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Quaternary Activity of the Bucaramanga Fault in the Departments of Santander and Cesar

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Abstract The 350 km long Bucaramanga Fault is the southern and most prominent segment of the 550 km long Santa Marta–Bucaramanga Fault that is a NNW striking left lateral strike–slip fault system. It is the most visible tectonic feature north of latitude 6.5° N in the northern Andes of Colombia and constitutes the western boundary of the Maracaibo Tectonic Block or microplate, the southeastern boundary of the block being the right lateral strike–slip Boconó Fault in Venezuela. The Bucaramanga Fault has been subjected in recent years to neotectonic, paleoseismologic, and paleomagnetic studies that have quantitatively confirmed the Quaternary activity of the fault, with eight seismic events during the Holocene that have yielded a slip rate in the order of 2.5 mm/y, whereas a paleomagnetic study in sediments of the Bucaramanga alluvial fan have yielded a similar slip rate of 3 mm/y. This recent activity is not reflected in surveys of instrumental seismicity that indicate a low level of seismic activity whereas the strong geomorphic expression of the fault trace, corroborated by field studies and landscape evolutionary models, suggests higher slip rates during the Pleistocene. The occurrence of a large transpressive duplex structure developed in a right hand restraining step–over along the northern stretch of the fault suggests fault locking that might explain this low level of seismicity. Recent results of GPS instrumentation of certain sectors of the fault indicate a confusing pattern of velocity vectors that are a reflection of considerable deformation within the shear zone of the fault.

Keywords: *Ocaña duplex structure, morphotectonic indicators, neotectonics, slip rate, recurrence interval, restraining step–over.*

Resumen Los 350 km de la Falla de Bucaramanga son el segmento sur y más destacado de los 550 km de la Falla Santa Marta–Bucaramanga que es un sistema NNW de movimiento lateral sinestral. Es el rasgo tectónico más visible al norte de la latitud 6,5° N en los Andes del norte de Colombia y constituye el límite occidental de la microplaca o Bloque Tectónico de Maracaibo, el límite suroriental del bloque inicia en Venezuela en la falla dextral conocida como Falla de Boconó. En los últimos años se han realizado estudios de neotectónica, paleosismología y paleomagnetismo en la Falla de Bucaramanga. Estos estudios han confirmado cuantitativamente la actividad cuaternaria de la falla, con ocho eventos sísmicos durante el Holoceno que han arrojado una tasa de desplazamiento de 2,5 mm/año, mientras que un estudio de paleomagnetismo en sedimentos del abanico aluvial de Bucaramanga arrojó una tasa de movimiento similar

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de 3 mm/año. Esta actividad reciente no se ve reflejada en los estudios de sismicidad instrumental que indican un nivel bajo de actividad sísmica, mientras que la fuerte expresión geomorfológica del trazo de falla, corroborado por estudios de campo y modelos de evolución del paisaje, sugiere altas tazas de desplazamiento durante el Pleistoceno. La presencia de un gran dúplex transpresivo desarrollado al lado derecho y que restringe el escalón *(step–over)* a lo largo del segmento norte de la falla sugiere que el bloqueo de la falla podría explicar el bajo nivel de sismicidad. Los resultados recientes de la instrumentación GPS de ciertos sectores de la falla indican un patrón confuso de los vectores de velocidad que son un reflejo de la deformación considerable dentro de la zona de cizalla de la falla.

Palabras clave: *estructura dúplex de Ocaña, indicadores morfotectónicos, neotectónica, tasa de deslizamiento, intervalo de recurrencia, escalón (step–over) restrictivo.*

1. Introduction

The NNW striking left lateral strike–slip Santa Marta–Bucaramanga Fault System (SMBF) is the most prominent fault system in the northern part of the Colombian Andes, north of 6.5° N latitude. North of this latitude the predominant tectonic grain of the northern Andes of Colombia changes from a predominant NE–SW orientation to a predominant NNW tectonic trend of most fault systems (Figure 1). This might well be a reflection of the E to SE directed convergence of the Caribbean Plate with the continental South American Plate (Audemard, 2014; Laubscher, 1987), whereas for the larger southern part of the Colombian Andes the convergence of the Nazca Plate has an ENE direction and is oblique (Audemard, 2014; Egbue & Kellogg, 2010; Freymueller et al., 1993; Mora–Páez et al., 2016, 2019; Taboada et al., 2000; Trenkamp, et al., 2002).

The SMBF can be divided in three major segments (Figure 2): (i) the northern segment, the Santa Marta Fault (SMF), constitutes the western margin of the uplifted block of the Sierra Nevada de Santa Marta (SNSM) over a distance of 150 km (Campbell, 1965; Laubscher, 1987; Tschanz et al.,1974) and consists of an arrangement of parallel to sub parallel faults and related NE striking reverse faults and anticlines and NW striking normal faults that display numerous morphotectonic features that indicate predominant left lateral displacement during the Quaternary (Idárraga–García & Romero, 2010), but also might have a ramp fault function related to the NW verging thrust systems of the SNSM Massif (Laubscher, 1987; Mora et al., 2017). (ii) The central segment, stretching over a distance of 100 km, is hidden under a thick cover of alluvial sediments of the Cesar–Ranchería and the Plato–San Jorge Basins of the Lower Magdalena Valley, where no surface expression occurs and where seismic profiles indicate predominantly west verging thrust faults and only indicate the vaguest possibility of the presence of subvertical faulting (Mora & Garcia 2006; Ujueta, 2003). The continuation of the strike–slip fault system has even been put in doubt by Ujueta (2003) who suggests the SMBF to consist of two completely different faults: The Santa Marta and the Bucaramanga Faults respectively. (iii) At the southwestern corner of the Cesar–Ranchería valley just north of the town of Pailitas, the fault re–appears with a recognizable fault trace (Cuéllar et al., 2012; Diederix & Bohórquez, 2013) and from there on towards the south the fault displays a continuous trace that passes the cities of Ocaña and Bucaramanga with a strong geomorphic expression all the way to the ancient village of Cepitá in the valley of the Chicamocha River (Figure 3; Diederix et al., 2009a). From there on further to the south the trace is less clear and the fault apparently terminates in a horsetail structure that connects to the NE striking right lateral east verging reverse faults of Soapaga and Boyacá (Acosta et al., 2007; Del Real & Velandia, 2013; Kammer & Sánchez, 2006; Toro, 1990; Velandia, 2005). The area of connection has been described as a transpressive duplex structure (Acosta et al., 2007; Velandia, 2005). This convergence of NNW striking strike–slip fault system in the north with the NE striking dextral fault systems in the south has been referred to as the Andean–Santander oriental syntaxis by Nevistic et al. (2003) and Rossello et al., (2010) that coincides with the culmination of the Eastern Cordillera in the Nevado del Cocuy of 5400 m altitude on the convex side of the convergence and that has resulted in an east verging salient of the Eastern Cordillera, suggested here to be named the Cocuy Salient.

Figures for the accumulated displacement since Paleozoic times range between 110 km and 45 km (Campbell, 1965; Cediel et al., 2003; Irving, 1971; Laubscher, 1987; Montes et al., 2010; Toro, 1990). Cediel et al. (2003) postulate a Grenvillian age (±1000 Ma) for the fault that they consider was then a continuation of the Algeciras or Suaza Fault as the authors call it. Other authors suggest an initiation of the fault during Mesozoic (Kammer & Sánchez, 2006; Mora et al., 2017; Toro, 1990) or Tertiary time (Eocene or Miocene) (Acosta et al., 2007; Boinet et al., 1989; Montes et al., 2010; Toro, 1990), some of them suggesting repeated phases of reactivation during the Cenozoic (Mora et al., 2017). The most significant of these phases of reactivation was the one that began in middle Miocene times (±13 Ma) and started the culmination phase of the Andean Orogeny.

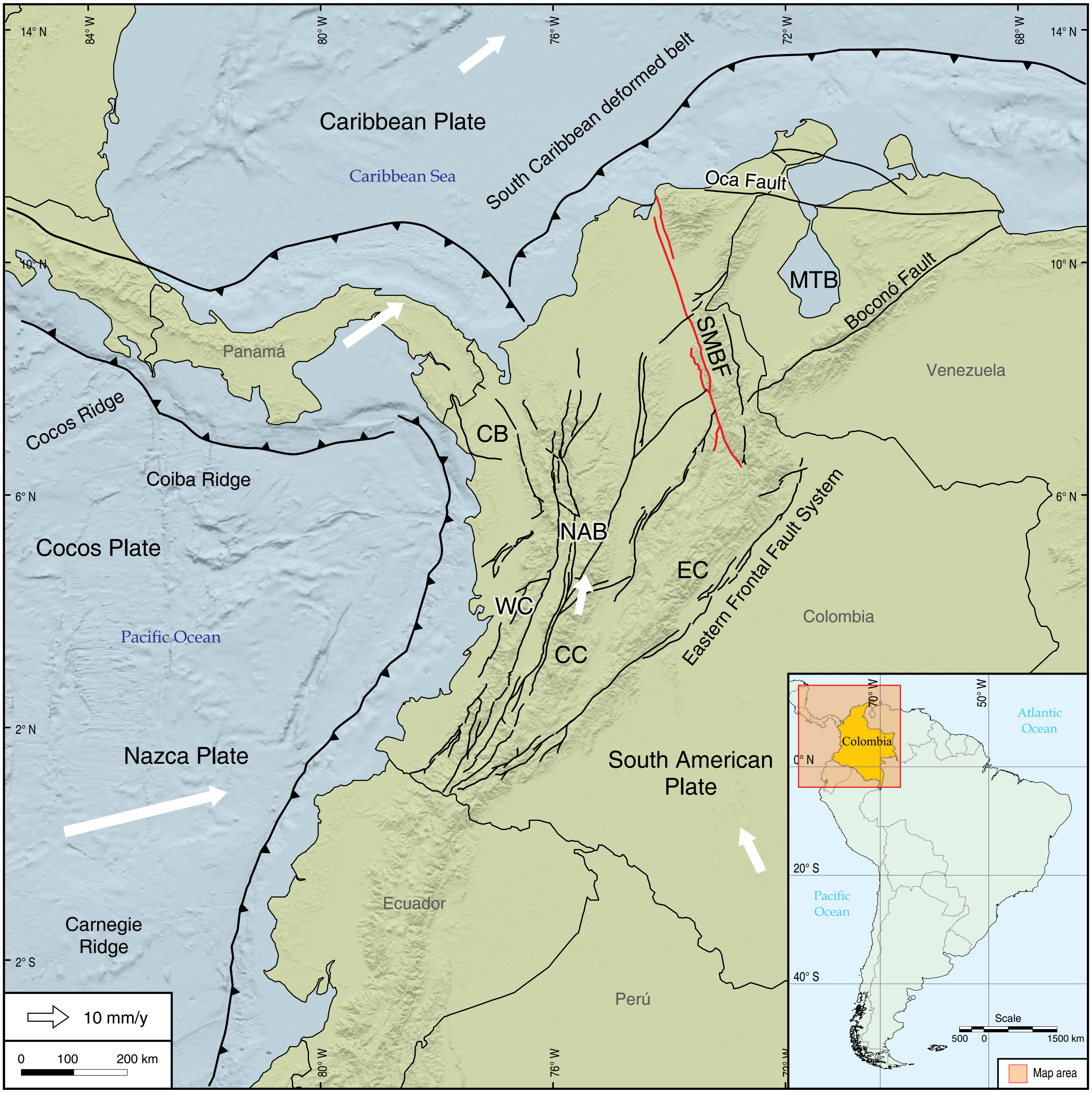


Figure 1. Regional tectonic setting: The position of the Santa Marta–Bucaramanga Fault System (SMBF) within the North Andean Block (NAB) and its relation to the Caribbean Plate convergence and the Maracaibo Tectonic Block (MTB). Velocity vectors (white arrows) are expressed with respect to ITRF2008 (Mora–Páez et al., 2019). (EC) Eastern Cordillera; (CC) Central Cordillera; (WC) Western Cordillera; (CB) Chocó Block.

