-dimensional model (Figure 12) can adequately reproduce the first-order structural style observed in the PGFB. Therefore, the palinspastic reconstruction is three-dimensionally valid (Figure 13), and the three-dimensional model constructed based on two-dimensional cross sections (Figure 12) most likely preserves volume before and after deformation (Dahlstrom, 1969). This type of partial verification, through palinspastic restoration (Figure 13) and forward modeling (Figures 14 and 15), is an adequate test of the validity of the three-dimensional model (Figure 12). Since the three-dimensional model was constructed using serial two-dimensional cross sections based on field observations and seismic interpretations, it can be considered admissible (e.g., Elliot, 1983). A palinspastic restoration that is capable of reproducing first-order structures if modeled forward, indicates that the three-dimensional model is viable for at least the first-order structures and kinematics of deformation. Because the exact degree of correlation between an open natural system, such as the PGFB and its three-dimensional representation in a digital model (Figure 12), cannot be exactly established, further verification is impossible (Oreskes et al., 1994). Internal geometric constraints such as those used in the two-dimensional approach only demonstrate that the model is internally consistent. Thus, the value of the two- and three-dimensional models presented here lies in their ability to demonstrate the viability of transpressional deformation in the northern Andes, a region where the contribution of strike-slip has been traditionally ignored.

DISCUSSION AND REGIONAL IMPLICATIONS

Two regional structures of the northern Andes terminate at the northern end of the PGFB: the north-trending Guaduas syncline and the east-northeast-trending Ibagué fault. Other north-trending faults and folds of the western flank of the Cordillera Oriental are deflected clockwise and diverge southwestward within the PGFB, where gentler, more spaced folds expose higher stratigraphic levels to the south and west (Figure 2). These changes are the expression of two very different structural styles: the PGFB accommodates east-northeast dextral transpressional deformation, whereas west-verging thrust faults and

