THE TERMINATION OF THE BUCARAMANGA FAULT IN
THE CORDILLERA ORIENTAL, COLOMBIA

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ABSTRACT

The Bucaramanga Fault is a large Late Tertiary strike-slip fault oriented N15W which ends in the Cordillera Oriental of Colombia. It is believed to have about 100 km of left-lateral displacement. Based on detailed mapping of its termination, regional structural cross-sections, and gravity modeling of the area, I present a model for the geometry of the fault termination. Two reverse faults oriented N30E, the Soapaga and Boyacá faults, absorb about 40 km of strike-slip displacement on a 12 km deep detachment. These faults probably originated as Jurassic normal faults which were reactivated late in the Andean Orogeny. The Soapaga Fault cross-cuts and deforms the main strand of the Bucaramanga Fault probably as a result of motion on a younger strand of the strike-slip system, the Chicamocha Fault. The Bucaramanga Fault may have developed as an escape structure in response to accelerated compression and accretion of the Chocó Block and Panamá Arc against the western margin of Colombia during Late Miocene time.
I. INTRODUCTION

In this thesis I attempt to show how the structure of the Cordillera Oriental of Colombia has been affected by the Mio-Pliocene Bucaramanga Fault, and how a large strike-slip fault terminates in a continental setting. The work is based on 1) my own field mapping at the southern end of the Bucaramanga Fault and 2) regional geology and gravity data acquired by Ingeominas (the Colombian geological survey). Using the combined data, I constructed structural cross-sections and a regional gravity model through the northern part of the Cordillera Oriental. From this information I was able to model crustal structure and fault chronology in the Cordillera Oriental, as well as the displacement at the southern tip of the Bucaramanga Fault.

The Cordillera Oriental of Colombia is a broad uplift of folded Cretaceous marine sedimentary rocks that formed during Mio-Pliocene time as a response to accelerated convergence between the Nazca and the South American plates (Fig. 1). One of the most dramatic geologic features of the Cordillera Oriental is the left-lateral Bucaramanga Fault, also of Mio-Pliocene age. It is such a continuous structure on the South American geologic map, that it was once called the "Great Colombian Fault." It belongs to the complicated system of faults near the boundary between the South American and Caribbean plates. After some controversy it was accepted in the 1960's as a left-lateral strike-slip fault with about 100 km of displacement (Campbell, 1965, Irving, 1971). From the Caribbean coast it trends S15E and ends 550 km inland in the Cordillera Oriental. There the Bucaramanga Fault appears to transfer into a system of thrust faults, dominated by the Soapaga Fault (Fig 2).
Large strike-slip faults, like the Bucaramanga Fault, have been recognized in most Phanerozoic orogenic systems. Many have accommodated hundreds of kilometers of displacement between adjacent blocks. Often these major continental breaks terminate abruptly, posing the problem of how to account for the large displacement at the ends of the fault. This is not a problem with strike-slip faults in oceanic settings where transform structures link sites of extension (mid-ocean ridges) or compression (trenches). The same explanation has been applied to some of the largest and best documented continental wrench faults, like the San Andreas Fault of California and the Alpine Fault of New Zealand, both of which are near the continental margin. In contrast, the southern end of the Bucaramanga Fault is far from plate boundaries, so it cannot be tied to trenches or spreading centers. Instead its displacement appears to be absorbed by the Soapaga Fault and its imbricates.
II. BACKGROUND INFORMATION

A. The Cordillera Oriental

A review of the main features of the Cordillera Oriental is necessary in order to understand how it has been affected by the Bucaramanga Fault. It has long been recognized that the northernmost portion of the Andes has a different character from the rest of the mountain chain (i.e., Megard, 1987). First, the ranges near the Pacific coast are underlain by oceanic material accreted in late Mesozoic and Cenozoic time, and second, the tectonics of the area have been affected by interactions with the Caribbean plate which produced structures unlike those seen any where else in the Andes. In Colombia, the Andes splits into three branches (Fig.1). The Cordillera Occidental is underlain by the accreted bodies of oceanic rocks mentioned above. Inboard of it is the Cordillera Central, predominantly made of Paleozoic metamorphic rocks and Mesozoic plutons, which is the site of the present day volcanic arc. The Cordillera Central has been a positive topographic feature since at least the late Cretaceous, but emerged dramatically in the late Eocene shedding coarse clastics to the east (Butler and Schamel, 1987). Easternmost and youngest is the Cordillera Oriental. It has been thrust eastward over the Guiana Shield developing a foreland basin to the east, but the range is also thrust-bounded on its western side. Thus, the Cordillera Oriental is usually presented as a broad uplift bounded on both sides by reverse faults (for example Julivet, 1970; Irving, 1971; Fabre, 1983). There are thick wedges of syn-orogenic clastics on both sides. This picture contrasts sharply with the model developed for the North American Cordillera of an asymmetrical structural belt verging away from the convergent margin.
The Cordillera Oriental has a maximum width of about 200 km at 6° N where it changes trend from N35E to N25W. Its width decreases progressively to the south until, at about 2° 30' N, it is no longer recognizable as a geological feature. At that latitude the Cordillera Oriental pinches out between the Magdalena Valley and the Garzón Massif. Some have considered that the Massif, a large block of uplifted Proterozoic rocks of high metamorphic grade, is the extension of the Cordillera Oriental (Julivert, 1970, Irving, 1971). The lithologies and structural style of the Garzón Massif, although poorly known, are different enough to consider it a distinct feature. Furthermore, the Massif seems to be bounded not by the Gualcaramo fault system, like the Cordillera Oriental, but by another fault system further east. It is notable that the Cordillera Oriental is at an angle of about 30° to the Pacific margin, in contrast to both the Central and Western Cordilleras which are essentially parallel to the coast.

The exposed geology of the Cordillera Oriental is dominated by folded Mesozoic sedimentary rocks. The three areas where Paleozoic sedimentary and metamorphic rocks crop out are called "massifs," following the European tradition. East of Bogotá Ordovician slate and phyllite form the Quetame Massif. In the area where the Bucaramanga Fault ends, Devonian sedimentary rocks, and a Paleozoic granitic pluton, are exposed on the high side of the Soapaga and Boyacá faults, forming the Floresta Massif. Along the northern extension of the Cordillera, there is a large area underlain by Precambrian and Paleozoic metamorphic rocks and Jurassic plutons which is called Santander Massif. The Bucaramanga Fault is the western boundary of this massif, and probably controlled its recent uplift.
Stratigraphy

The region of the termination of the Bucaramanga Fault (Fig. 2) is characterized by Paleozoic to early Mesozoic sedimentary and crystalline rocks along the Floresta-Santander Massif, and Cretaceous to Oligocene sedimentary rocks to the east and west of it. Figure 4 shows a composite stratigraphic column of the area.

High grade gneiss and migmatite of the Bucaramanga Gneiss outcrop in small areas on the northern part of the map. This unit, which has been dated at 945 ± 40 Ma (K/Ar in hornblende; Goldsmith and others, 1971), is believed to form the basement of much of the Cordillera Oriental. Overlying the Bucaramanga Gneiss are low-grade schist and phyllite of the Silgará Formation. This must be older than the 471 ± 22 Ma age from the Chuscales Stock which intrudes it in the Floresta Massif (Ingeominas, 1983).