The focus of the present chapter is on the southern part of the Bucaramanga Fault (BF) that extends from the town of Pailitas in the Department of Cesar in the north to the ancient village of Cepitá in the Department of Santander in the south, a distance of approximately 300 km. Along this stretch the fault has a very strong morphologic expression, well visible on aerospace imagery (Figure 3) that is clear evidence of Quaternary and recent activity. The fault in this sector constitutes the western boundary of the Precambrian to Mesozoic age Santander Massif that has been uplifted along the fault. It is the expression of a strong vertical component along this strike–slip fault (Julivert, 1959, 1961; Ward et al., 1973). Some remarkable features that occur along the fault are worth of mention: At ca. 120 km north of the city of Bucaramanga the fault makes a right hand step–over (Aydin & Nur, 1985; Sylvester, 1988) of 15 to 20 km width of separation and a longitudinal overlap of the two branches of 70 km between

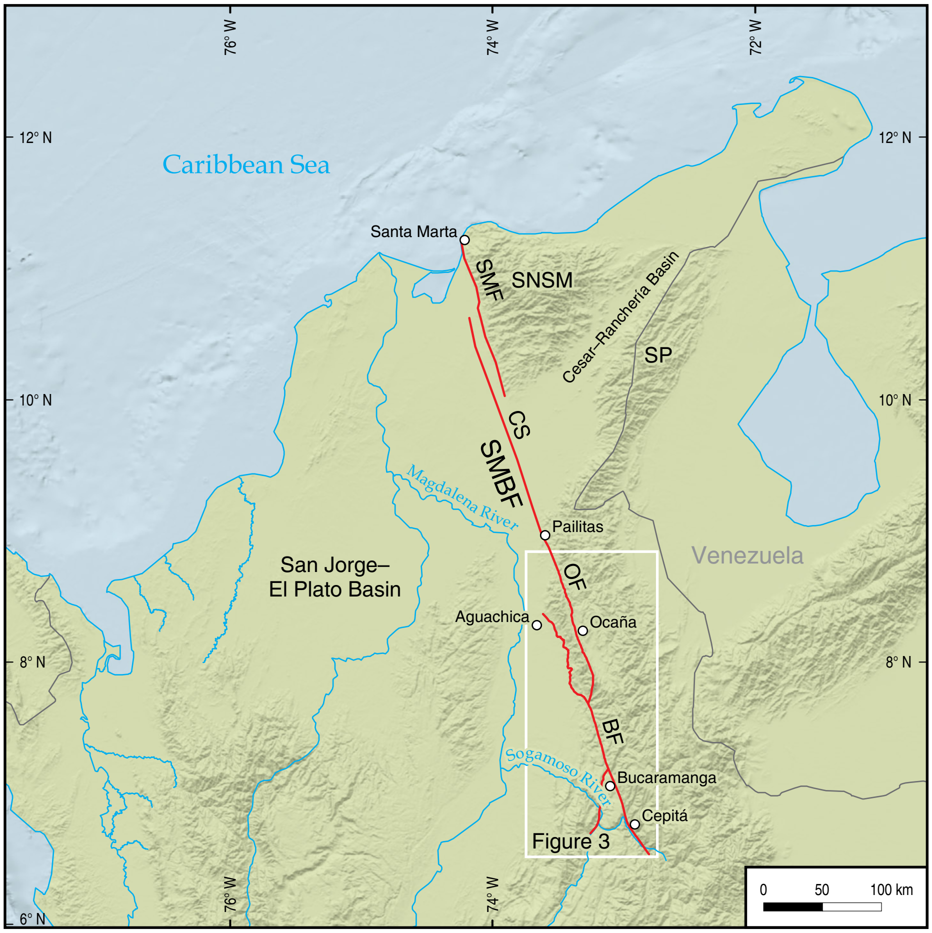


Figure 2. The Santa Marta–Bucaramanga Fault System (SMBF) and its division in three major segments: (SMF) Santa Marta Fault, in the north; (CS) Cesar segment, in the center; (BF) Bucaramanga Fault, in the south. (SNSM) Sierra Nevada de Santa Marta; (OF) Ocaña Fault; (SP) serranía del Perijá.

the village of La Esperanza in the south and Aguachica in the north. This configuration of geometry and sense of fault displacement corresponds to a restraining step–over which is known as a transpressive duplex structure (Figure 4; Cunningham & Mann, 2007; Mann, 2007; Storti et al., 2003; Sylvester, 1988; Woodcock & Schubert, 1994; Yeats et al., 1997). A short distance beyond the town of Aguachica to the north the western branch disappears under a thick alluvial cover of the Magdalena valley, whereas the eastern branch continues to the north where, 60 km further to the north, it also disappears under a thick alluvial cover of the Cesar–Ranchería valley a short distance to the north of the town of Pailitas. This branch of the fault has been given several different names in the past such as Algarrobo, Carmen, or Boloazul Fault (Cuéllar et al., 2012), but because it passes through the outskirts of the well–known town of Ocaña, we propose to name it the Ocaña Fault and to name the duplex structure also after the town of Ocaña (Figure 5).

Another notable feature along the fault is the large Bucaramanga alluvial fan on which the city of Bucaramanga is built. The fault traverses the city marking the foot of the escarpment of the Santander Massif. The Bucaramanga fan is a confined deposit of more than 300 m thickness (De Porta, 1959; Julivert, 1963) that has filled a fault wedge basin as defined by Crowell (1962) that developed at the junction of the BF and the left lateral reverse Suárez Fault. Both the tectonic basin and the large fan infill are the result of fault activity of the interacting Bucaramanga and Suárez Faults at least since Pliocene times (Diederix et al., 2008).

Along the stretch of fault between Bucaramanga and the village of Cepitá in the valley of the Chicamocha River to the south, numerous morphotectonic indicators, such as sagponds, L–shaped spurs, shutteridges, stream offsets, aligned fault saddles, and stream deviations can be identified that, because of their alignment along the fault trace, can be taken as evidence of recent fault activity (Diederix et al., 2008, 2009a; Velandia et al., 2007). The most remarkable of these features is the 2.5 km left hand northward offset of the Suratá River that has been considered to be the main feeder stream of the large Bucaramanga fan that has now been abandoned because of this offset (Diederix et al., 2009b; Jiménez et al., 2015). In one place a few kilometers to the north of Bucaramanga and to the north of the Suratá River, a paleoseismologic study has been carried out in a sagpond deposit next to the fault trace that yielded evidence of 8 seismic events during the Holocene and a possible slip rate of 2.5 mm/y (Diederix et al., 2008). A paleomagnetic study carried out by Jiménez et al. (2015) on sediments of the Bucaramanga fan produced a comparable slip rate of 3 mm/y for the middle Pleistocene (800 000 years). The present work presents a description of the more salient structural features that are evidence of Quaternary activity of the BF.

2. Materials and Methods

Methods of neotectonic survey rely in the first and foremost place on the use and interpretation of aerospace imagery. In this case it meant the use of digital elevation models (DEMs) based on the satellite radar data of the Satellite Radar Topographic Mission (SRTM) of NASA and the ALOS PALSAR satellite radar system of the Japan Aerospace Exploration Agency (JAXA) with spatial resolution of 30 and 12.5 m respectively, and the European satellite radar system Sentinel. The satellite radar systems, because of their shadow effect, give an excellent representation of the topography that is particularly useful for lineament analysis. But the most important tool for the identification of the often subtle expression of geomorphic and in particular morphotectonic terrain features that can be an indication of recent tectonic activity, is no doubt the aerial photo in stereo view. Annotation of the photo pairs of the interpreted terrain features is transferred by visual means onto 1:25 000 scale topographic map sheets on which drainage has been emphasized by manually marking all stream channels. This is necessary for visual referencing with the drainage that has been marked by the interpreter on the aerial photos. Annotation of the topographic map sheets includes the marking of fault traces and all possible drainage anomalies, geomorphic markers, and morphotectonic indicators. These will be indicated on the topographic map sheets together will all occurrences of Quaternary deposits along the fault trace. This will result in so–called "strip maps", which are maps that only mark belts of a few kilometers width that include the fault trace with all morphotectonic indicators that have been registered alongside the fault trace. The registration of these indicators has been done on topographic map sheets at a scale of 1:25 000 and could therefore not be reproduced for this paper. One of the most important objectives of a neotectonic survey is to select sites along the fault trace that are promising for making an excavation across the fault trace where it crosses Quaternary deposits, such as fluvial terraces or alluvial fans. These excavations are known as trenches that permit detailed outcrop mapping that include visible evidence of fault displacement in sediments that can be dated geochronologically (McCalpin, 2009; Yeats et al., 1997). This is the field of paleoseismology that, in combination with quantified displacement data, serve to calculate slip rate of the fault, recurrence intervals, and date of the last seismic event (McCalpin, 2009; Yeats et al., 1997).

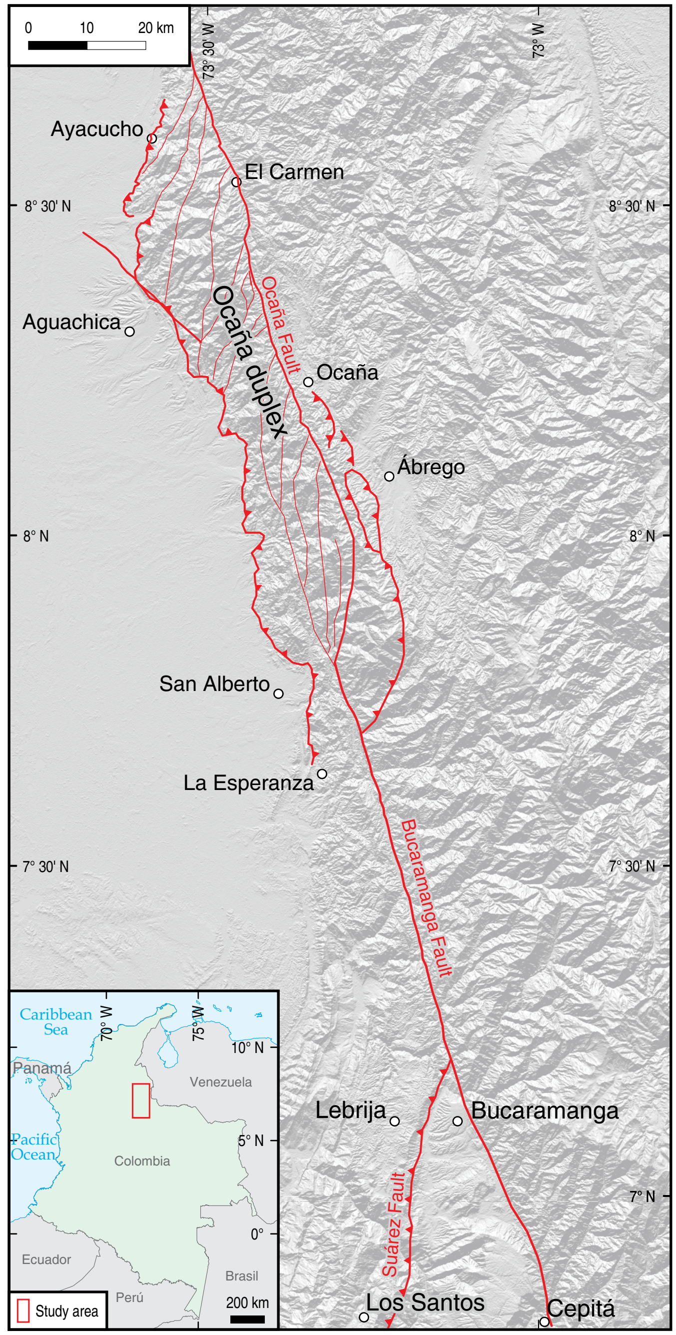


Figure 3. DEM of the Bucaramanga Fault between the town of Ayacucho in the north (Cesar Department) and Cepitá/Los Santos in the south (Santander Department). Note the position of the Ocaña duplex between the Ocaña and Bucaramanga Faults and the convergence of the Bucaramanga and the Suárez Faults.