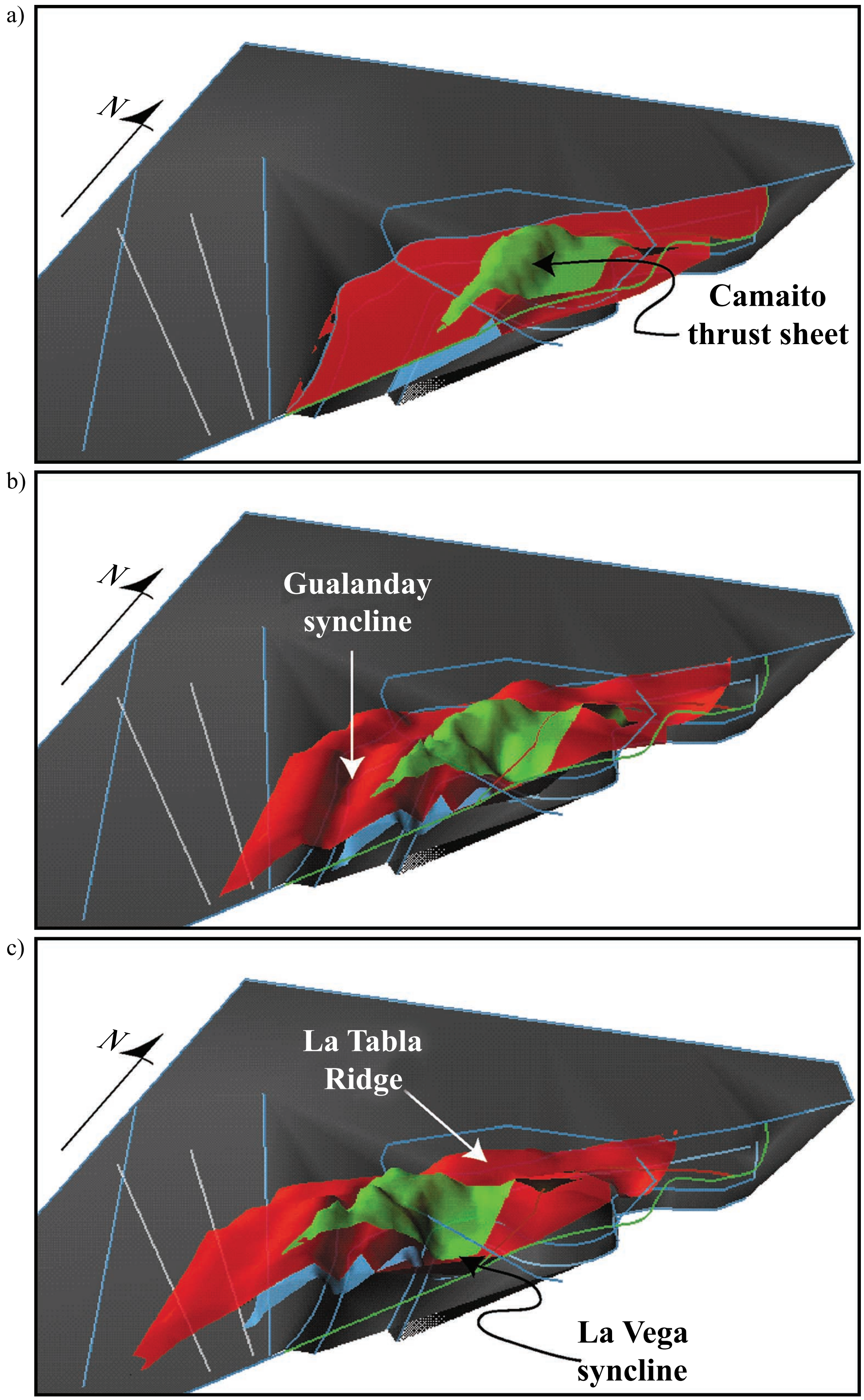


Figure 15. Sequential steps of deformation of the forward model. (a) First increment simulating the propagation of the Camaito fault. (b) Intermediate state, showing the development of a syncline in the back of a thrust sheet, similar to the Gualanday syncline. (c) Final state resembling first-order structures of the PGFB.

folds along the western flank of the Cordillera Oriental apparently accommodate east-west contraction (Namson et al., 1994). These sharp contrasts can be interpreted in terms of the interaction between the Ibagué fault and structures of the Cordillera Oriental that serve to transfer deformation from one system to the other.

The Ibagué Fault, Southern Border of a Rigid Indenter

Strikingly different structural styles and trends across the Ibagué fault indicate that this fault, whose length has not really been established (70 km: Cediel and Cáceres, 1988; 150 km: Ingeominas, 1988), is a fundamental tectonic boundary. Bold changes in the distribution, style, and magnitude of deformation to the south and to the east of this fault can be interpreted as the result of the east-northeast translation of a rigid indenter along the Ibagué fault into the domain of the Cordillera Oriental (Figure 16).

First, the minimum displacement of the Ibagué fault can be inferred from the regional geologic map and from observation of regional outcrop patterns. This fault traverses the Cordillera Central into the PGFB, where the northernmost exposures of the Ibagué Batholith granodiorite, and the north-trending topographic front of the Cordillera Central (marked by the 1000-m contour interval in Figures 2 and 16) are separated approximately 30 km. Because the Ibagué Batholith granodiorite is not exposed farther east beyond the PGFB, 30 km may be considered a first-order