A sequence of unmetamorphosed Devonian through Carboniferous sedimentary rocks up to 1400 m thick lie depositionally on the Silgará Formation (Reyes, 1984). These include the Devonian marine Floresta and Tibet formations and the Carboniferous fluvial Cuche Formation. In the Floresta Massif two small plutons, the Busbanza and Belén granites, intrude the Silgará Formation. Their relationship to the upper Paleozoic sedimentary rocks is not clear. They have been mapped both as pre-Devonian and as Jurassic (Cediel, 1972; Vargas and others, 1974).

The Girón Formation is a sequence of upper Triassic to Jurassic conglomerate, arkose, and claystone of obvious continental origin (Cediel, 1969). It covers relatively large areas of the southwestern portion of Figure 2. Its thickness varies from 0 to 5000 m in the western flank of the Cordillera Oriental. In the Floresta Massif felsic volcanic and hypabyssal rocks of the Onzaga Rhyolite intrude into and are interbedded with the Girón Formation.
FIGURE 4. Composite stratigraphic column of the northern Cordillera Oriental. See text for references.
There is an extensive belt of acid plutons in the Santander Massif. These include granite, granodiorite and quartz monzonite. Based on the age of the Pescadero granite (194 ± 7 Ma, K/Ar; Goldsmith and others, 1971), which is located just north of Figure 2, an early Jurassic age is assigned to the belt.

Cretaceous to recent sedimentary rocks cover the eastern half of Figure 2. Their stratigraphy is well described by Reyes (1984), Fabre (1983), Renzoni (1967), and others. During the early Cretaceous two separate basins existed on opposite flanks of the Floresta-Santander Massif (Fabre, 1983). In the deepest part of the Cocuy basin to the east, the sequence starts with almost 4000 m of Lower Cretaceous marine sedimentary rocks. These are calcareous shales of the Macanal Formation and coarse cross-bedded sandstones of the Las Juntas Formation. By Barremian time the Floresta-Santander high had subsided below sea-level and deposition took place over the entire area occupied by the Cordillera Oriental. In the area of the termination of the Bucaramanga Fault up to 500 m of dark shale, limestone and sandstone of the Tibasoza Formation followed by 500 m of coarse sandstone of the Albian Une Formation were laid down. Marine deposition persisted until the end of the Cretaceous resulting in 600 m of dark shale, chert, and limestone of the Chipaque Formation, and clastics of the Guadalupe Group.

A transition to continental environments is recorded in the Maastrichtian Guaduas Formation. It is composed of 400 m of dark claystone, and lesser sandstone and coal seams indicative of deltaic conditions. The entire Tertiary section is composed of continental sedimentary rocks. There are the fluvial sandstones of the Lower Socha (Paleocene) and Picacho (Eocene) Formations separated by overbank deposits of the upper Socha Formation. These total 600 m in thickness. The lower Tertiary sequence is capped by the Oligocene Concentracion Formation which has a bank of oolitic ironstone at
its base followed by 1400 m of variegated shales with some thick sandstones. This cycle of nearly continuous sedimentation, which started during the earliest Cretaceous, ended with the intense deformation of the Andean orogeny.

Flat-lying fluvial and lacustrine deposits of the Plio-Pleistocene Tilatá Formation unconformably overlie the deformed Lower Tertiary and Cretaceous beds. Near Paipa and Iza just south of Figure 2, there are small rhyolitic plugs and lava flows of highly potassic composition (J. M. Jaramillo, personal communication). These are probably as young as Pliocene, since there are ash-beds interbedded with the Tilatá Formation (Fabre, 1983).

B. Bucaramanga Fault

The Bucaramanga Fault is believed to have left-lateral displacement of about 100 km. The northern portion of the fault forms the western boundary of the Santa Marta Massif, and the southern part bounds the Santander Massif. Along most of its 550 km length, the eastern block is uplifted, having a maximum of 12 km of vertical relief in the Santa Marta Massif (Tchantz and others, 1974). This relationship is inverted at the southern end of the fault, where the western block is elevated at least 6 km with respect to the eastern block where the Bucaramanga and Soapaga Faults meet. In the Santander Massif, where the Bucaramanga Fault is best exposed, it crops out as a remarkably straight feature demonstrating that, at least in that area, it has a near-vertical dip. Near Bucaramanga, the fault is marked by slivers of highly deformed and altered rocks of unclear origin, as well as zones of cataclasis and of mylonitization.
As it approaches the Soapaga Fault, the trend of the Bucaramanga Fault changes from S15E to almost north-south (Fig. 2). The fault plane probably changes from vertical to steeply west-dipping through this bend. There are several smaller fault strands in this area. The first one from west to east feeds the Boyacá Fault and is sometimes called the Onzaga Fault (Vargas and others, 1974). Next is the Guantiva Fault which has two interweaving strands. The map pattern shows that they total about 5 km of left-lateral slip. East of the Guantiva Fault is the main strand of the Bucaramanga Fault, and last is the Chicamocha Fault which is not usually recognized as part of the Bucaramanga system. Due to its rectilinear trace, orientation, and relationship to the Soapaga fault, I think it is the most recently active strand of the Bucaramanga system.

**Displacement Across the Fault**

It is difficult to determine the displacement across the Bucaramanga Fault because thick upper Tertiary and Quaternary sedimentary rocks cover most of the terrain on its west side. The correlations which have been proposed as pins across the fault are between regional trends of large geologic provinces or between samples of the basement drilled by oil wells in the Lower Magdalena Basin with outcrops of basement in the Santa Marta massif. Both methods are very questionable.

C. J. Campbell (1965), who published the first (and only) comprehensive study on the fault, correlated geologic provinces and gross stratigraphy across the fault and concluded that at least 100 km of movement were necessary to restore the paleogeography. He observed that the Cretaceous and Tertiary stratigraphy of the Cesar Basin and Middle Magdalena Basin are similar. Nevertheless, during the Cretaceous there were several subsiding basins in northern South America which accumulated similar sedimentary sequences. The Cesar Basin and the Middle Magdalena Basin were
part of this larger Cretaceous system, whatever their exact paleogeography was. Finding generalized correlations between them is not a very useful marker of fault displacements. It is difficult to establish good correlations in the Tertiary stratigraphy because most of the post-Paleocene section is not present in the Cesar basin. Furthermore, the stratigraphy in neither basin is exposed; most of the knowledge is derived from well data which is not widely available.

Campbell also pointed out that belts of Jurassic batholiths, Precambrian gneisses and Paleozoic metamorphic rocks exist in both the Central Cordillera and the Santa Marta Massif, and that 110 km of displacement would align these belts. In general we can say that the K-Ar ages of the Jurassic plutons on both sides of the fault are within 15 m. y. of each other (Tschantz and others, 1974; Alvarez, 1983), so they could truly belong to the same belt, but the Paleozoic metamorphic belt of the Santa Marta massif is Permian while that of the Central Cordillera is Ordovician in age. Therefore, the tie is weak.

Irving (1971) and Tschantz (1974) correlate phyllites drilled by the Algarrobo-1 well at a depth of 2538 m in the San Jorge Basin, and dated at 86 ± 4 (K - Ar), with the Santa Marta Metamorphic belt. They argue that rocks of this type and age do not occur anywhere else in the Santa Marta Massif, so that this correlation implies 110 km of displacement of the Bucaramanga Fault. There are several problems with this correlation. First, Irving (1971) states that the dated sample in Algarrobo-1 is believed to come from a large boulder in a Miocene conglomerate encountered near the bottom of the well. Second, the correlation, if correct, conflicts with some of the regional tectonic ideas. The Santa Marta Metamorphic belt is of oceanic character and is believed to have accreted to South America in the late Cretaceous or Paleocene on a suture related to the Romeral Fault. Today, this fault lies almost 100 km outboard of
Algarrobo-1. Third, the K-Ar ages of the Santa Marta Belt fall between 36 and 47 m.y. (Tschantz, 1974). There is a 40 m. y. difference with the Algarrobo-1 sample, which may be due to resetting of K-Ar by an Eocene pluton, but the difference calls into question the correlation.