Another aspect of fieldwork includes the selection of sites for the establishment of geodetic stations as part of the GeoRED project after Mora–Páez et al. (2002). The objective of this is to establish a number of such stations in at least a 15 km wide swath across the fault system or across individual faults that,

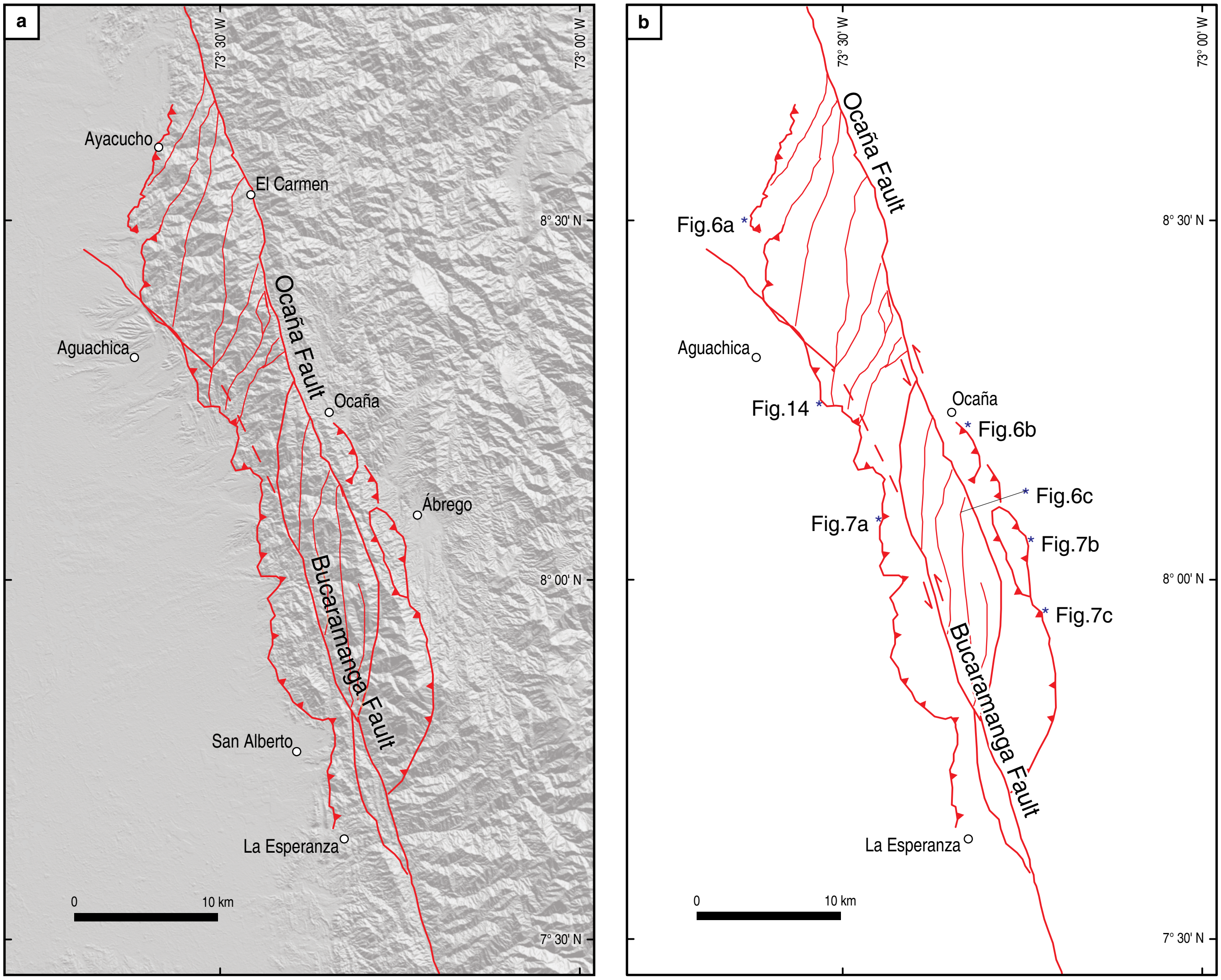


Figure 4. DEM of the Ocaña duplex and its structural cartographic presentation. Note the 70 km longitudinal overlap and the 15 to 20 km separation of the two fault branches that mark the step–over.

over a period of a number of years, will monitor the relative change in position of each of these stations and that in turn will permit to establish the magnitude of elastic deformation of the crust on either side of the fault. This can give an indication of future fault failure through the process of elastic rebound on reaching the elasticity limit, that is: An instantaneous return to the original state in the form of an earthquake.

3. Regional Tectonic Setting

The BF is situated in the northern part, north of 7° N latitude, of the North Andean Block (NAB), the crustal block that makes up almost the entire Andean mountain zone of Colombia, Ecuador, and Venezuela (Figure 1; Irving, 1971). The tectonic grain of the southern half of this block has a predominant NNE to NE strike direction that is roughly parallel to the Pacific Ecuadorian–Colombian coastline and the offshore Nazca subduction trench. The Nazca Plate converges obliquely with respect to ITRF2008 at a velocity of 51 mm/y towards the South America continent (Mora–Páez et al., 2019). This oblique convergence translates into strain partitioning with a present–day trench normal movement of 4.3 mm/y and a trench parallel movement of 8.1 mm/y (Audemard, 2014; Audemard & Audemard, 2002; Gutscher et al., 1999; Mora–Páez et al., 2016, 2019) that determines the predominant right lateral strike–slip activity of the numerous faults in the southern half of the NAB (Costa et al., 2006) and is at the origin, together with the collision of the Carnegie Ridge as the driving force, of the NNE directed tectonic escape of the NAB at a velocity of 8.6 mm/y (Audemard 1993, 2014; Audemard & Audemard, 2002: Audemard & Castilla 2016; Egbue & Kellogg, 2010; Gutscher et al., 1999; Mora–Páez

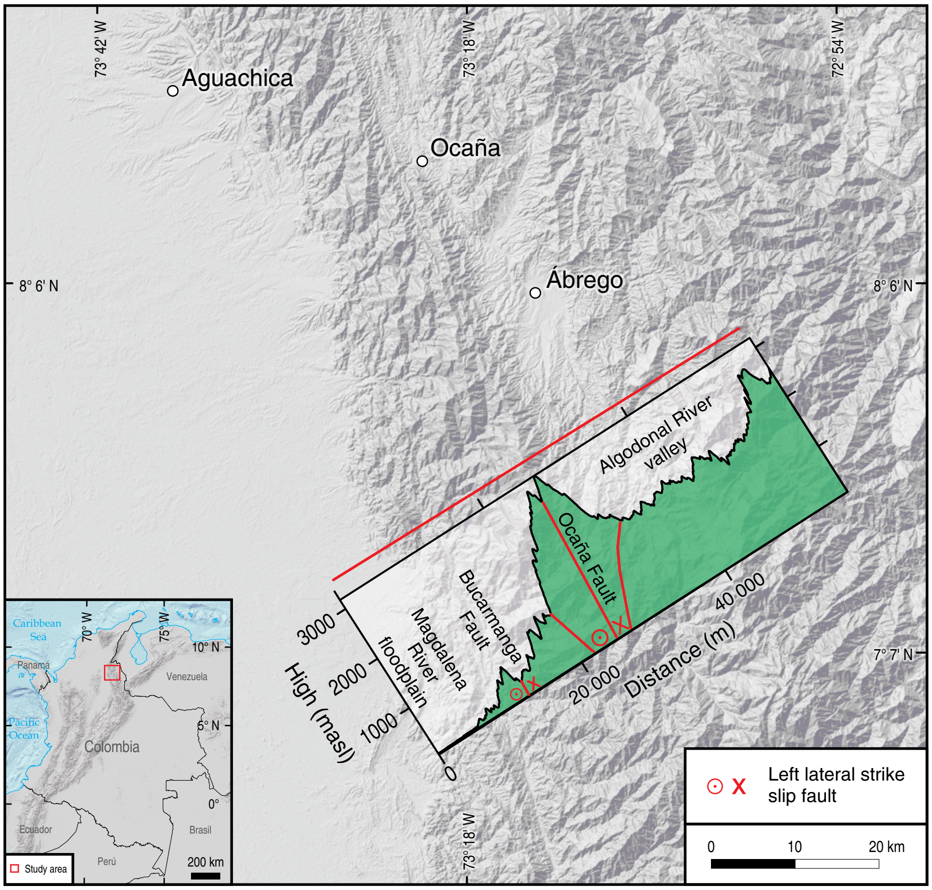


Figure 5. Cross profile of the Ocaña duplex along the west flank of the Eastern Cordillera with the Magdalena River floodplain at 200 masl in the west and the Algodonal River valley at 1300 masl in the east. Observe the upward diverging array of the exterior faults characteristic of flower structures.