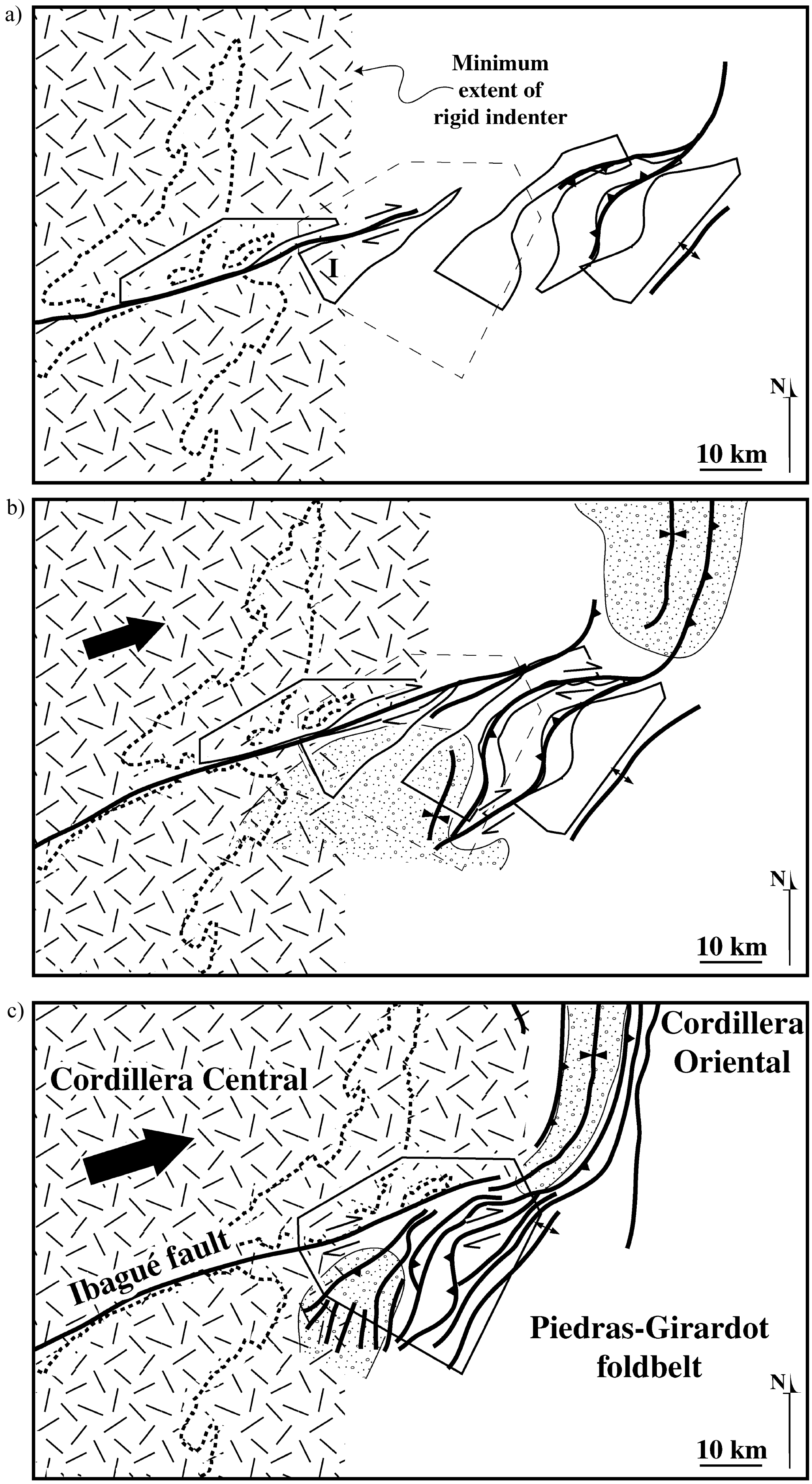


Figure 16. Semiquantitative reconstruction of the east-northeast translation of the rigid indenter of the Cordillera Central (showing its minimum extent) along the Ibagué fault. Note that block I and the outline of the study area (diamond-shaped polygon) are kept fixed as reference. (a) Palinspastic restoration for the latest Cretaceous with 30 km of dextral displacement along the Ibagué fault. All other blocks are as in Figure 14. (b) Paleogene configuration. Stippled areas indicate areas where the accumulation of molasses took place. (c) Present configuration.

approximation of the minimum displacement of the Ibagué fault. The vertical component of the Ibagué fault could be more than 1000 m, if it is assumed that the northern block was covered by a Mesozoic sedimentary sequence (Figure 3) that was later completely eroded, at least in the vicinity of Piedras.