My view is that the amount of displacement on the Bucaramanga Fault is not well constrained and may be much smaller than these 100-km estimates.

Age of the Fault

The earliest movement of the Bucaramanga Fault is hard to determine with certainty. The Oligocene to Pliocene sedimentary rocks in the Lower Magdalena Basin, west of the fault, are dominated by carbonate facies (Duque-Caro, 1978). This indicates that there was no source of clastics to the east. The Santa Marta Massif had not been uplifted, and the Bucaramanga fault was presumably not active. The first coarse clastic facies in the basin are of Pleistocene age.

There is no evidence that the Bucaramanga Fault has seen recent activity. According to Campbell (1965), many small streams in the vicinity of the town of Bucaramanga are displaced by the fault in a left-lateral sense. This observation seems the product of the prejudice of the author. One can find just as many streams with the opposite "displacement." Undeformed Quaternary sedimentary rocks cover most of the northern half of the fault. No recent earthquakes have been registered on the Bucaramanga fault (Pennington, 1981). Nevertheless, near the town of Bucaramanga is the epicenter of a large number of small earthquakes, the so called "Nido de Bucaramanga," which are sometimes attributed to the fault. Pennington (1981) showed that these events originate within a very small region of the lithosphere at a depth of 158 km within the subducted Caribbean plate beneath South America.
III. FIELD WORK

A. Logistics

I spent 45 days in the field during the summer of 1989. I began with a reconnaissance of the region and then concentrated on mapping in detail and sampling two key areas of more limited extent. One is the Sativa area and the other is the Corrales area. I chose the Sativa area because that is where the regional maps show the Bucaramanga Fault giving way to the Soapaga Fault (Vargas and others, 1976; Ulloa and others, 1973). Mapping in the Corrales area allowed me to determine the dip of the Soapaga Fault. This work was supported by Esso Colombiana Ltd. They provided a field vehicle, maps, and aerial photographs, and they paid all field expenses.

The Sativa area is located 240 kilometers north of Bogotá, at the northern end of the Altiplano Cundi-Boyacense. The plateau has an average elevation of 2600 m. It is relatively flat and broken by a series of north-south trending mountain ranges separated by deep river valleys. Within my field area elevations vary between 1700 and 4000 m. The steep topography made the mapping a rather strenuous exercise, but at the same time provided some good rock exposures along ridges and cliffs, and gave a tridimensional view of some of the structures.

Small farms cover most of the area except for the high "paramos," above 3500 m, where it is impossible to grow crops. They are subsistence farms with few modern comforts and a limited cash economy. There are a number of coal mines in the Maastrichtian section exploited by very primitive means, as well as some limestone quarries. Acéreas Paz de Rio, the largest steel mill in Colombia, is located in the town of Belencito, to the south of my field area. The ore for the mill comes from banks of oolitic ironstones in the Oligocene Concentracion Formation, which occurs in the footwall of the
Soapaga Fault. The chief geologist from the mine, Italo Reyes, let me look at their geologic maps and drill logs. He also indicated to me some of the key outcrops in the region.

My field work was mostly on private land. Generally the farmers were curious and friendly and believed that I was looking for gold or emeralds. The people have a very vague understanding of what a map is and little feeling for the different kinds of rock. The best explanation I could give for my presence was that I was "an engineer studying soils." I encountered only one hostile farmer which is surprising given the amount of violence in Colombia today. The greatest threat I had to face were the mangy farm dogs which came barking and snarling out of every house. Only one went as far as grabbing me by the pant leg, but I punished him with a well-aimed potato.

B. Sativa Area

The Bucaramanga Fault ends against the Soapaga Fault near the town of Sativa Norte. There is a set of well-exposed large folds in the footwall of the Soapaga Fault that I hoped would shed some light on the kinematics at the termination of the strike-slip fault. I also planned to conduct detailed structural analyses of small-scale structures along the Bucaramanga Fault. Unfortunately very few small structures are exposed.

Map Units

I describe the map units in the area from oldest to youngest. The abbreviations used on Figure 3 are shown in parenthesis. The Devonian Floresta and Tibet Formations (Df) underlie the highlands to the west of the map area. Nearer the Bucaramanga Fault are brown sandstone and purple claystone of the Carboniferous Cuche Formation (C), which rarely crops out. To the east, along the trace of the Bucaramanga Fault and in the
hanging wall of the Soapaga Fault are red claystone, arkosic sandstone, and conglomerate of the Jurassic Giron Formation (Jg), which is thought to lie unconformably on the Paleozoic rocks (Cediel, 1969). The conglomerate includes clasts of quartz-muscovite schist probably derived from the Lower Paleozoic Silgara Formation, in addition to arkosic sandstone of intraformational origin, and rare limestone of unknown origin. Outcrops of Giron sedimentary rocks are very poor, and in most cases it is difficult to determine bedding attitudes.

The oldest Cretaceous rocks in the area belong to the upper portion of the Tibasoza Formation (mKt). Near Corrales, the Tibasoza lies unconformably on the Giron Formation, but that relationship is not exposed in this area. It forms small outcrops along the hanging wall of the Soapaga Fault and includes thick beds of limestone with pelecypod fossils and interlayered gray shale. Overlying the Tibasoza Formation are 500 m of coarse, very well indurated quartz sandstone of the Albian Une Formation (mKu). The thickness of this unit and other Cretaceous and Tertiary formations are from sections measured by Reyes (1984) within 20 kilometers of the Sativa area. His measurements agree well with my observations. The Tibasoza sandstone forms large cliffs on the upthrown block of the Soapaga Fault north of Sativa Norte.

Depositionally overlying the Une Formation is the Cenomanian Chipaque Formation (uKc), which is well-exposed in the hanging wall of the Soapaga Fault east of the Bucaramanga Fault. It is characterized by two resistant bodies of sandstone, each about 50 m thick, separated by a section of calcareous gray shale, black shale, and thinly-bedded sandstone. The Chipaque is elsewhere overlain by the Santonian La Luna Formation; in this area blocks of La Luna black chert occur as float topographically above the Chipaque Formation.
The oldest rocks east of the Soapaga Fault are the Campanian Pinos and Tierna Formations (uKp and uKt), which occur in the core of the large anticline that parallels the fault. The Pinos is a section of well-laminated black shales, and the Tierna Formation forms a rib of quartzose, glauconitic sandstone about 40 m thick. These rocks are overlain by the Maastrichtian Guaduas Formation (TKg), characterized by a thick section of dark claystone interbedded with finely laminated grey sandstone and several coal seams. On the flanks of the anticline, overlying the Guaduas Formation, is a unit of brown, cross-bedded sandstone 130 m thick which comprises the lower part of the Socha Formation (Tps). This is overlain by variegated claystone and interbedded sandstone of the upper Socha Formation (Tpa). The Picacho Formation (Tpp) overlies the upper Socha Formation. It is composed of about 200 m of coarse, white, poorly indurated sandstone with layers of pebble conglomerate that mark the oldest coarse clastic rocks in the Cretaceous to Oligocene basinal sequence. Most of the pebbles are metamorphic quartz of unknown provenance.