et al., 2016, 2019; Mothes et al., 2016; Nocquet et al., 2014, 2016; Trenkamp et al., 2002; Witt et al., 2006) that began with the opening of the Jambeli graben in the Gulf of Guayaquil in Ecuador during late Pliocene times between 5 and 2 Ma ago (Audemard, 1993, 2014; Egbue & Kellogg, 2010; Gutscher et al., 1999; Mothes et al.,2016; Witt et al., 2006). This northward movement of the NAB is facilitated by slip along the Eastern Andean Frontal Fault zone that runs all the way from the Gulf of Guayaquil to the Caribbean in Venezuela, a distance of approximately 2000 km and on the basis that it connects the Nazca and Caribbean Plates and perhaps also the Atlantic Plate, merits to be considered a transform fault belt (Audemard, 1993, 2014; Audemard & Audemard, 2002; Audemard et al., 2005; Diederix et al. 2020; Nocquet et al., 2014, 2016; Pennington, 1981). Within the NAB and occupying its northeastern corner, sits the Maracaibo Tectonic Block (MTB), a smaller microplate that moves semi–independently from the NAB in a NE direction, along the NNW striking left lateral strike–slip SMBF that defines its western boundary and the northeast striking right lateral strike–slip Boconó Fault of the Merida Andes of Venezuela (Arnaiz–Rodríguez & Audemard, 2014; Audemard, 2014; Laubscher, 1987) that is part of the transform fault belt or Eastern Frontal Fault System as we prefer to call it. The northern margin of the MTB, is formed by the right lateral strike–slip Oca–Ancón Fault (Arnaiz–Rodríguez & Audemard, 2014; Laubscher, 1987). The south apex of the MTB is marked by the termination of the SMBF and a series of left lateral strike slip and west verging reverse faults that all have a more or less similar strike as the BF (Velandia et al., 2007) and coincide with a marked 90° left hand curvature of the transform belt that, further to the northeast, continues as the Boconó Fault after another 90° but right hand curvature of the transform belt south of the town of Cúcuta (Audemard, 2014; Diederix et al., 2009b). This structural configuration is known as the Pamplona indenter (Audemard, 2003, 2014; Audemard & Audemard, 2002; Audemard et al., 2006; Boinet et al.1985; Rodríguez et al., 2018). The NNW orientation of the BF and other faults in the northern part of the Eastern Cordillera, north of 6.5° N latitude (Velandia et al., 2007), contrasts with the NNE structural grain of the southern half of the cordillera. The meeting point of these two structural tendencies has been described by Nevistic et al. (2003) and Rossello et al. (2010) as the Andean–Santander oriental syntaxis that coincides on its convex side with the culmination of the Eastern Cordillera in its highest peak, the Nevado del Cocuy of 5550 m altitude that results in an eastward directed salient structure in the foothill front of the Eastern Cordillera and is part of the structure known as the Pamplona indenter defined by Boinet et al. (1985). Rossello et al. (2010) propose that the control on the syntaxis structure is an inherited one and represents the imprint of the Triassic – Jurassic graben structures striking in directions that coincide with the present–day orientation of the fault structures that are in part a result of the tectonic inversion of these graben structures during the Andean orogenic phase from the middle Miocene onwards to the present (Audemard, 2014; Cediel et al., 2003; Sarmiento–Rojas, 2001; Taboada et al., 2000). Rossello et al. (2010) propose a triple junction of three graben structures striking NNE (Eastern Cordillera), NNW (Santander Massif and BF), and NE (Mérida Andes and Boconó Fault in Venezuela). The triple junction in this setting coincides with the Nevado de Cocuy high. He therefore suggests these structural trends in principle to be inherited structures. On the other hand, and seen in a wider perspective, the structural trends in the northern half of the NAB are strongly influenced by the E–W to ESE directed flat slab subduction of the Caribbean Plate together with the eastward directed collision of the Panamá Arc indenter (Audemard, 2014; Kellogg & Bonini, 1982; Kellogg & Vega, 1995; Mora–Páez et al., 2019). The actual NNW orientation and left lateral slip of the Bucaramanga and other faults mentioned above are in agreement with the W–E to WNW–ESE oriented Caribbean Plate convergence and the deformation ellipse for a left lateral shear model in a WNW–SSE oriented stress field (Audemard, 2014; Wilcox et al., 1973).

The BF terminates in the south in the axial zone of the Eastern Cordillera where it starts to ramify in a horsetail like fashion while bending slowly to a south to southwest orientation linking up with the SW striking east verging reverse Faults of Boyacá and Soapaga (Acosta et al., 2007; Kammer & Sánchez, 2006; Toro, 1990; Velandia et al., 2007;). These two faults have a right lateral strike–slip component. The fault curvature and the horsetail like termination of the BF have also been described as a compressive duplex structure by some authors (Acosta et al., 2007; Del Real & Velandia, 2013; Toro, 1990; Velandia et al., 2007).

3.1. The Bucaramanga Fault between Pailitas and Cepitá, Southern Segment

The southern segment of the SMBF is known as the Bucaramanga Fault proper (BF) and stretches from the town of Aguachica (Department of Cesar) in the north all the way to the village of Cepitá (Department of Santander) in the south, situated on the banks of the Chicamocha River, covering a distance of 250 km (Figure 3). Aguachica marks the northern termination of the BF proper, the northernmost 80 km constituting the western branch of a right hand step–over with the Ocaña Fault that continues a further 60 km to the north to disappear under the thick alluvial cover of the Cesar Basin a few kilometers north of the town of Pailitas in the Department of Cesar (Cuéllar et al., 2012; Mora & Garcia, 2006.

3.2. The Ocaña Duplex Structure

The overlap between the two faults is produced by a right hand restraining step–over which, in combination with the left hand lateral strike–slip movement of the BF, has created a transpressive stress field that has given rise to a large pressure ridge known as a transpressive duplex structure (Cunningham & Mann, 2007; Mann, 2007; Storti et al., 2003; Sylvester, 1988; Woodcock & Schubert, 1994) that we have named the Ocaña duplex (Figure 4; Diederix & Bohórquez, 2013). The longitudinal overlap between the two parallel fault branches, the BF in the west and the Ocaña Fault in the east, is 80 km and the width of separation varies between 20 and 15 km. The field expression of this structure is in the form of a long mountain range or sierra that varies in height between 3500 m in the south, in the Pelado Hill, and 1500 m in the north near the village of Ayacucho in the Department of Cesar. This sierra has no name in the existing topographic maps and we have therefore baptized it as the Ocaña Range (cerro de Ocaña). This duplex structure, apart from the two major controlling faults, has developed into a so–called "positive flower structure" (Cunningham & Mann, 2007; Mann, 2007; Sylvester, 1988,) with outward verging reverse and thrust faults in both flanks and oblique transverse faults crossing the central body (Figures 4, 5). These cross faults have developed deeply incised V–shaped valleys (Figure 6c). The central body of the duplex structure is made up of mostly crystalline basement rocks of the Santander Massif ranging in age from Neoproterozoic to Jurassic. Along both flanks Tertiary sedimentites of fluvial gravels and sands occur that have been folded and faulted with predominantly N–S to NNW–SSE strike direction. These deposits are overlain unconformable by Quaternary deposits consisting of coarse debris and torrential flow deposits including occasional olistoliths. These deposits in turn have been deformed by means of folding, tilting, and faulting in immediate vicinity of the faults that mark the duplex structure on both flanks of the range (Figure 7a–7c) with similar strike directions.

The Ocaña Range probably has risen during the Pliocene – Pleistocene rather rapidly. Presently it constitutes a climatic barrier that captures de humidity of the Magdalena valley in the west and causes a rainfall shadow on its eastern side where, in the region of the towns of Ocaña and Ábrego, all agricultural practice is under irrigation. There are notable drain-

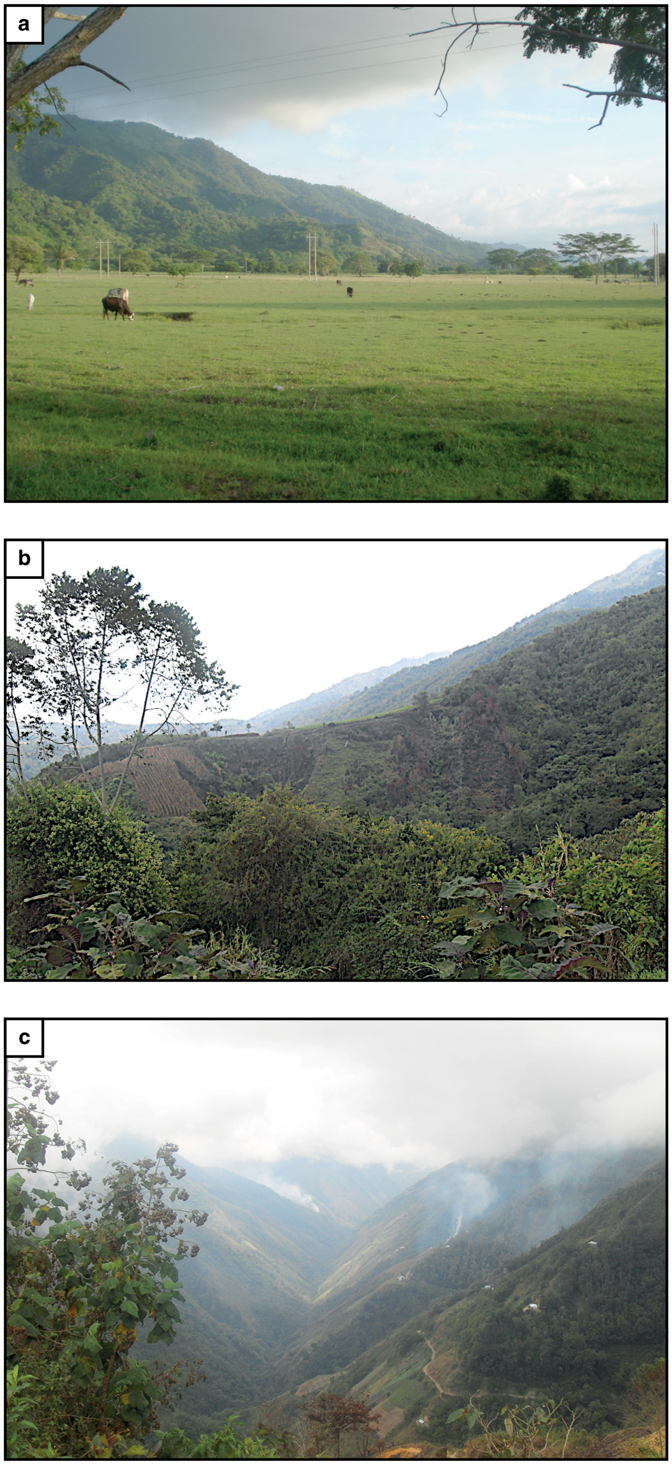


Figure 6. External fault controlled limits of the Ocaña duplex with: **(a)** the west flank, looking south from the village of Ayacucho. **(b)** The east flank on the Algodonal River valley side, looking south as seen from a few km south of Ocaña. **(c)** The deep V–shaped valleys of the obliquely oriented faults traversing the interior of the duplex structure to the southwest of Ocaña.