Second, the Ibagué fault separates provinces with markedly different structural styles. The northern block of the Ibagué fault has behaved apparently as a rigid block because it contains undeformed strata in a region where rocks of the same age are ubiquitously folded and faulted. Its relative rigidity is demonstrated by the presence of undeformed Cenozoic strata overlapping the Ibagué Batholith granodiorite along the western margin of the Magdalena Valley (Raasveldt, 1956; Barrero and Vesga, 1976; Schamel, 1991). South of the Ibagué fault, in contrast, the same crystalline rocks are thrust upon folded and faulted Mesozoic and Cenozoic strata (Butler and Schamel, 1988; Schamel, 1991). The Ibagué fault also marks a significant change along the eastern margin of the Magdalena Valley, as large north-trending, west-verging thrust faults mark the topographic front of the Cordillera Oriental north of the Ibagué fault. South of it, the doubly vergent PGFB breaks this trend, and the topographic and deformation front of the Cordillera Oriental recedes eastward several tens of kilometers (Figure 2). The relative rigidity of the northern block may be related to the absence of one or all of the weak units present elsewhere in the stratigraphic sequence (Figure 3) or in the Triassic–Jurassic sequence. If one or all these units are indeed absent across this fault, it would indicate that it has been a tectonic boundary for a very long time, controlling sedimentation patterns since the Mesozoic.

Third, at least 30 km of east-northeast dextral, rigid-body translation of the northern block of the Ibagué fault were accommodated in different ways, depending on the relative position of cover rocks with respect to this rigid block. The segment of the western flank of the Cordillera Oriental immediately north of the PGFB is directly in front of this east-northeast advancing block and apparently accommodates this contraction along the major faults of Bituima and Cambao and folding in the Guaduas syncline. The amount of east-west shortening calculated for these structures, between 16 and 26 km (for the southernmost two sections of Namson et al., 1994), is only one component of deformation, because the direction of tectonic transport in this part of the northern Andes (east-northeast) is approximately parallel to the Ibagué fault. Consequently, these structures should accommodate slightly larger amounts of east-northeast–west-southwest shortening. Therefore, the amount of contraction independently calculated for the western flank of the Cordillera Oriental (Namson et al., 1994), immediately north of the PGFB, is compatible with the amount of contraction calculated in this paper for the PGFB (about 32 km of east-northeast–west-southwest contraction) and the minimum displacement of the Ibagué fault (30 km).

Thus, the contraction imposed by the east-northeast advancing northern block of the Ibagué fault (Cordillera Central) has two manifestations in the Mesozoic-Cenozoic cover of this part of the Magdalena Valley and Cordillera Oriental. North-trending folds and faults along the western flank of the Cordillera Oriental, and a diverging transpressional fold belt in the PGFB. Both systems record similar amounts of contraction, and both are compatible with the amount of contraction imposed by the rigid indenter. This complex, non-coaxial system records about 30 km of east-northeast–west-southwest contraction in a style that can be compared to escape tectonics (Molnar and Tapponier, 1975; Tapponier et al., 1982). The termination of two regional structures, Guaduas syncline and Ibagué fault, at the northern tip of the PGBF is the confirmation that this point represents the southeastern corner of the rigid indenter (Figure 16). South of it, the diverging trends of faults and folds and transpressional style of the PGFB represent the progressive wrinkling of the cover sequence as the southern corner of the rigid indenter advanced to the east-northeast. East of this point, the nearly linear north-south folds and faults of the western margin of the Cordillera Oriental represent the leading edge of the rigid indenter. The synchronous evolution of this system is constrained by Paleogene syntectonic molasses (in the Guaduas and Gualanday synclines) that were accumulated as thrust sheets propagated in response to the east-northeast advance of the rigid indenter. Further propagation of the thrust sheets folded the molasses previously accumulated (Figures 16a to 16c).

The reconstructions presented in this paper (Figures 13–16) contradict regional and local interpretations that indicate that structures of the Cordillera Oriental only accommodate deformation perpendicular to the structural trend (Colleta et al., 1990; Dengo and Covey, 1993; Namson et al., 1994; Cooper et al., 1995; Roeder and Chamberlain, 1995; Kammer, 1999). The kinematics of the PGFB reveal that an east-northeast–west-southwest direction of tectonic transport has been dominant in this part of the Andes throughout the Tertiary. This constitutes a significant contribution to the deformation, ruling out the possibility of plane strain in west- to northwest-verging structures in the western flank of the Cordillera Oriental. This also demonstrates that full deformation partition between the Cordilleras Oriental and Central is not a viable alternative. Therefore, a deformation gradient must exist from west to east, with dominant northeast-trending dextral strike-slip faulting in the Cordillera Central, grading eastward to northwest-southeast contraction in the eastern Cordillera Oriental. This deformation gradient most likely was imposed by the northeastward advance of a deformation front related to the emplacement of the Caribbean Plate. Thus, the role of strike-slip deformation in the Cordillera Oriental is at least locally significant and must be incorporated in regional models of deformation in the northern Andes.