The Concentracion Formation (Tco) lies conformably on the Picacho Formation and is exposed in the footwall of the Soapaga Fault in most of the map area. Its base is a layer of red, oolitic ironstone several meters thick. This is overlain by up to 1400 m of variegated claystone, poorly indurated brown sandstone, and thin coal beds. These are well-exposed in the Chicamocha River valley, which has less vegetation than the surrounding mountains.

The Soapaga Fault and Related Structures

Although the Soapaga Fault is never exposed in the area, it can be located with certainty because it juxtaposes widely different lithologies. It trends N30E across the map with a slightly sinous trace. In the northern part of the map it marks the break in
slope between cliffs of Une and Tibasoza Formations and gentler slopes of the Concentracion Formation. In the southern part, the fault separates red soils of the Girón Formation from yellow soils of the Concentracion. A sliver of Cretaceous rocks, bounded by an imbricate splay of the Soapaga Fault, intervenes between Jurassic and Oligocene rocks southwest of Sativa Sur.

The geometry of the hanging-wall is hard to discern within the Jurassic rocks because of their poor exposure. Northeast of the intersection with the Bucaramanga Fault, there is an open cylindrical anticline which involves the Cretaceous units next to the Soapaga Fault (Fig. 5). Away from the fault the upthrown block dips gently to the west. The geometry suggests that the sedimentary cover has been passively folded over a crystalline basement block similar to folds seen in the Rocky Mountain Foreland region (Erslev, 1986).

The Tertiary and upper Cretaceous beds in the footwall of the Soapaga Fault are folded in a tight anticline-syncline pair. These folds parallel the fault, persist for 16 km in the map area, and extend to the south. The anticline has a moderately to steeply-dipping west limb and steep to overturned east limb. A fault separates it from the east-vergent recumbent syncline. The attitude of the pair of folds suggests that this fault is an east-vergent reverse fault related to the Soapaga Fault. Northeast of Sativa Norte there is another fault which juxtaposes Oligocene Concentración Formation with the Maastrichtian Guaduas Formation. It is probably a back-thrust to the reverse fault described above. These structures are shown in the Sativa cross-section (Fig. 9B).

The Bucaramanga Fault

The Bucaramanga Fault trends almost north-south in the map area. It occurs along the Las Leonas Creek and Carichona Creek. For most of its trace it is the contact between Girón and Cuche Formations on the west side and Une and Chipaque Formations
Figure 5. Photograph of large cylindrical anticline north of Sativa Norte. Picture taken looking north.

Figure 6. Photograph of the Soapaga Fault in the Corrales area. Cretaceous strata in the hanging wall are overturned. Picture taken looking south.
on its east side. It also juxtaposes rocks with discordant bedding attitudes. The fault itself is only exposed in one outcrop near its intersection with the Soapaga Fault. In this outcrop there is a chaotic mass of large breccia blocks of Une sandstone and one vertical fault scarp oriented N62E with striations plunging 30° to the southwest. The Bucaramanga Fault seems to dip steeply to the west, but the outcrop is too poor to measure it.

As it approaches the Soapaga Fault, the Bucaramanga Fault turns sharply to the east. There are Jurassic redbeds on the outside of the bend and Cretaceous sandstone in the middle. The structure of the sandstone in the interior of the bend is complex. A west-dipping reverse fault has beds dipping 40° E in its upper plate and steeply east-dipping or vertical beds in its lower plate. South of the bend, there are several shear zones parallel to the Soapaga Fault. These have sheared and recrystallized sandstone in contact with Girón redbeds, which are the only relatively ductile fabrics observed in the whole area. These shear zones are probably small splays of the Soapaga Fault.

C. Corrales Area

Because I was unable to determine the dip of the Soapaga Fault near Sativa I mapped a small area 5 km north of the town of Corrales where the fault crosses a ridge (Fig. 2). The upper plate rocks are the Chipaque, Une and Girón Formations, and a highly fractured and altered granite body. The sedimentary units are clearly overturned, dipping about 70° west. They are in the overturned limb of a large anticline which I discuss in a later section. The Concentración Formation occurs in the lower plate dipping steeply to the west. Although the fault plane is not exposed in this area either, the solution to a three-point problem reveals that it dips 55° west (Fig. 6).
D. Fission-Track Samples

In an effort to determine the timing of the uplift of the hanging wall of the Soapaga Fault I collected two samples for apatite fission track dating. The objective was to find out if the age of the uplift in the areas directly affected by the Bucaramanga Fault was different from the Plio-Pleistocene age of uplift interpreted from palynological data of the Tilatá Formation (Van Der Hammen and others, 1973). One sample was taken from the Belén Granite in the Floresta Massif, and a second one from a granite along the Soata- Onzaga road near the Bucaramanga Fault (see Fig. 3). Kevin Crowlie from the University of Miami in Ohio performed the analysis and dating for Esso Colombiana Ltd. (Crowlie, 1989). The Belén Granite yielded an age of $22.3 \pm 4$ Ma, and the granite from the Santander Massif of $30.8 \pm 5.8$ Ma. Both ages are surprisingly old. The main phase of Andean deformation in this area started in the middle Miocene, most probably less than 15 Ma.

The confined track lengths of both samples are much shorter than expected. This indicates that some of the tracks have undergone partial annealing during a complex cooling history. The confined track length distribution for both samples is characteristic of "mixed ages" (Gleadow and others, 1986; Green, 1988). This means the apatites have some old, partially annealed tracks, and some younger more pristine ones. Therefore, ages obtained by counting the track density do not record the most recent uplift event, but some complex thermal history. The uncertainty about the thickness of Tertiary sedimentary rocks which has been eroded off the Floresta-Santander Massif, makes it impossible to interpret these mixed apatite ages.

Shagam and others (1984) obtained 13 apatite fission-track ages from the Santander Massif, as part of a study in western Venezuela and eastern Colombia. The ages range from $3.8 \pm 0.8$ Ma to $18.9 \pm 0.3$ Ma, and are widely scattered. The two samples
which they collected closest to the termination of the Bucaramanga Fault have a 5 m.y. spread even though they came from within 4 km of each other, and from the same fault block. The authors could not explain satisfactorily these age variations either in terms of uplift of several individual fault blocks, or of regional uplift at variable rates. Since they did not examine the track length distribution of the samples, it is likely that their study was plagued with partially annealed tracks and they did not realize it.

E. Conclusions

My mapping revealed that the Soapaga Fault cross-cuts and deforms the Bucaramanga Fault, and it shows the style of some of the deformation. Nevertheless, the problem of accommodating large left-lateral offset of the Bucaramanga Fault has a much more regional scope. I failed to find any clear evidence of transcurrent displacement on the Bucaramanga Fault and my attempt at defining the timing of uplift did not pay off. The geographical area affected by the deformation is too large for me to map in detail. It involves not only the Soapaga Fault, but also the Boyacá Fault located 20 km to the west, the Chicamocha Fault to the northeast, and other structures in the Santander Massif. In order to shed some light on this problem I constructed regional cross-sections using published data. The first step involved understanding the gross crustal structure of the Cordillera Oriental as revealed by gravity data.
IV. GRAVITY MODEL OF THE CORDILLERA ORIENTAL

I modeled the present day crustal structure of the Cordillera Oriental using the Bouguer gravity anomaly map of Colombia (Bermudez and others, 1985). The profile is 400 km long. It extends from the eastern flank of the Cordillera Central, across the Magdalena Basin, over the Cordillera Oriental at the latitude of the Floresta Massif, and into the Eastern Llanos (Fig. 7). As expected for a mountain range of this size, the observed gravity profile has a long wavelength low, of about -150 mgals, with short wavelength highs superimposed on it.