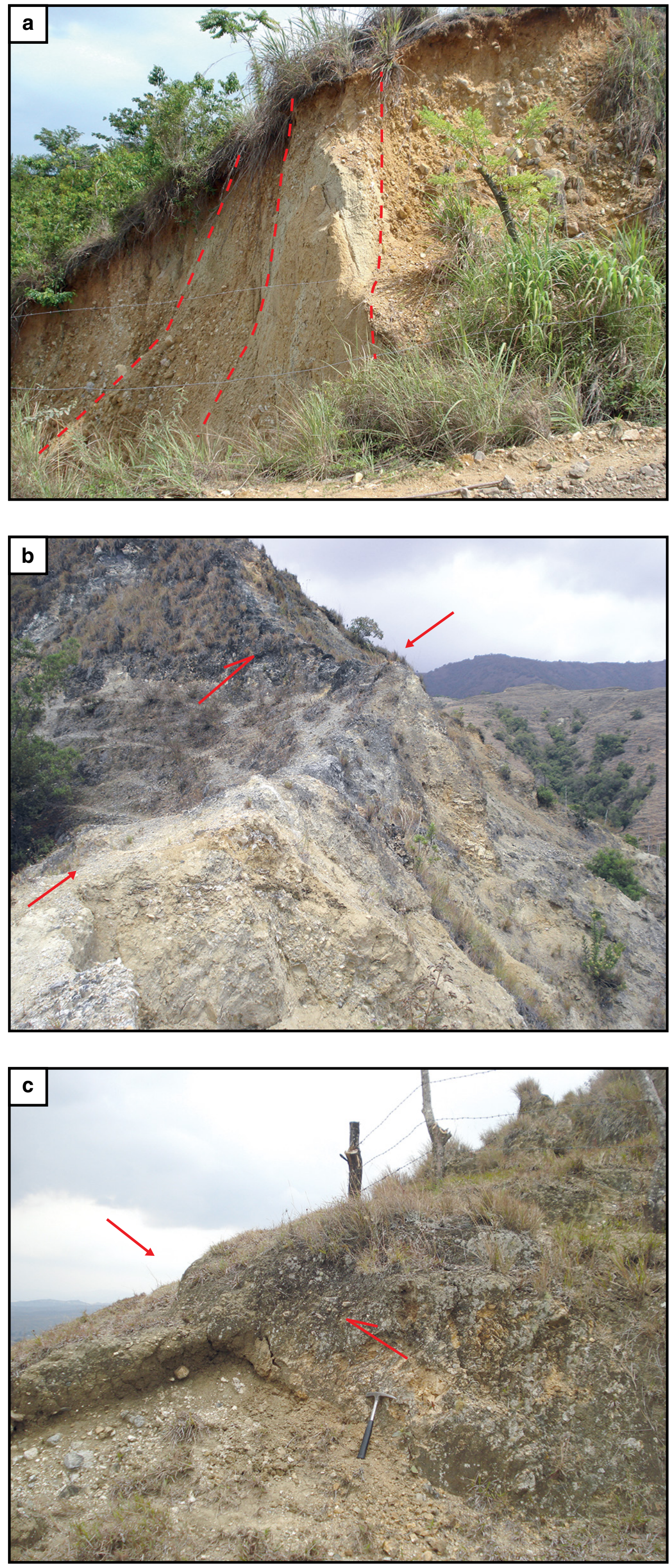


Figure 7. Field evidence of the flower structure of the Ocaña duplex with: **(a)** upturned to overturned Quaternary strata by the west verging external thrust faults near San Alberto looking north. **(b)** Precambrian rocks overthrusting Tertiary strata west of Ábrego looking north Arrows point to the fault trace. **(c)** Precambrian rocks overthrusting Quaternary debris deposits by the east verging thrusts, to the west of Ábrego looking south. Arrow points to the fault trace.

age anomalies on that side of the range where present–day drainage is all directed northeastward towards the Catatumbo and Zulia Rivers that end in the Maracaibo Lake in Venezuela, whereas it appears that the original drainage before uplift of the range was all directed westward to the Magdalena River. Another feature could possibly support this hypothesis: Because the very coarse, possibly upper Pleistocene gravels of debris and torrential flows with the occasional olistoliths overlying the Tertiary on the east side of the range are profoundly saprolitized. This suggests conditions of very high humidity in an environment of tropical rainforest in a high rainfall area. These conditions are distinct from the present–day semi–arid climate prevalent in this part of the Department of Norte de Santander. Altogether this could point to a phase of rapid uplift of the range in the not too distant past, certainly during Pliocene – Pleistocene times.

3.3. The Ocaña Fault

The Ocaña Fault continues northward in a NNW direction to just beyond the Pailitas town where the fault cannot be traced any further under a thick cover of alluvial sediments of the Cesar–Ranchería valley. In the sector between the village of Guamalito in the south and Pailitas in the north the fault displays a very straight trace along which rather numerous aligned morphotectonic indicators can be found and, importantly, are seen to cross small patches of alluvial valley fill, that could well present suitable conditions for the excavation of trenches for paleoseismologic studies that will permit the establishment of fault slip rates and recurrence intervals of major pre–historic seismic events when security conditions will allow field work to be realized (Diederix & Bohórquez, 2013).

3.4. Southern Segment of the Bucaramanga Fault

The continuation southward of the BF beyond the southern tip of the duplex structure is remarkably straight and accentuated by the deep V–shaped valley eroded by the El Playón and Río Negro Rivers following the fault trace. This fluvial erosion has obliterated most of the morphotectonic terrain features that would have permitted to conduct detailed neotectonic mapping and to find suitable sites for the excavation of paleoseismologic trenches. This situation changes when approaching the city of Bucaramanga, from where onwards to the south where the Chicamocha River canyon makes a sharp southward bend at the village of Pescadero, the BF is marked by a strong escarpment created by uplift of the Santander Massif induced by the vertical component of movement of the BF (Julivert, 1959, 1961). Morphotectonic indicators along this segment of the fault are abundant and bear witness to the predominant left lateral displacement of the fault, such as displaced and deviated stream courses, shutteridges, L–shaped spurs, triangular facets, and small sagponds (Diederix et al., 2008; Ingeominas & Gobernación de Santander, 1997).

3.5. The Bucaramanga Fan

The most remarkable feature in this sector is the presence of the large, confined Bucaramanga fan that is the over 300 m thick alluvial infill (De Porta, 1959; Julivert, 1963) of the fault wedge basin (Crowell, 1962) that has been created by fault displacement at the junction of the left lateral BF and the left lateral reverse Suárez Fault. Growth of the Bucaramanga fan has been by progradation in a northwesterly direction following the gradual opening and deepening of the basin in the same direction (Diederix et al., 2008). The proximal part of the fan presents a remarkable flat and undissected surface on which all town development has taken place. This is the preserved surface of the fan that contrasts sharply with the middle and distal parts of the fan that are profoundly dissected as these have fallen prey to progressive headward erosion that has created badland conditions marked by the presence of "stone pillars", known as "estoraques". The flat proximal fan surface has been preserved because the erstwhile feeder river has changed position as a result of left lateral displacement along the BF that led to the abandonment of the fan (Figure 8a, 8b; Jiménez et al., 2015). The present lack of a feeder stream of the Bucaramanga fan that could count for the great mass of sediment that has filled the deep basin is a significant feature. The obvious candidate for having been the feeder stream responsible for the transport of the great mass of sediments that makes up the Bucaramanga fan, is the Suratá River that comes down from the Santander Massif and cuts across the fault trace 2.5 km to the north of the fan apex from which it has been displaced by left lateral displacement of the BF (see above; Diederix et al., 2008; Jiménez et al., 2015). The reason for the abandonment of the fan by the Suratá River and the northward displacement of the river has been the growth of a pressure ridge along the trace of the fault at the fan apex. This pressure ridge is a prominent hill that emerges from the fan surface right in the city center at the foot of the escarpment and is known as the Morro Rico (Figure 9). It is made up of metamorphic rocks, but along its flanks coarse gravel deposits of the fan have been upturned to above the fan surface and are not a colluvial deposit as the geological map suggests, because all material consists of fan gravels and not of metamorphic colluvial debris. This pressure ridge must have functioned as a shutteridge at the time, that forced the feeder river to seek another outlet to the northwest at the same time as it started a process of increased down cutting caused by a regional lowering of base level during periods of glaciations during the Pleistocene. Simultaneous with the down cutting, the Suratá River continued its migration northward by the left lateral displacement of the fault that today has reached a dis-

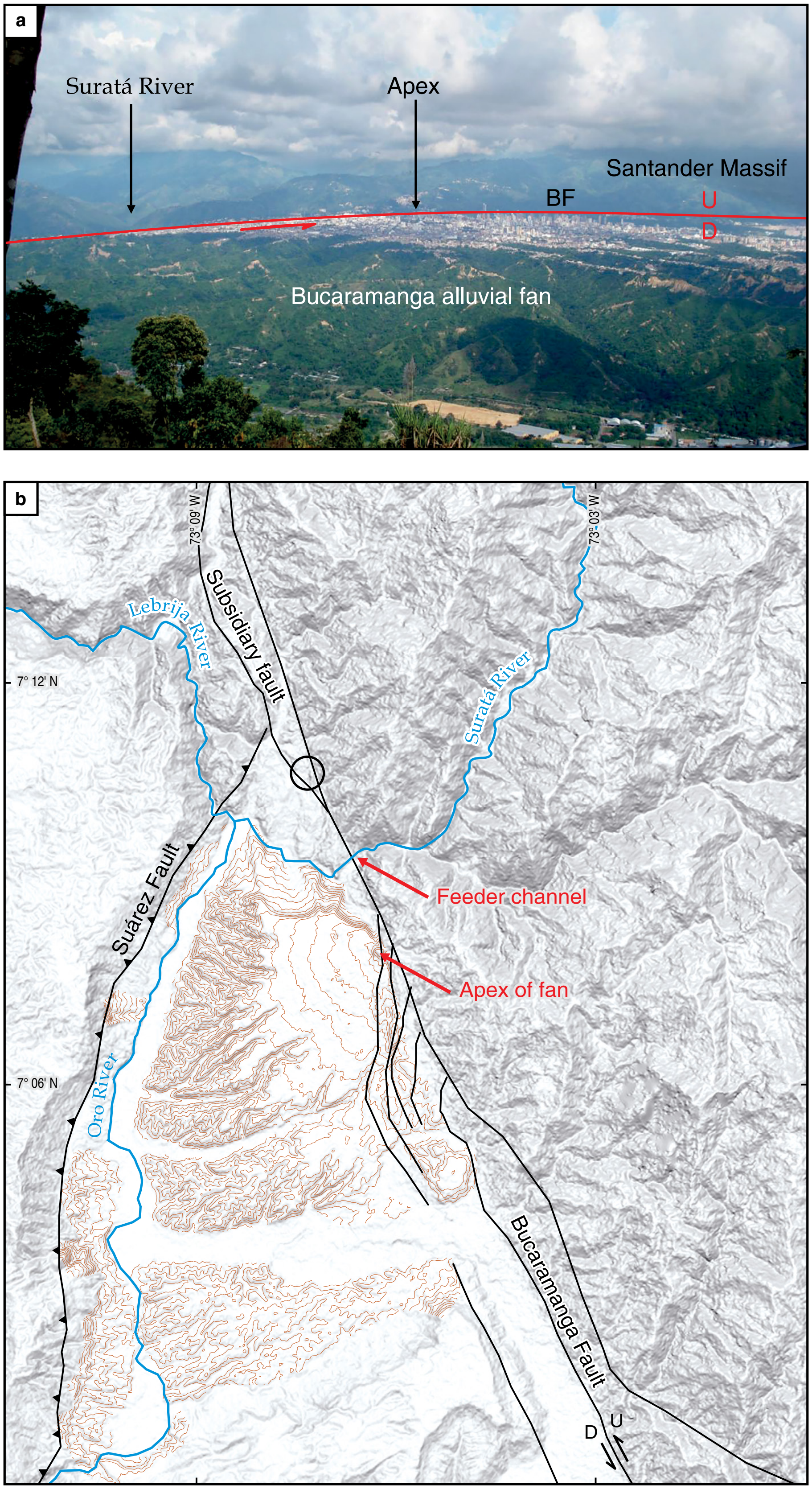


Figure 8. (a) View to the east of the Bucaramanga city built on the flat convex surface of the Bucaramanga alluvial fan and the 2.5 km northward displacement of the Suratá River from its original position at the fan apex. **(b)** Plan view of the Bucaramanga alluvial fan illustrating the flat proximal part and displacement of the feeder river. Note the strong contrast between the flat surface of the proximal fan with the highly dissected badland morphology of the mid– and distal parts of the fan. (BF) Bucaramanga Fault; (U) up; (D) down.