CONCLUSIONS

The Piedras-Girardot fold belt is a dextral transpressional system in which approximately 32 km of east-northeast–west-southwest contraction are recorded as a result of the east-northeast insertion of a rigid block of the Cordillera Central. Structures in this fold belt define a sigmoidal sinistral stepover, with faults verging outwardly in opposite directions. This fold belt accommodates contraction along north- and northwest-trending segments of the Cambao, Cotomal, and Camaito faults, dextral strike-slip along their northeast-trending segments, and extension along the north-trending Luní fault. A synthetic three-dimensional model of this fold belt was constructed using simple linear interpolation from serial admissible cross sections. A palinspastic reconstruction agrees well with kinematic data and reveals approximately 17 km of contraction west-southwest in the Cambao fault, approximately 7 km in the Camaito fault, and approximately 8 km to the east-northeast in the Cotomal fault. A three-dimensional forward model, built using the constraints from the palinspastic reconstruction, successfully reproduces first-order structures and topography in the northwestern Piedras-Girardot fold belt. The Ibagué fault imposes a strike-slip component into thrust faults of the Cordillera Oriental that were previously interpreted to accommodate only dip slip.

ACKNOWLEDGMENTS

This work was financially and logistically supported by Colciencias, Ecopetrol, the Integrated Interpretation Center of Conoco Inc., the Corporación Geológica Ares, the Science Alliance Center for Excellence of the University of Tennessee, and the AAPG Gordon I. Atwater memorial grant. Identification of paleontologic material was kindly made by Fernando Etayo-Serna. Thorough reviews by William Dunne, Tomás Villamil, Hans Avé Lallemant, Germán Bayona, and Fabio Colmenares are greatly appreciated. The authors, however, remain responsible for all omissions or errors of fact or interpretation.

REFERENCES CITED

Audemard, F. A., 2001, Quaternary tectonics and present stress tensor of the inverted northern Falcon Basin, northwestern Venezuela: Journal of Structural Geology, v. 23, p. 431–453.

Barrero, D., J. Alvarez, and T. Kassem, 1969, Actividad ígnea y tectónica en la Cordillera Central durante el Meso-Cenozoico: Boletín Geológico del Ingeominas, v. XVII, p. 145–173.

Barrero, D., and C. Vesga, 1976, Mapa geológico del cuadrángulo K-9 Armero y parte sur del J-9 La Dorada: Ingeominas, scale 1:100,000.

Bayona, G., D. F. García, and G. Mora, 1994, La Formación Saldaña: Producto de la actividad de estratovolcanes continentales en un dominio de retroarco, *in* F. Etayo Serna, ed., Estudios Geológicos del Valle Superior del Magdalena: Bogotá, ECOPETROL, p. I 1–I 21.

Bowland, C. L., and E. Rosencrantz, 1988, Upper crustal structure of the western Colombian basin, Caribbean Sea: Geological Society of America Bulletin, v. 100, p. 534–546.

Burke, K., P. J. Fox, and A. M. C. Sengör, 1978, Buoyant ocean floor and the evolution of the Caribbean: Journal of Geophysical Research, v. 83, p. 3949–3954.

Burke, K., C. Cooper, J. F. Dewey, P. Mann, J. L. Pindell, 1984, Caribbean tectonics and relative plate motions, *in* W. E. Bonini, R. B. Hargraves, and R. Shagam, eds., The Caribbean-South American plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 31–64.

Bürgl, H., and Y. Dumit, 1954, El Cretáceo Superior de la región de Girardot: Boletín Geológico del Ingeominas, v. II, p. 23–48.

Butler, K., and S. Schamel, 1988, Structure along the eastern margin of the Central Cordillera, Upper Magdalena Valley, Colombia: Journal of South American Earth Sciences, v. 1, p. 109–120.

Casas, A. M., D. Gapais, T. Nalpas, K. Besnard, and B. T. Roman, 2001, Analogue models of transpressive systems: Journal of Structural Geology, v. 23, p. 733–743.