The model consists of a broad crustal root, wedges of sedimentary rocks in the foreland basins which flank the Cordillera, and basement blocks uplifted by the Soapaga and Boyacá Faults in the Floresta Massif. I assume the density of the upper mantle is 3300 kg/m³. For the root of the Cordillera I used 2950 kg/m³, and for the sedimentary rocks 2450 kg/m³. This density is probably appropriate for the young molassic sedimentary rocks in the foreland basins, but may be too low for the Jurassic and Cretaceous sedimentary rocks at the bottom of the section. The thickness of the crust is assumed to be 35 km for the Guiana Shield and only 30 km for the Magdalena basin as a result of late Jurassic extension.

The calculated gravity profile shows that the long wavelength negative anomaly is due to the root associated with the topographic elevation of the Cordillera. The root is much wider than the mountain range itself, but not as thick as isostatic calculations predict. For an average elevation of 3000 m, and 5000 m of sedimentary cover, local isostatic balance would require the crust to be 45 km thick below the Cordillera. The
FIGURE 7. Gravity model of the Cordillera Oriental. The crustal model shows the location of the main fault blocks, and the density of each block in kg/m³. Density of the upper mantle was 3300 kg/m³. Gravity data from Bermudez and others (1985).
observed gravity is best reproduced by a root only 38 to 39 km thick but much wider than the mountain range. The area of this root (and presumably its mass) is approximately the same as that required by the isostatic model. Therefore, regional isostatic balance is preserved. Regional, rather than local, isostatic compensation is consistent with the idea that the Llanos foreland basin is due to the flexure of lithosphere as the Cordillera Oriental was thrust over the Guiana Shield loading and depressing it (Fabre, 1983). The flexural rigidity of the plate supports part of the load and distributes it over a wider region.

The short wavelength anomalies over the range itself are produced by the distribution of sedimentary rocks in the major fault blocks. A sharp gradient characterizes the Soapaga fault, and there is a broad gravity high associated with the area to the west of the Boyacá fault. The gravity low 25 km east of the Soapaga fault is probably due to a thickened sedimentary section in the core of the Cravo Sur-Horqueta anticline which will be discussed with the regional structural cross-sections (Fig. 9 C). The calculated gravity profile fits the observed data well except for the gentle gradient associated with the Eastern Llanos. This discrepancy may be due to low density inhomogeneities within the Guiana Shield.
V. STRUCTURAL CROSS SECTIONS

I present three cross-sections through the area of the termination of the Bucaramanga Fault. They are located on Figure 2. The southernmost one is a regional cross-section. It includes the Floresta Massif and extends to the eastern foreland. The next one to the north is the Sativa section, which traverses the area I mapped in detail and shows the intersection of the Bucaramanga and Soapaga Faults. The northernmost cross-section, near the town of Soatá, is well within the domain of the Bucaramanga Fault. It was necessary to bend the two northern sections in order to keep them orthogonal to the compressional structures thus minimizing displacements out of the plane of the section.

The sections are based entirely on published maps of Ingeominas and my own mapping. Data from the wells in the foreland were not available. The cross-sections are made using the methods of Woodward and others (1989), attempting to make them geometrically correct, balanced, and retrodeformable. I represented all folds as kink-folds, which make it easier to maintain stratigraphic thickness on fold hinges, and to balance the section. This is partly an abstraction, in the cubist tradition, of the real geometry of the structures, but as the photograph in Figure 8 shows, some large kink-folds do exist in the area. Ramp and cut-off angles are 15-25° for the most part.

The stratigraphy is controlled by three columns. In the first one, measured on the Floresta Massif (Reyes, 1984), the Lower Cretaceous is completely absent and an post Albian section overlies 0 to 500 m of Devonian and Jurassic sedimentary rocks, or Paleozoic schist. These are the only exposures of pre-Cretaceous rocks, so we can only speculate about their role within the thrust belt. The second column is measured east of
Figure 8. Photograph of large kink-fold north of Susacón which involves Upper Cretaceous shales. Picture taken looking southeast.
the Soapaga fault and along the Cravo Sur River (Fabre, 1983). It is almost 8 km thick spanning from the base of the Cretaceous up to the Eocene Concentración Formation. In contrast to the Floresta Massif, here the Lower Cretaceous is over 3 km thick. The third column comes from the foothills of the Cordillera where 2.3 km of continental lower Tertiary sedimentary rocks are exposed, capped by the syn-orogenic conglomerates of the Guayabo Formation (Ulloa and Rodríguez, 1976). Lastly wells in the Eastern Llanos show that the pre-Andean sedimentary sequence thins out very quickly away from the Cordillera (Fabre, 1983).

The sequence of deformation shown in the sections started with thin-skinned thrusts in the core of the belt. The thrusts get progressively younger towards the foreland. The faults which bring basement to the surface occurred late in the orogenic cycle. They cross-cut the earlier structures. This sequence is based partly on the assumption of forward propagation of thrusts (Woodward and others, 1989), and partly it emerged from the process of drawing the cross-sections. Although the final sections are not completely satisfactory, the process of constructing them brought to light some important aspects of the mountain belt.

A. Regional Cross-Section

In order to place in context the termination of the Bucaramanga Fault, I drew a structural cross-section from the Floresta Massif to the Eastern Llanos. The section, shown in figure 9 C, and located in figures 1 and 2, is 140 km long and includes most of the Cordillera Oriental. It is drawn 25 km south of the termination of the Bucaramanga Fault so, it should not be greatly affected by strike-slip displacements.

I will first discuss the thin-skinned deformation of the fold belt, and then the basement-involved structures related to the Bucaramanga Fault. The detachment levels
the surface and on the presence of incompetent layers within the stratigraphy. Folds of
the Tertiary and upper Cretaceous units, which outcrop just east of the Soapaga Fault,
have wavelengths on the order of 4 km, and amplitude of about 1 km. These relatively
small folds are probably the product of displacement on a detachment within the shales of
the upper Cretaceous Chipaque Formation. Folds further east of the Soapaga fault are
much larger, with wavelengths of about 12 km and amplitudes of 5 km. Furthermore,
the Lower Cretaceous crops out in the core of the anticlines. A detachment probably runs
at the base of the Cretaceous in the shales of the Macanal Formation. In the vicinity of
Bogotá (180 km to the southwest) salt diapirs reach the surface and are believed to
originate within the upper Jurassic or lowermost Cretaceous (Campbell and Bürgi, 1965).
Evaporite layers would provide an ideal detachment surface if present in
the area of the cross section. East of Bogotá in the eastern slope of the Cordillera, thick
Ordovician slates and phyllites crop out within the thrust belt. Nevertheless these rocks
are absent from the Floresta Massif, and lacking any evidence for their existence in the
area of the cross-section, I did not involve them within the deformation. For the thrusts
in the foreland I used a detachment near the base of the Tertiary, mainly because I never
have heard that any of the oil wells in that area has reached the Cretaceous. Since the
Cretaceous is thin in that area, including it within the thrusts would not affect the
geometry of the cross-section greatly.