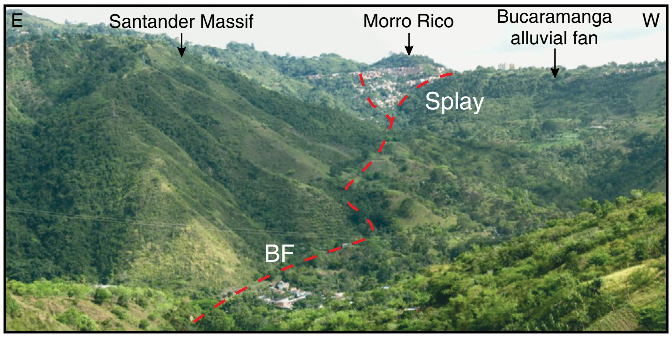


Figure 9. View to the south of the trace of the Bucaramanga Fault (BF) climbing up from the depth of the Suratá River valley to the fan apex where a pressure ridge, the Morro Rico hill, has developed between the splay faults and that has caused the offset of the Suratá River as a feeder stream of the Bucaramanga alluvial fan.

tance of 2.5 km. This distance of 2.5 km serves as the reference for calculating the slip rate of the BF if proper dating can be obtained. This was done by Jiménez et al. (2015) who used paleomagnetism to establish a minimum age for the fan deposits of 800 000 years (the Brunhes–Matuyama chron transition) and which implied a slip rate of 3 mm/y for the Late Pleistocene. This slip rate agrees fairly well with the slip rate of 2.5 mm/y that was obtained by Diederix et al. (2009a) by means of a paleoseismologic study of sagpond sediments that registered 8 seismic events over the last 8500 years (Figure 10). However it might well be possible that the fault slip rate was higher during most of the Pleistocene as is suggested by the strong morphologic expression of the fault (comparable to the Boconó Fault in Venezuela) and the freshness of the flat surface of the proximal part of the Bucaramanga fan that so far has escaped regressive erosion that has turned the greater part of the fan in the badlands that constitute such a dominant aspect of present–day morphology around the city of Bucaramanga (Figure 8b). In the distal part of the fan on the west bank of the Río de Oro trunk river, the fan sediments have been deformed by folding and upturning at the foot of the Suárez Escarpment (Figure 11; Diederix et al., 2009a; Julivert, 1963), This is clear evidence of the recent activity of the Suárez Fault which has created an escarpment that reaches heights of 700 m. (Figure 12). The Suárez Fault is a reverse to thrust fault with a left lateral strike slip component that presents evidence of Quaternary to Holocene activity, with coarse debris slope and scree deposits, being overthrusted by Cretaceous formations. These debris or scree deposits are the product of active processes of degradation of sandstone deposits of Jurassic age that crop out next to the fault scarp.

3.6. Planation Surface

Other indicators or geomorphic markers that constitute reference levels for detecting evidence of fault activity can be found in remnants of an erstwhile Miocene – Pliocene planation surface that covered most of the north Andean region and that was subsequently dismembered by fault activity of the Bucaramanga and Suárez Faults (Julivert, 1963; Kroonenberg et al., 1990; Page, 1986). Remnants of this surface occur at different altitudes: One on the Páramo de Berlín of the Santander Massif to the east of Bucaramanga at an altitude of 3700 m, the second one is the Mesa de Los Santos at the base of the Bucaramanga Escarpment at an altitude of 1700 m, and the third one is the Lebrija plateau that represents the surface in the hanging wall of the Suárez Fault at an elevation of 1300 m (Figure 13). The displacement of this once continuous surface is the result of the activity of the two faults during the late Pliocene – Quaternary and is possibly ongoing today. The uplift rate estimated to BF is 0.5 mm/y and to Suárez Fault is 0.12 mm/year, according with data of fission track of Santander Massif that was obtained in others researches (Page, 1986).

3.7. Southern Termination of the Bucaramanga Fault

In the area of Floridablanca just south of the Bucaramanga city a number of high angle reverse faults splay off from the main branch of the BF into the fan surface (Diederix et al., 2008). Further to the south, from Piedecuesta towards Cepitá, the morphologic expression of the fault gradually diminishes until reaching the southern termination of the fault where it starts to branch out into a number of smaller faults in a horsetail like structure, curving towards the west, and to eventually link up with the Boyacá and Soapaga Faults that strike in a SW direction, have a reverse movement with vergence to the southeast and a right lateral strike–slip component (Kammer & Sánchez 2006; Velandia et al., 2007). Some authors have described this arrangement to take the form of a transpressive duplex structure (Acosta et al., 2007; Del Real & Velandia, 2013; Toro, 1990; Velandia et al., 2007).

4. Geodesy

Instrumentation of principal faults by means of GPS field stations has been initiated in 2015 and covers two distinct areas. The first one is projected as a multi–lateral block of 8 stations along the main BF between Río Negro in the south to just beyond El Playón in the north where the fault is remarkably rectilinear in outline. The other area covers a more or less irregular block situated over the Ocaña duplex structure with the southern extreme just to the south of Ábrego and in the north reaches the village of González consisting of a total of 6 stations. In addition, using high precision digital level and invar bar code rods, four short leveling lines have been laid out across the traces of the external thrust faults, two on either side of the duplex (Figure 14), in an attempt to monitor horizontal and vertical displacement of the outward verging low angle reverse faults that are an expression of the typical positive flower structure

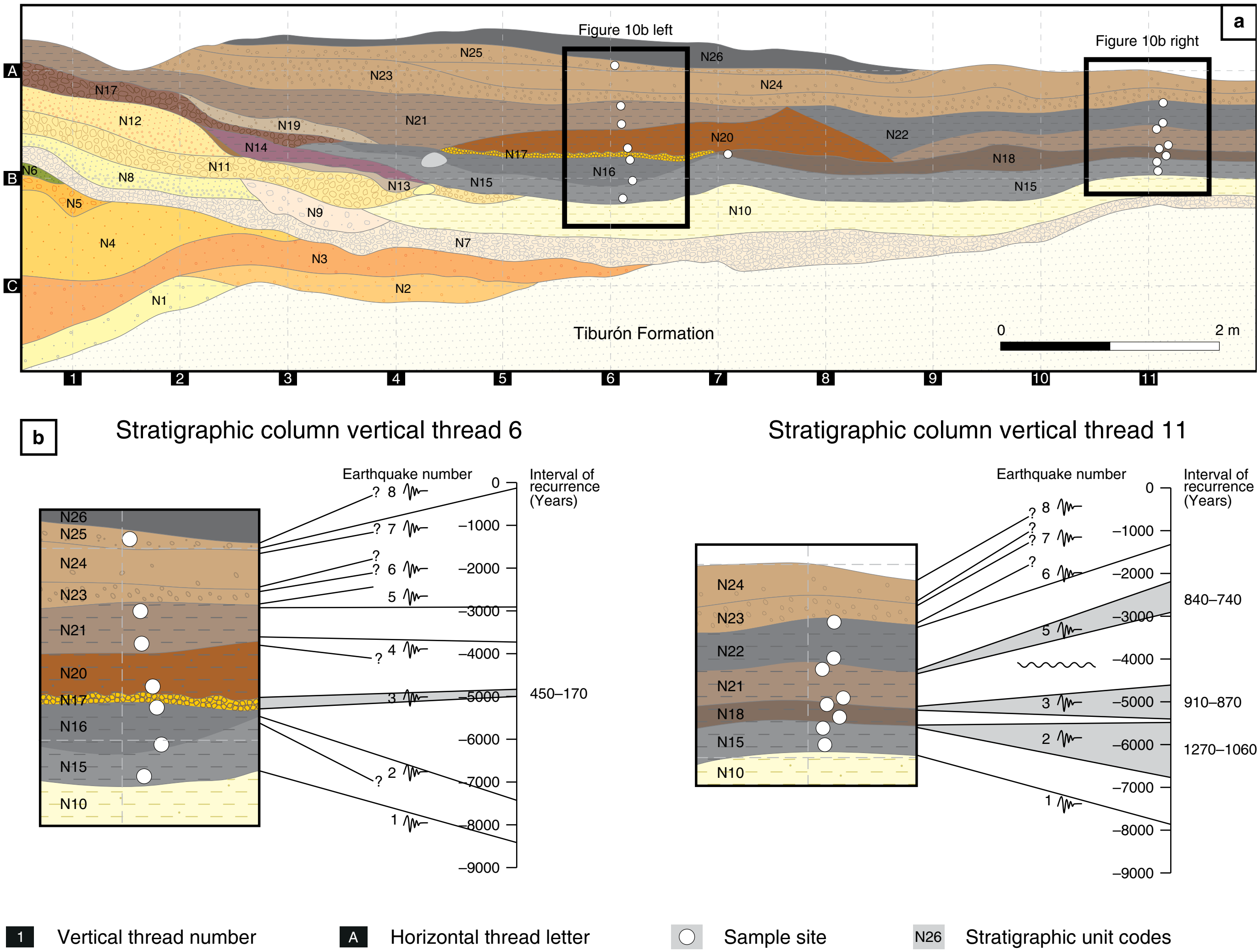
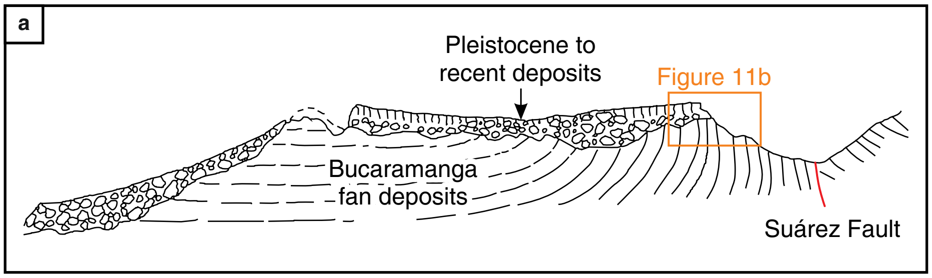


Figure 10. (a) Exposed crosscut of sag pond deposits in the mining front of a stone quarry (7° 10' 16.48" N, 73° 7' 22.49" W) next to the Bucaramanga Fault trace and **(b)** detailed paleoseismologic log of the exposed wall indicating the registration of Holocene seismic events. A good example of "seismic stratigraphy" in the strict sense. Taken from Diederix et al. (2009a).

of the transpressive duplex. This recent history of instrumentation covers too short a period to construct time series that could detect displacement tendencies, but preliminary results seem to follow recent instrumentation efforts over the Ibagué and Algeciras Faults in the Tolima and Huila Departments that have so far yielded highly chaotic vector orientations that seem to confirm the suspicion that all stations are situated well within the boundaries of the shear zones of these faults. It is a well–known fact that the kinematics of crust deformation along major continental strike–slip faults includes a wide shear zone characterized by vertical axis block rotation and translation intimately related to fault displacement (Hernandez et al., 2014).