Case, J. E., and W. D. MacDonald, 1973, Regional gravity anomalies and crustal structure in Northern Colombia: Geological Society of America Bulletin, v. 84, p. 2905–2916.

Case, J. E., S. L. Duran, R. A. Lopez, and W. R. Moore, 1971, Tectonic investigations in western Colombia and eastern Panama: Geological Society of America Bulletin, v. 82, p. 2685–2712.

Cediel, F., and C. Cáceres, 1988, Geologic map of Colombia: Bogotá, Colombia, Geotec Editions, scale 1:2,000.000.

Cediel, F., J. Mojica, and C. Macía, 1981, Las formaciones Luisa, Payandé y Saldaña sus columnas estratigráficas características: Geología Norandina, v. 3, p. 11–19.

Colletta, B., F. Hebrard, J. Letouzey, P. Werner, and J. L. Rudkiewicz, 1990, Tectonic style and crustal structure of the Eastern Cordillera (Colombia) from a balanced cross-section, *in* J. Letouzey, ed., Petroleum and tectonics in mobile belts: Paris, Editions Technip, p. 81–100.

Cooper, M. A., et al., 1995, Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and middle Magdalena Valley, Colombia: AAPG Bulletin, v. 79, p. 1421–1443.

Dahlstrom, C. D. A., 1969, Balanced cross sections: Canadian Journal of Earth Sciences, v. 6, p. 743–757.

Dengo, C. A., and M. C. Covey, 1993, Structure of the Eastern Cordillera of Colombia: A tectonic model of the Colombian Andes: AAPG Bulletin, v. 77, p. 1315–1337.

DePorta, J., 1965, La estratigrafía del Cretácico Superior y Terciario en el extremo S del Valle Medio del Magdalena: Boletín de Geología Universidad Industrial de Santander, v. 19, p. 5–50.

Diaz de Gamero, M. L., 1996, The changing course of the Orinoco River during the Neogene: A review: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 123, p. 385–402.

Edgar, N. T., J. I. Ewing, and J. Hennion, 1971, Seismic refraction and reflection in Caribbean sea: AAPG Bulletin, v. 55, p. 833–870.

Elliot, D., 1983, The construction of balanced cross sections: Journal of Structural Geology, v. 5, p. 101.

Etayo Serna, F., 1994, Epílogo: A modo de historia geológica del Cretácico del Valle Superior del Magdalena, *in* F. Etayo Serna, ed., Estudios Geológicos del Valle Superior del Magdalena: Bogotá, Universidad Nacional, ECOPETROL, p. XX 1–XX 5.

Etayo Serna, F., et al., 1986, Mapa de terrenos geológicos de Colombia: Bogotá, Colombia, Publicaciones Geológicas Especiales del Ingeominas, v. 14, p. 235.

Feininger, T., 1970, The Palestina fault, Colombia: Geological Society of America Bulletin, v. 81, p. 1201–1216.

Freymueller, J., J. Kellogg, and V. Vega, 1993, Plate motions in the north Andean region: Journal of Geophysical Research, v. 98, p. 21,853–21,863.

Frohlich, C., K. Kadinsky-Cade, and S. D. Davis, 1995, A reexamination of the Bucaramanga, Colombia, earthquake nest: Bulletin of the Seismological Society of America, v. 85, p. 1622–1634.

Florez, M., and G. A. Carrillo, 1994, Estratigrafía de la sucesión litológica basal del Cretacico del valle superior del Magdalena, *in* F. Etayo Serna, ed., Estudios Geológicos del Valle Superior del Magdalena: Bogota, Colombia, ECOPETROL, p. II 1–II 26.

Gómez, E., and P. E. Pedraza, 1994, El Maastrichtiano de la región Honda-Guaduas, limite N del Valle Superior del Magdalena; registro sedimentario de un delta dominado por rios trenzados, *in* F. Etayo Serna, ed., Estudios Geológicos del Valle Superior del Magdalena: Bogota, Colombia, ECOPETROL, p. III.1–III.20.

Hubach, E., 1945, La formación ''Cáqueza,'' región de Cáqueza (oriente de Cundinamarca): Compilación Estudios Geológicos Oficiales de Colombia, v. 6, p. 23–26.