The Desespero Syncline is the controlling structure of the cross-section. It
exposes the entire Cretaceous to Oligocene sedimentary pile. For that reason the base of
the syncline is also the minimum depth to basement for the hanging wall of the
Guacaramo fault. In order to bring the Lower Cretaceous to the surface in the Cravo
Sur-Horqueta anticline, just west of the Desespero Syncline, it is necessary to build an
anticlinal stack of three large duplexes. Most of the shortening of the interior of the Cordillera is taken up within the stack. The Cravo Sur-Horqueta anticline coincides with a 40 mgal Bouguer gravity low which confirms that it is not a basement-cored structure (Fig. 7). In contrast the Paya Anticline, located east of the Desespero Syncline, is associated with a gravity high, which I interpret as due to a basement block uplifted by the Guaicaramo fault. Two other reasons to think that the Guaicaramo Fault is a basement structure are, first, that it appears to have controlled the deposition of the Cretaceous Cocuy basin and therefore is a reactivated normal fault with a long history (Fabre, 1983). Second, one earthquake located at 30 km depth appears to coincide with the fault (Suarez and others, 1983). The recent activity of the Guaicaramo fault confirms that it moved late in the structural cycle, cross-cutting an already deformed stratigraphy. The Tabiona thrust and the recumbent anticline in its hanging wall belong to the older set of structures. The thrust sheets become progressively younger towards the foreland, each deforming the pre-existing ones. Pleistocene syn-orogenic conglomerates of the Guayabo Formation are involved in the thrust-sheets. The last exposed thrust is 8 km east of the Yopal thrust, but the beds in its footwall are folded, so I interpret one more fault to the east under the recent alluvial cover.

The restored section (Fig. 9 D) shows the stratigraphic variations in the area of the cross-section. The thrust belt developed at the site of the Cretaceous to Eocene Cocuy Basin. Most published structural cross-sections of thrust belts involve wedge shaped sedimentary prisms which thin towards the foreland. The basal detachment simply climbs up the base of the wedge. In the case of the Cordillera Oriental the basal detachment had to scoop down one slope of the Cocuy Basin and up the other. It was necessary to use a front-loader rather than a bulldozer to build this mountain range. The restored section is 185 km long, while the deformed fold belt, east of the Soapaga fault,
is only 90 km long. This implies 50% shortening within the sedimentary cover. Perhaps the greatest difficulty with this structural interpretation is the deficit in the basement necessary to balance the shortening of the cover. The thickened root of the Cordillera must reflect this shortening but the cross-section does not shed any light on how the shortening of the cover feeds into the lower crust. It probably takes place west of the area of the cross-section.

In the Floresta Massif there is a large recumbent anticline in the hanging wall of the Soapaga Fault. This structure involves the Lower Paleozoic metamorphic rocks, two elongated granite plutons, and Devonian to Cenomanian sedimentary rocks. The granite bodies are so intensely fractured and altered that it is impossible to collect a coherent sample bigger than your fingernail. Reyes (1984) describes them as having a cataclastic fabric. In the footwall of the Soapaga Fault the Tertiary beds are folded into a recumbent syncline. This structural pattern of recumbent hanging-wall anticline and overturned foot-wall can be modeled as a result of fault-propagation folding (Suppe, 1985). Figure 10 shows the proposed development of the Floresta Anticline starting with the undeformed sedimentary section and ending with a fold which matches the present day structure. The deformation requires a detachment at about 12 km depth. In stage II the anticline grows as the fault propagates up the section. When the anticline locks-up, the fault breaks through the forelimb limb leaving some of the overturned beds in the footwall (step III, Fig. 10). This explains the steepness of the fault plane observed in the field. The folds and fault accommodate a total of 20 km of shortening. The fracturing of the granite in the core of the anticline probably took place as it folded at shallow crustal level. The fault propagation model can only explain the development of the west limb of the footwall syncline. The east limb requires a pre-existing
I. Undeformed section. There may be a normal fault controlling the wedge of Jurassic sediments.

II. As the fault propagates up, the section folds as a recumbent anticline. There are Paleozoic metamorphic rocks and granite folded in the core of the anticline.

FIGURE 10. Development of the Floresta Anticline.
IIIa. A step faults breaks through the overturned limb. The anticline rides the ramp, becoming tighter as it moves through the kink in the fault.

III b. The back limb of the footwall syncline requires a pre-existing ramp which I left out of Stage I for simplicity.

FIGURE 10 continued. Development of the Floresta Anticline.
structure, such as the ramp-fold shown in Figure 10, III b.

The Boyacá Fault is located 15 to 20 km west from the Soapaga Fault in the Floresta Massif. It remains roughly parallel to the Soapaga Fault for its entire length. In its hanging wall there is a broad, gentle anticline that exposes over 3 km of Jurassic strata. In the core of the fold there are Jurassic rhyolitic volcanic rocks, granitic intrusives, and Paleozoic sedimentary and metamorphic rocks.

Because the thick Jurassic red-beds are absent from the foot-wall block, it is probable that the Boyacá Fault originated as a normal fault during Jurassic time. For several reasons it is unlikely that the difference in stratigraphy across the Boyacá Fault is due to large strike-slip displacement. First, the fault has a sinuous map trace, indicating that it is a fairly low-angle structure. Second, to the southwest the fault ends within a system of thrusts of the same orientation without any indication of transcurrent displacement. And third, there are no correlative Jurassic sedimentary rocks to the north on the eastern block of the Bucaramanga system. The pre-existing normal fault acted as a ramp when the Boyacá Fault became reactivated. The anticline exposed on the surface is the product of movement over this ramp. The length of the beds in the footwall is constrained by the position of the ramp, which in turn is controlled by the surface anticline. About 16 km of shortening are represented in the cross-section.

B. Sativa Cross-Section

The second cross-section is located about 20 km north of the regional one (Fig. 9 B). It includes the area I mapped in detail near Sativa. It cuts the Bucaramanga Fault just before its intersection with the Soapaga Fault. I have simplified the structure of the fold-belt by eliminating many small normal faults which shatter the older compressional folds and faults. The structure of the fold-belt east of the Soapaga Fault is
similar to that shown in the regional cross-section except that there are several
significant back-thrusts. These include the Socotá and Chiscas faults, which are rather
enigmatic structures. They persist for at least 70 km to the north and cut through a
significant portion of the stratigraphic section. Fabre (1983) speculated that the
Chiscas Fault may be one of the bounding normal faults of the Cocuy Basin which
reactivated during the Andean compression, but I was unable to draw a meaningful
cross-section incorporating this idea. Instead, I present the back-thrusts as being
detached at the base of the mid-Cretaceous. They probably accommodate part of the
shortening represented by the duplex structure of the Lower Cretaceous. The back-
thrusts form an independent structural panel, so they could have developed
simultaneously with the duplex stack which underlies them, or they may post-date it.
Only the strange "scoop" structure west of the Sácama Fault clearly cross-cuts older
structures. It may require displacement out of the plane of the section.

In the footwall of the Soapaga Fault there is an anticline-syncline pair which I
described earlier. The folds are steep and sometimes recumbent and involve upper
Cretaceous to Oligocene rocks (Fig. 3). I interpret them to be the product of a thrust
rooting in the Soapaga Fault which propagated up the section. This fault is out-of
sequence with respect to the thin-skinned deformation. In this cross-section the
Bucaramanga Fault appears as a inconspicuous splay of the Soapaga Fault. Here the
structures related to the Soapaga Fault also require about 20 km of shortening, but
because of the displacement out of the plane of the section of the Guantiva and
Bucaramanga Faults it is not possible to measure it exactly.

The structures on the hanging wall of the Boyacá Fault are similar to those
shown in the regional cross-section. Again there are thick Jurassic sedimentary rocks
and volcanic rocks in the hanging wall which are absent from the footwall suggesting that the fault is a reactivated Jurassic normal fault.