5. Seismicity

Since 1993 the Red Sismológica Nacional de Colombia (RSNC) covers the area of the Departments of Santander and Norte de Santander crossed by the BF and has registered a large number of shallow (0–50 km) seismic events, the vast majority of low magnitude, in a wide area on both sides of the BF. Events of magnitude M ≥ 4.0 have been few and their distribution has been disperse, but some notable events are worth of mention: One of these has been the M ≥ 5.4 earthquake with a depth of 3–4 km that occurred on the 7 July 1999, near the village of Sativasur in Boyacá, with the epicenter situated almost on top of the BF trace at its southern termination (Figure 15). Another notable event occurred on the 12 July 1974 near the village of Guaca in Santander not far to the east of the BF at the altitude of the Mesa de Los Santos and had a magnitude of M ≥ 4.8 and a depth of 25 km. A third event worth mentioning has been the M ≥ 5.7 earthquake of Ocaña that happened on the 30 August 1973 and caused notable damage as far away as Bucaramanga and Cúcuta (Ramírez, 2004). However the hypocenter of this quake was at a depth 160 km and therefore its relation with the Ocaña



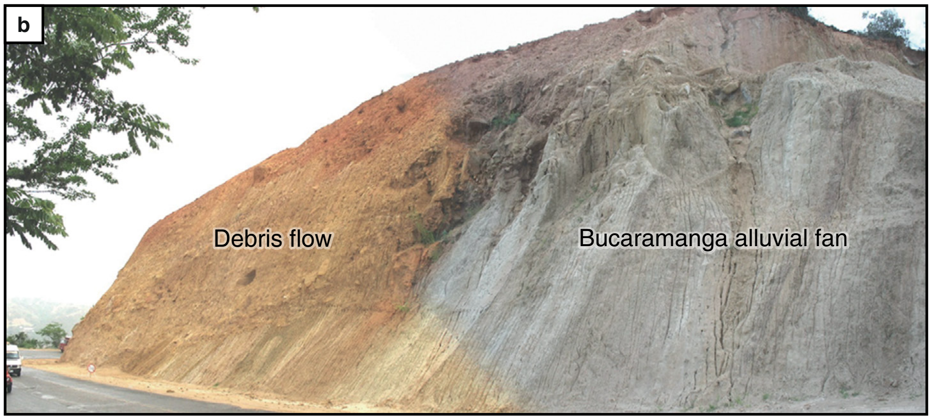


Figure 11. Tectonic deformation that has produced a progressive unconformity in the distal Bucaramanga fan deposits covered by Pleistocene to recent coarse gravels, in contact with the active Suárez Fault . The outcrop is located on the roadway Girón – Palonegro airport and the photograph was taken looking south. (a) adapted after Julivert (1963).

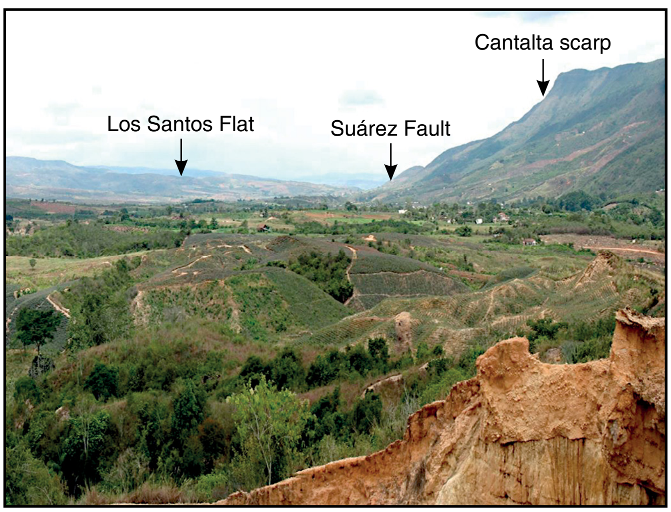


Figure 12. The 500 m high escarpment of the Suárez Fault, looking south from a position (6° 57' 8.49" N, 73° 9' 33.40" W) along the Palonegro airport road.

Fault must be discarded. Three shallow seismic events with magnitudes close to M = 4.0 occurred in 2011, 2012, and 2016 in the sector along the BF between Río Negro and El Playón.

A temporal seismic network was installed and operated during a period of 500 days in 2009 and 2010 that registered 1500 events of low magnitude of which almost 100 could be localized. These indicated a distribution concentrated in a wide zone on both sides of the BF between Río Negro and El Playón in Santander. Other vague concentrations or clusters were identified along the east flank of the Santander Massif, in the area between Arboledas and Salazar and around the town of Suratá not far from Bucaramanga.

Outside the direct range of the BF there is significant seismic activity in the western foothills of the Eastern Cordillera close to the town of Puerto Wilches on the Magdalena River. To the east of the area of direct influence of the BF there is notable seismic activity in a wide area of influence of the Boconó Fault System where it enters Colombia from Venezuela and where it makes a 90° left bend that marks the northern end of the structure known as the Pamplona indenter (Audemard, 2003; Audemard & Audemard, 2002; Audemard et al., 2006; Boinet et al., 1985). This is an area of elevated seismic activity related to fault systems of west verging reverse faults that run in a NNW direction more or less parallel to the BF. Some major historic earthquakes have occurred in this area: The 1644 Pamplona earthquake of M ≥ 7.2 and the 1875 M ≥ 6.8 Cúcuta earthquake of which recently the culprit fault has been identified, it being the northern branch of the Boconó Fault, the Aguascalientes Fault, that runs in an E–W direction just to the south of Cúcuta town (Audemard et al., 2006; Rodríguez et al., 2018).

Twenty–nine of the large number of low magnitude seismic events has yielded focal mechanisms that indicate a variety of faults, the majority of which are strike–slip faults with a dom-

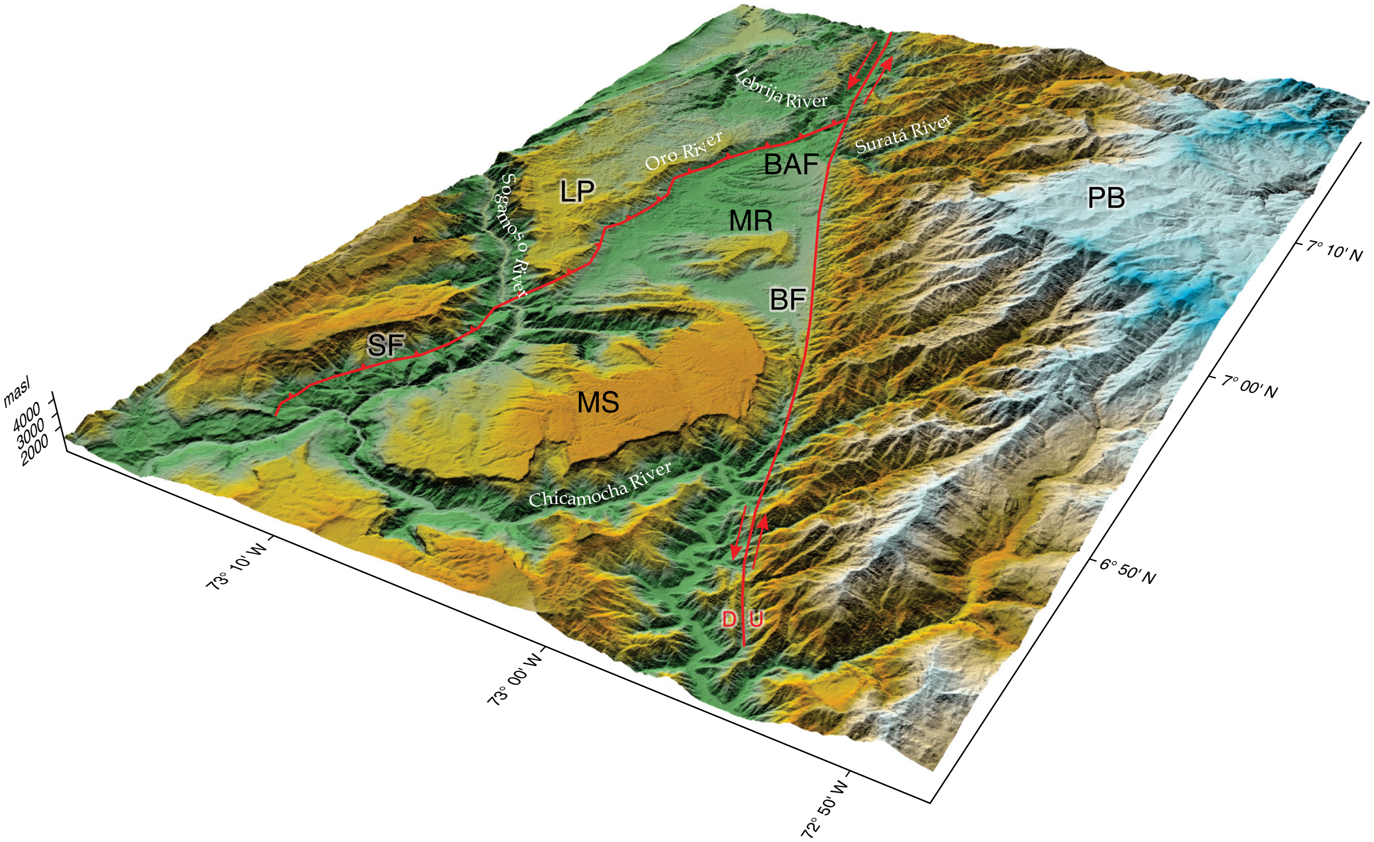


Figure 13. Oblique DEM image of the Bucaramanga area at the convergence of the Bucaramanga Fault (BF) and Suárez Fault (SF) that have dismembered the Miocene – Pliocene planation surface showing the Páramo de Berlín remnant surface (PB) in the east, the Mesa de Los Santos (MS), Mesa de Ruitoque (MR), and Bucaramanga alluvial fan (BAF) surfaces in the center, and the Lebrija Plateau (LP) in the west, dissected by the Sogamoso River.

inant left lateral movement, the rest being reverse, and some are normal faults. They all respond to a regional compressive stress field with a broadly WNW–ESE orientation no doubt a reflection of the convergence of the Caribbean Plate with northwestern South America. The sigma 1 direction of the stress field has been particularly well established in Venezuela on the basis of focal mechanism inversion (Audemard & Audemard, 2002; Audemard & Castilla, 2016; Audemard et al., 2005) and has been the subject of study by other authors (Colmenares & Zoback, 2003; Cortés & Angelier, 2005; Egbue & Kellogg, 2010; Kellogg & Bonini, 1982; Taboada et al., 1998, 2000).

6. Results

The SMBF system has been the subject of numerous studies conducted since 1933 (Campbell, 1933 in Ujueta, 2003), the history of which has been related by Ujueta (2003) in great detail. Some of these studies covered the entire system as a whole while others had a partial interest focusing either on the SMF or the BF based on the consensus that the system consisted of two, or even three distinct segments that could be treated in isolation. In fact it is generally accepted that the northern part is the SMF proper that constitutes the western margin of the uplifted block of the SNSM, constituting the northwest corner of the MTB, presently in process of active tectonic escape to the NE (Audemard, 1993, 2014; Audemard & Audemard, 2002; Audemard et al., 2005, 2006; Idárraga–García & Romero, 2010; Laubscher, 1987; Mora et al., 2017; Mora–Páez et al., 2019; Page, 1986; Paris et al., 2000). The southern part is the BF proper that marks the western boundary of the Santander basement massif (Julivert, 1959, 1961) almost over its entire length covering a distance of 350 km and the main subject of this paper. In between these two, the connection or the continuation, of the two major faults has for a long time been in doubt because the surface expression of it cannot be detected in the thick pile of alluvial fill of the Cesar–Ranchería/Lower Magdalena Valley between Curumaní in the south and Bosconia in the north, a distance of 100 km. However more recent work by Mora & Garcia (2006) who have obtained, re–processed, and re–interpreted seismic reflection data of seismic lines across the projected fault trace, have found evidence of continuation of the fault by identifying a wide zone of vertical faulting that very likely represents the continuation of the SMBF.