Ingeominas, 1988, Mapa geológico de Colombia: Bogotá, Colombia, Ingeominas, scale 1:1,500.000.

Kafka, A. L., and D. J. Weidner, 1981, Earthquake focal mechanisms and tectonic processes along the southern boundary of the Caribbean Plate: Journal of Geophysical Research, v. 86, p. 2877–2888.

Kammer, A., 1999, Observaciones acerca de un origen transpresivo de la Cordillera Oriental: Geología Colombiana, v. 24, p. 29–53.

Kammer, A., and J. Mojica, 1995, Los pliegues de la barrera Guataquí-Girardot: ¿Producto de un despegue de la cobertera Cretácica de la Cordillera Oriental?: Geologia Colombiana, v. 19, p. 33–43.

Kellogg, J., and W. E. Bonini, 1982, Subduction of the Caribbean Plate and basement uplifts in the overriding South American Plate: Tectonics, v. 1, p. 251–276.

Kerr A. C., J. Tarney, A. Nivia, G. F. Marriner, A. D. Saunders, 1998, The internal structure of oceanic plateaus: Inferences from obducted Cretaceous terranes in western Colombia and the Caribbean: Tectonophysics, v. 292, p. 173–188.

Ladd, J. W., 1976, Relative motion of South America with respect to North America and Caribbean tectonics: Geological Society of America Bulletin, v. 87, p. 969–976.

Laubscher, H. P., 1987, The kinematic puzzle of the Neogene Northern Andes, *in* J. P. Schaer and J. Rodgers, eds., The anatomy of mountain ranges: Princeton, New Jersey, Princeton University Press, p. 211–227.

Lowell, J. L., 1972, Spitsbergen Tertiary orogenic belt and the Spitsbergen fracture zone: Geological Society of America Bulletin, v. 83, p. 3091–3102.

Malfait, B. T., and M. G. Dinkelman, 1972, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean Plate: Geological Society of America Bulletin, v. 83, p. 251–271.

Malavé, G., and G. Suárez, 1995, Intermediate-depth seismicity in northern Colombia and western Venezuela and its relationship to Caribbean plate subduction: Tectonics, v. 14, p. 617–628.

Mann, P., C. Schubert, and K. Burke, 1990, Review of Caribbean neotectonics, *in* G. Dengo and J. E. Case, eds., The Caribbean region: Geological Society of America, The Geology of North America, v. H., p. 307–338.

McClay, K., and M. Bonora, 2001, Analog models of restraining stepovers in strike-slip fault systems: AAPG Bulletin, v. 85, p. 233–260.

McCourt, W. J., J. A. Aspden, and M. Brook, 1984, New geological and geochronological data from the Colombian Andes; continental growth by multiple accretion: Journal of The Geological Society (London), v. 141, p. 831–845.

Molnar, P., and P. Tapponier, 1975, Cenozoic tectonics of Asia: Effects of a continental collision: Science, v. 189, p. 419–426.

Montes, C., 2001, Three dimensional structure and kinematics of the Piedras-Girardot foldbelt in the northern Andes of Colombia: Ph.D. Dissertation, The University of Tennessee, Knoxville, 212 p.

Mosquera, D., A. Nuñez, and C. Vesga, 1982, Mapa geológico preliminar de la plancha 244 Ibagué: Bogotá, Colombia, Ingeominas, scale 1:100,000.

Namson, J., R. Cunningham, and G. Woodcock, 1994, Structural geology and hydrocarbon potential of the northern part of the upper Magdalena Basin, Colombia (Abs.): AAPG Annual Convention, Tulsa, Oklahoma, p. 221.

Oldow, J. S., A. W. Bally, and H. G. Avé Lallemant, 1990, Transpression, orogenic float, and lithospheric balance: Geology, v. 18, p. 991–994.

Oreskes, N., K. Shrader-Frechette, and K. Belitz, 1994, Verification, validation, and confirmation of numerical models in the Earth Sciences: Science, v. 263, p. 641–646.

Pennington, W. D., 1981, Subduction of the eastern Panamá basin and seismotectonics of northwestern South America: Journal of Geophysical Research, v. 86, p. 10,753–10,770.