C. Soatá Cross-Section

The third and northernmost cross-section is dominated by wrench-related structures of the Bucaramanga system. The structural style of the Santander Massif is different from that seen in the other two sections. There are large blocks of basement, as well as slivers of Cretaceous to Paleozoic sedimentary rocks, bounded by steep strike-slip and reverse faults. I represent these as transpressional flower structures which are characteristic of wrench deformation (Christie-Blick and Biddle, 1985). There is no hope of balancing or retrodeforming this portion of the cross-section. Although my solution to the structure of the fold-belt in this cross-section is retrodeformable, it seems rather forced. A thick section of Lower Cretaceous rocks crops out in the footwall and hanging wall of the Sacama Fault. Just 25 km to the west this section is absent and the Mid-Cretaceous sedimentary rocks rest on Carboniferous rocks. This leaves little space for the Lower Cretaceous section to thin out. At the same time back-thrusts with relatively large displacements complicate the structure. It is easy to visualize a basin, bounded by normal faults on both sides, which upon being compressed would deform on thrusts of opposite vergence. Unfortunately when I attempt to draw the cross-section rigorously, the geometry does not work out. The tail end of the Soapaga Fault projects into this cross-section. If the structural model is correct, the Bucaramanga and Chicamocha Faults must feed into this low angle shear zone at about 12 km depth.
D. Implications for the termination of the Bucaramanga Fault

1) The shortening within the thrust-belt east of the Floresta Massif could only take place before displacement of the Soapaga Fault and Boyacá Faults occurred. The basement faults cut and deform the pre-existing detachments. They were active late in the orogenic cycle, probably during the Pliocene.

2) The distribution of the Girón redbeds near the Boyacá Fault, and of Lower Cretaceous sedimentary rocks near the Guaicaramo Fault indicates that they originated by the reactivation of Mesozoic normal faults. There is also a wedge of redbeds in the hanging wall of the Soapaga Fault. In that case a reactivated normal fault could not generate the recumbent folds seen today, but it may have nucleated the ramp of the reverse fault. Thus the location of the pre-existing normal faults controlled the development of the basement-involved faults in the Cordillera Oriental.

3) The structures associated with the Boyacá and Soapaga Faults require about 36 km of shortening which probably represents the transform of left-lateral slip on the Bucaramanga Fault system.

4) The geometry of the Floresta Anticline is best reproduced by a fault-propagation-fold with a detachment at about 12 km depth. The Boyacá Fault also seems to flatten at that depth making it necessary to postulate a regional crustal detachment. This implies that the Soapaga and Boyacá faults can only accommodate the strike-slip displacement of the Bucaramanga Fault down to 12 km. Below this depth either the strain must be absorbed by a different mechanism, or the Bucaramanga Fault itself only cuts down to 12 km near its southern termination.
A. Pre-Andean structural controls

During the Late Jurassic and Early Cretaceous an episode of extension and crustal thinning affected the region of the Cordillera Oriental (Fabre, 1983). Large elongated grabens seem to have developed on each side of the ancestral Santander-Floresta massif, which remained as a positive area. The Tablazo basin, to the west of the ancestral Santander-Floresta massif, contains up to 2500 m of Jurassic redbeds and continental deposits of the Girón fm, covered by 800 m of Lower Cretaceous paralic clastics. In the Cocuy basin, to the east of the massif, the Jurassic redbeds are not exposed, but there are over 3000 m of Lower Cretaceous marine sedimentary rocks. Fabre (1983) interpreted this period of rapid subsidence as reflecting thinning of the crust and lithosphere by extension accompanied by elevated heat flow. Acid volcanic rocks of this age, such as the Onzaga Rhyolite, as well as basic alkaline dikes and hydrothermal mineralization are the manifestations of the high heat flow. Using the McKenzie (1978) model, Fabre estimated that the crust may have thinned by as much as 50% to allow the observed subsidence.

From the Middle Jurassic to the early Cretaceous the North American plate was in the process of breaking away from Gondwana (Pindell, 1985). North America moved away from South America at 2 to 3 cm/yr in a N55W direction (from data in Pindell, 1985). It is reasonable that South America would undergo some extension along this vector developing grabens oriented about N30W (Fig. 11 a). Some of the normal faults which bounded these large grabens were reactivated during the Andean compressional phase as thrust faults. That is the case for the Boyaca Fault, and probably the Guaicaramo fault as well.
Starting in the Aptian the Cocuy and Tablazo Basins, and the Santander Massif, began to subside together. Mid Cretaceous marine sedimentary rocks of similar facies covered the entire area. This episode of progressively slowing subsidence, which continued at least until the end of the Cretaceous, occurred as heat flow returned to normal after crustal extension ended (Fabre, 1983). Lower Paleocene sandstones were the first truly continental sedimentary rocks to accumulate. Until this time the source of clastics had been the Guyana Shield to the east, but in the late Paleocene the composition of the sandstones in the Cocuy basin changes. Chert fragments, quartz arenites, and sericitic schists mix with detritus coming from the craton. According to Fabre (1983) this indicates that the Santander Massif was uplifted at this time, and provided the new source of sedimentary rocks. Simultaneously the Tablazo basin to the west experienced its first deformation. During the Eocene and early Miocene subsidence resumed on both the Cocuy and the Tablazo basins and up to two kilometers of continental sedimentary rocks accumulated.

B. The Andean Orogeny and the Bucaramanga Fault

The present-day configuration of the northern Andes is the product of processes which culminated very recently. Tectonism in the area is the product of the interaction of the South American, Nazca, and Caribbean plates. The onset of thrusting in the Cordillera Oriental is marked by the first molassic sedimentary rocks which were shed from both sides of the range during the middle Miocene. A flexural basin began to develop over the Eastern Llanos, which has accumulated over 4000 m of detritus up to the present. The basins which had existed since the early Mesozoic were shortened and telescoped by thrusting and folding. The fold-belt developed there perhaps because the thinned crust was a weak region where deformation became localized. The Plio-Pleistocene
Figure 11a. Mid-Jurassic reconstruction of northwestern South America after Pindell (1985). Plate motions are in cm/yr relative to South America.
Figure 11 b. Reconstruction of the Circum-Caribbean at 19 Ma. Modified from Burke and others (1984). Plate motion of Nazca relative to South America are from Pardo-Casas and Molnar (1987).
Figure 11 c. Reconstruction of the Circum-Caribbean at 9 Ma. Modified from Burke and others (1984). Plate motion of Nazca relative to South America are from Pardo-Casas and Molnar (1987).
Figure 11 d. Present day circum-Caribbean region. Modified from Burke and others (1984). Plate motion of Nazca and Caribbean relative to South America are from Drummond, 1981.
Tilatá Formation lies flat over the folded Lower Tertiary and Cretaceous beds (see SW corner of Fig. 3). This means that most of the compressional deformation within the range had stopped by Pliocene time and the thrust front had migrated east. As I mentioned earlier, the Guaicaramo Fault in the eastern foothills of the Cordillera is seismically active, and Pliocene conglomerates are cut by the thrusts in the foothills. Palynological data show that the Tilatá Formation, which today occurs in the cool highlands of the Cordillera, was deposited in a warm tropical environment. This is interpreted to indicate that the area was near sea level at that time, and has been uplifted since the Plio-Pleistocene (Van der Hammen, 1973). Molnar and England (1990) have challenged similar interpretations of recent uplift of the Himalayas and the Colorado Plateau. They argue that the fossils show climatic changes, not variations in elevation. There should not be a lag between the time of deformation and time of uplift of a mountain range. Unfortunately there are no constraints on the timing of the uplift of the Cordillera Oriental other than Van der Hammen's study, so I cannot contribute to this debate.