Pindell, J. L., 1993, Regional synopsis of Gulf of Mexico and Caribbean evolution: Proceedings of the Gulf Coast Section Society for Sedimentary Geology (SEPM) Foundation 13th Annual Research Conference, p. 251–274.

Pindell, J., and J. F. Dewey, 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: Tectonics, v. 1, p. 179–211.

Pindell, J. L., and S. F. Barrett, 1990, Geological evolution of the Caribbean region; a plate tectonic perspective, *in* G. Dengo and J. E. Case, eds., The Caribbean region: Geological Society of America, The Geology of North America, v. H., p. 405–432.

Price, R. A., 1986, The southeastern Canadian Cordillera; thrust faulting, tectonic wedging, and delamination of the lithosphere: Journal of Structural Geology, v. 8, p. 239–254.

Raasveldt, H. C., 1956, Mapa geológico de la plancha L-9 Girardot: Bogotá, Colombia, Servicio Geológico Nacional, scale 1:200,000.

Ramsay, J. G., and R. J. Lisle, 2000, The techniques of modern structural geology, volume 3: Applications of continuum mechanics in structural geology: San Diego, California, Academic Press, 360 p.

Restrepo Pace, P. A., 1999, Fold and thrust belt along the western flank of the Eastern Cordillera of Colombia; style, kinematics and timing constraints derived from seismic data and detailed surface mapping: Thrust Tectonics Conference, Royal Holloway University of London, p. 112–114.

Roeder, D., and R. L. Chamberlain, 1995, Eastern Cordillera of Colombia; Jurassic-Neogene crustal evolution, *in* A. Tankard, J. R. Suárez, and H. J. Welsink, eds., Petroleum basins of South America: AAPG Memoir 62, p. 633–645.

Rosencrantz, E., M. I. Ross, and J. G. Sclater, 1988, Age and spreading history of the Cayman Trough as determined from depth, heat flow, and magnetic anomalies: Journal of Geophysical Research, v. 93, p. 2141–2157.

Schamel, S., 1991, Middle and upper Magdalena basins, Colombia, *in* K. T. Biddle, ed., Active margin basins: AAPG Memoir 52, p. 283–301.

Schreurs, G., and B. Colletta, 1998, Analogue modelling of faulting in zones of continental transpression and transtension, *in* E. Holdsworth, E. Strachan, and J. Dewey, eds., Continental transpressional and transtensional tectonics: The Geological Society (London) Special Publications, v. 135, p. 59–79.

Schubert, C., 1981, Are the Venezuelan fault systems part of the southern Caribbean plate boundary?: Geologische Rundschau, v. 70, p. 542–551.

Sylvester, A. G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666–1703.

Taboada, A., L. A. Rivera, A. Fuenzalinda, A. Cisternas, P. Hervé, H. Bijwaard, J. Olaya, and C. Rivera, 2000, Geodynamics of the northern Andes: Subductions and intracontinental deformation (Colombia): Tectonics, v. 19, p. 787–813.

Tapponier, P., G. Peltzer, A. Y. Le Dain, R. Armijo, and P. Cobbold, 1982, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticine: Geology, v. 10, p. 611–616.

Tikoff, B., and K. Peterson, 1998, Physical experiments of transpressional folding: Journal of Structural Geology, v. 6, p. 661–672.

Tellez, N. I., and G. J. Navas, 1962, Interferencia de direcciones en los pliegues cretacico-terciarios entre Coello y Gualanday: Boletín de Geología Universidad Industrial de Santander, v. 9, p. 45–61.

van der Hilst, R. D., and P. Mann, 1994, Tectonics implications of tomographic images of subducted lithosphere beneath northwestern South America: Geology, v. 22, p. 451–454.

Villamil, T., 1999, Campanian-Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 153, p. 239–275.

Westbrook, G. K., 1990, Gravity anomaly map of the Caribbean region, *in* G. Dengo and J. E. Case, eds., The Caribbean region: Geological Society of America, The Geology of North America, v. H., scale 1:5.000.000.

Wilcox, R. E., T. P. Harding, and D. R. Seedy, 1973, Basic wrench tectonics: AAPG Bulletin, v. 57, p. 74–96.

Zeil, W., 1979, The Andes, A geological review: Berlin-Stuttgart, Gëbruder Borntraeger, 260 p.