Simultaneous with these events, dramatic developments were taking place in the paleoCaribbean. The Caribbean plate is believed to be a fragment of Jurassic Pacific ocean floor which was captured between the North and South American plates (e.g. Burke and others, 1984). Since sometime in the Eocene the Caribbean fragment has been moving eastward along the northern margin of the South American plate. As a result, a complex system of right lateral strike-slip faults, oriented east-west, cut through northern Colombia and Venezuela (Fig. 1). Some workers have placed the Caribbean-South America plate boundary at this fault system (Molnar and Sykes, 1969; Dewey, 1972), but as Kellogg and Bonini (1982) have argued it is probably more correct to place the plate boundary farther north along the Caribbean Deformed Belt.
The beginning of the deformation of the Cordillera Oriental coincides with a period of accelerated convergence between the Nazca plate and South America (Fig. 11 b). From the time of magnetic anomaly 6 (19.9 Ma) to anomaly 5 (10.6 Ma) the plates converged at 14 cm/yr off the southern coast of Colombia (Pardo-Casas and Molnar, 1987). This pulse of compressional deformation is recognized all along the Andean Cordillera. Mégard (1984) called it the Quechuan Phase in the Peruvian Andes. Nevertheless, it appears that at that time, most of the margin of Colombia was exposed to the Caribbean plate, not to theNazca plate (Fig. 11 c; Burke and others, 1984). The high rate of convergence between Nazca and South America may still be the ultimate cause of deformation in the Colombian Andes for two reasons. First, the Caribbean plate was being driven by the motion of the Nazca plate, so probably South America-Caribbean convergence also became faster as the Nazca plate accelerated with respect to South America. Second, between 12.3 Ma and 11.8 Ma the Panama Arc and the Choco Block, which were part of the Caribbean fragment, accreted to the Colombian margin (Duque-Caro, 1990).

I propose that the left-lateral Bucaramanga Fault developed as an escape structure due to increased compression and accretion of an island arc against the western margin of Colombia. Because during Miocene and Pliocene time the motion of the Caribbean plate was predominantly eastward relative to South America, the northern edge of Colombia acted as a free boundary (Fig. 11 c and d). It was possible for the block east of the Bucaramanga Fault to move north. The case is analogous, in a smaller scale, to the strike-slip faults which cut China and South East Asia north of the Himalayas (Tapponnier and others, 1986).
C. Sequence of faulting at the end of the Bucaramanga Fault

In spite of the relative complexity of the area it is clear that the Boyacá and Soapaga Faults absorb a large portion of the strike-slip displacement of the Bucaramanga Fault. Figure 12 shows a sketch map of the termination of the Bucaramanga Fault. The estimates of shortening come from the structural cross-sections.

The Bucaramanga Fault retains a very straight surface trace until it approaches the Soapaga Fault. Forty kilometers north of its termination, it begins to bend to the west until it is oriented almost north-south. Probably the fault plane becomes progressively more inclined through this bend, turning into an oblique thrust. As described earlier, the Bucaramanga Fault makes a tight bend just before its intersection with the Soapaga Fault. I interpret this as deformation resulting from reactivation of the Soapaga Fault. The latter extends to the northeast of the termination of the Bucaramanga Fault, probably feeding into the Chicamocha Fault. Although I did not map this relation in the field I think it is reasonable. It is not clear how the Chicamocha Fault links back to the Bucaramanga Fault to the north of the map area.

I interpret the field relationships in terms of two stages of motion on the Soapaga Fault which absorb strike-slip displacement on two strands of the Bucaramanga system active at different times. First, as a response to movement on the main strand of the Bucaramanga Fault, the Soapaga Fault begins to propagate and the Floresta anticline develops as described earlier. Second, as the main strand of the Bucaramanga Fault becomes inactive, displacement transfers to the Chicamocha strand, further east. At this time the Soapaga fault reactivates and propagates to the northeast, taking up the motion on the Chicamocha Fault.
FIGURE 12. Schematic map of the termination of the Bucaramanga Fault. Arrows show amount of shortening or strike-slip displacement in kilometers.
Because neither the Boyacá nor the Soapaga Faults are perfectly orthogonal to the Bucaramanga Fault, they must have a small component of oblique slip which would be very difficult to detect in the field. The structures associated with the two reverse faults total about 36 km of shortening, which would require about 38 km of left-lateral slip on the Bucaramanga Fault once we account for the orientation of the faults. To this we need to add the displacement of the Chicamocha Fault which is hard to quantify but is probably on the order of 5 km.

In summary, these simplistic geometric calculations show that the compressional structures at the termination of the Bucaramanga Fault account for no more than 45 km of strike-slip displacement. This is less than half of the displacement assigned to the fault by Campbell (1965) or Irving (1971). The zone of transfer may cover an area even larger than that I describe above, including structures in the Santander Massif and in the Middle Magdalena Valley, which will require a lot more work to unravel. Alternatively the displacement on the Bucaramanga Fault may be much smaller than has been previously thought.
VII. CONCLUSIONS

The termination of the Bucaramanga Fault occurs in a complex region where several structural systems interact. I present the following sequence of events to explain the present day configuration of the area.

1) Pre-Andean Structures. As a consequence of the Jurassic rifting of North America away from Gondwana the northeast corner of South America underwent extension. This resulted in normal faulting and crustal thinning, producing elongated basins oriented N30E. These basins continued to subside until Oligocene time accumulating thick sedimentary packages.

2) Andean Orogeny. Convergence between the Nazca plate and South America accelerated during the Middle and late Miocene. In response to increased compression and to the accretion of an island arc against the western margin of Colombia, the area of the Tablazo and Cocuy basins began to be telescoped by thrusting and folding.

2.1) The initial deformation in the Cordillera Oriental was thin-skinned. By Pliocene time the thrust front had migrated to the exterior portion of the present-day mountain belt.

2.2) The Bucaramanga Fault system developed after the thin-skinned deformation of the core of the Cordillera had already taken place. It originated as an escape structure due to compression against the western margin of Colombia while the northern margin remained unconfined. The left lateral motion of the Bucaramanga fault was absorbed by the reactivation of Jurassic normal faults of the appropriate orientation. These are the Soapaga and Boyacá Faults which bring basement to the surface in the core of the Cordillera Oriental.
2.2.1) Like most strike-slip systems, the Bucaramanga fault was active for an extended time. Different branches of the system moved at different times. The initial displacement of the main branch of the Bucaramanga system was absorbed by motion on the Boyacá Fault and by the first stage of motion of the Soapaga Fault. Later, the main strand of the Bucaramanga system became inactive and displacement occurred on the Chicamocha strand, further east. In order to absorb this motion, the Soapaga fault extended to the northeast, and its older portion became reactivated. This sequence explains the cross-cutting relationships seen in the field.

The structures at the termination of the Bucaramanga Fault require about 45 km of left-lateral motion. This is less than half of the displacement estimated by earlier workers (Campbell, 1965; Irving, 1971). Given the uncertainty of the methods used to estimate the displacement of the fault, and the complexity of the region this disagreement is not surprising.

Another aspect of the termination of the Bucaramanga Fault is still puzzling. All the cross-sections indicate that the Soapaga and Boyacá faults flatten out at about 12 km depth. Therefore they can only absorb transcurrent motion to that depth. I have pushed the problem of accommodating the displacement of the Bucaramanga Fault down to 12 km. Either the Bucaramanga fault only cuts down to 12 km throughout its length and the upper crust is detached from the lower crust, or there is a low angle shear zone feeding down to the base of the crust west of the Cordillera Oriental.
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