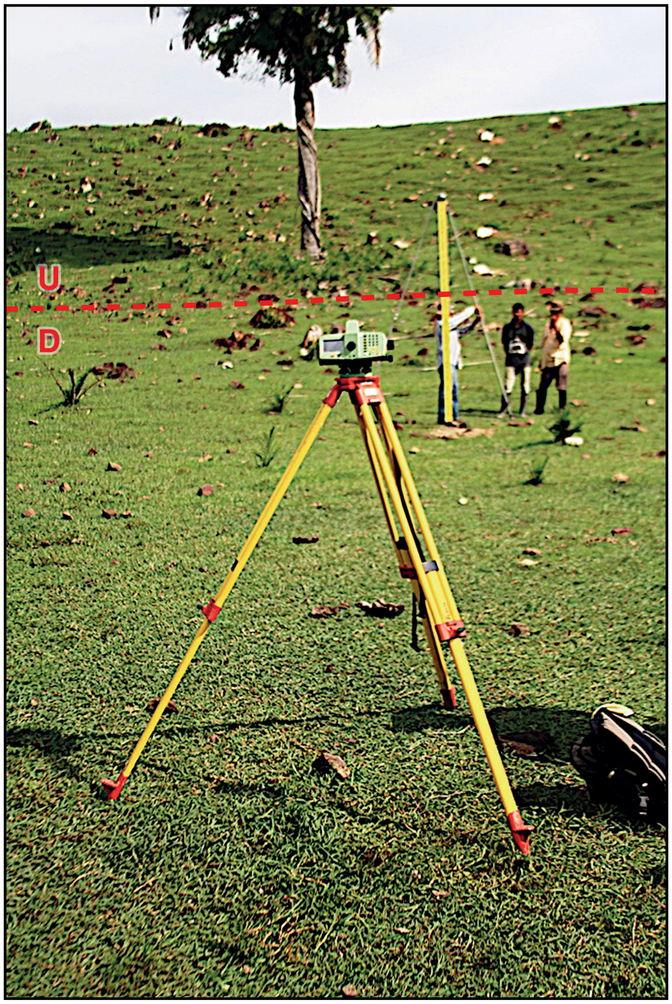


Figure 14. Precise levelling work using digital level and invar rods over benchmarks laid out across the thrust faulted escarpment in Quaternary gravels on the west flank of the Ocaña duplex. Locality to the southeast of Aguachica.

There have always been, and there still are differences of opinion on the age of the fault. These opinions vary widely between a Neoproterozoic age (Cediel et al., 2003) who postulate a direct connection of the SMBF and what is now known as the Algeciras Fault System (or the Suaza System as they call it) of southern Colombia, and a Pliocene – Pleistocene age (Duque–Caro, 1980), with intermediate ages of the Late Cretaceous – early Cenozoic (Irving, 1971; Tschanz et al., 1974) and the Miocene – Pliocene (Boinet et al., 1989). Other authors propose the possibility that the system has had several phases of re–activation since an initial activity during the Cretaceous (Mora et al., 2017). Similar widely varying opinions exist on the degree of activity and the magnitude of accumulated displacement since fault initiation. These vary between 240 km (Alberding, 1957 in Ujueta, 2003), 110 km (Campbell, 1965; Ujueta, 2003), 45 km (Boinet et al., 1989; Mora–Páez et al., 2016). Most of these estimates have been based on correlation of rock assemblage of the Central Cordillera and the SNSM, but none of these have been solidly substantiated. Laubscher (1987) postulated a displacement of 100 km based on kinematic analysis related on the convergence of the Caribbean Plate and continental South America that, at the same time gave rise to the spectacular uplift of the SNSM crustal block. The most recent estimates for age and displacement have been presented in Mora et al., (2017) who calculated a 113 km of left lateral displacement since the Paleocene based on the retro–juxtaposition of schists of the northwestern SNSM with similar rocks encountered in the El Difícil High in the Lower Magdalena Valley at the north end of the San Lucas Range. These latest estimates are in agreement with earlier estimates by Boinet et al. (1989), Campbell (1933) in Ujueta, (2003), Kellogg (1984), and Laubscher (1987) for the SMF only. Boinet et al. (1989) erroneously considered however that the BF presently is inactive.

Mora et al. (2017) state that the entire SMBF system was active since the Cretaceous and has been reactivated several times during the Cenozoic and continues to be active today. This had already been confirmed by Diederix et al (2009a) who established Holocene activity with a slip rate of 2.5 mm/y based on results of paleoseismologic studies conducted at a site located a short distance north of the city of Bucaramanga (Diederix et al., 2009a), while Jiménez et al (2015) reached a comparable slip rate based on paleomagnetic data obtained from samples of the Bucaramanga alluvial fan.

There has also been some controversy on the type of faulting of the SMBF. Julivert (1970) and Ward et al. (1973) considered the BF to be a high angle reverse fault only, which has been responsible for the uplift in the order of 2000 m of the Santander Massif. However the general consensus is now that we deal certainly with a major strike–slip fault system that is also the western boundary of the MTB presently in a process of active tectonic escape to the northeast with respect to the NAB and the South American continent (Arnaiz–Rodríguez & Audemard, 2014).

A major result of the present study is that, for the first time, a major transpressive structure along a restraining step–over in the BF has been identified and described (Diederix & Bohórquez, 2013). Further studies of this structure and surveys of instrumental seismicity could lead to conclusions of the importance of this structure for the seismic behaviour of the BF and its implications for seismic hazard.

7. Discussion

The focus of the present paper is exclusively on the behaviour and activity of the SMBF System during the Andean Orogeny since middle Miocene times and does not pretend to contribute to any analysis or interpretation of its activity during earlier orogenic episodes spanning the time between the Precambrian and the Miocene, other than mentioning literature references.

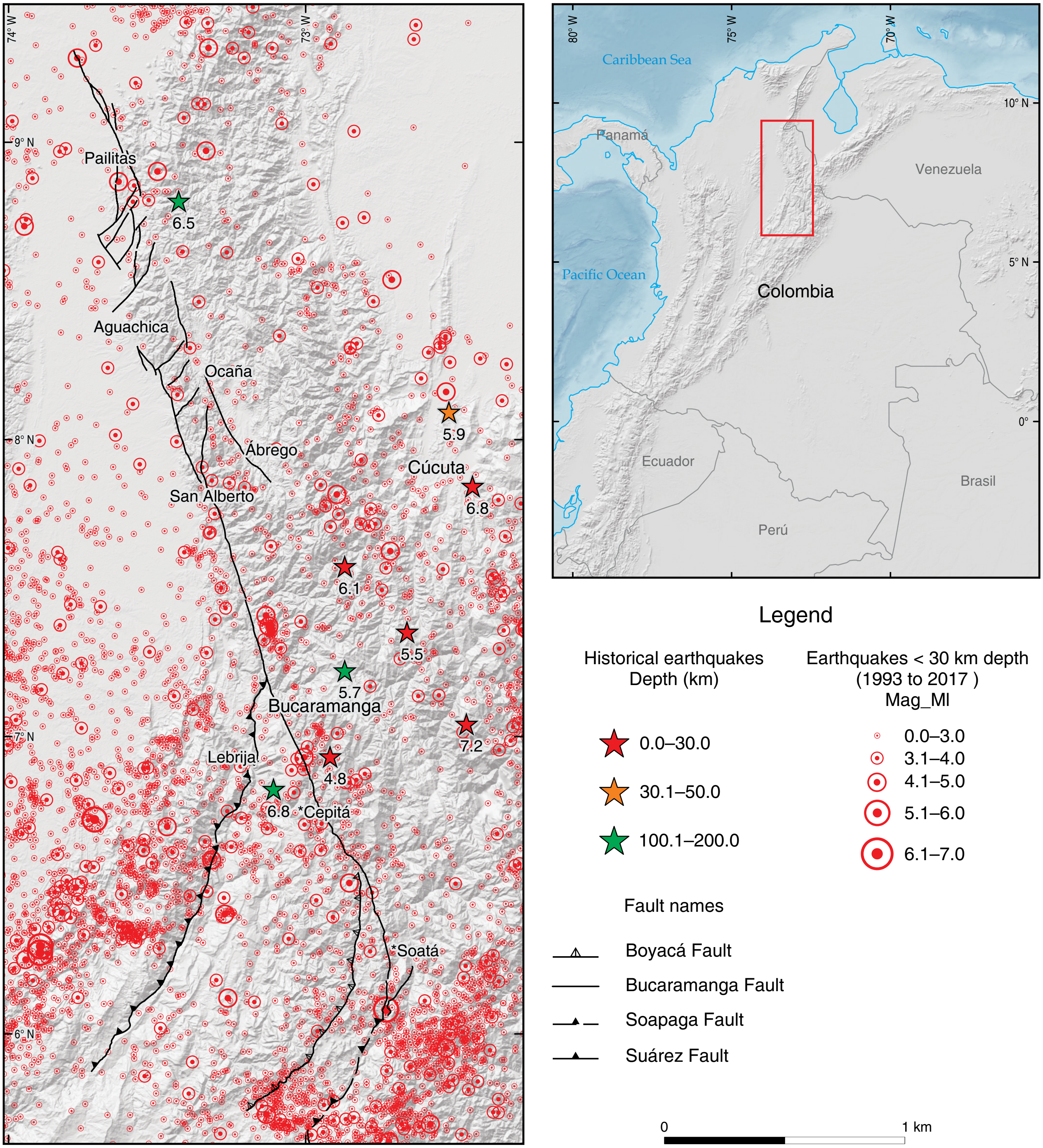


Figure 15. Plot of seismic events that have occurred between 1993 and 2017 on both sides of the Bucaramanga Fault. Source: Database of the SGC–Red Sismológica Nacional de Colombia (SGC–RSNC).

Consensus now exists that the SMBF is one single fault system that is continuous over a distance of 550 km from the Caribbean coast to the interior of the Eastern Cordillera and that it constitutes the western boundary of the MTB presently in a process of tectonic escape to the northeast (Audemard, 1993, 2014; Freymueller et al., 1993; Laubscher, 1987; Paris et al., 2000; Pennington, 1981; Taboada et al., 2000; Vargas & Mann, 2013; Velandia et al., 2007). Doubt has existed on whether the system is really continuous as there is no real surface expression of faulting in the vast alluvial cover of the 100 km wide

Cesar valley nor did there seem to exist until recently firm seismic or gravimetric evidence of a vertical fault structure existing in the subsurface of the Cesar–Ranchería valley (Ujueta, 2003). However, recent work by Mora & Garcia (2006) mention that reprocessing and re–interpretation of existing subsurface seismic data has led to the confirmation of the existence of a vertical fault structure that follows the lineament of the projected central segment of the BF that crosses the Cesar valley, but they consider that it must be a strike–slip fault structure of low level activity. Moreover, as it is generally accepted that the MTB is in active tectonic escape to the NE with respect to the NAB, this movement must be facilitated by a continuous left lateral strike–slip fault and therefore the continuity of the fault across the Cesar valley is a necessity (Arnaiz–Rodríguez & Audemard, 2014; Laubscher, 1987). Related to this is the possibility of a clockwise rotation of the SNSM block during the Pliocene, as described by Montes et al. (2010) and suggested by others before. This however implies that at one stage, before the rotation, the fault bounding the SNSM block on the actual west flank must have had a NW orientation, different therefore from the present NNW orientation of the SMF, and that fault must have pivoted at the south point of the SNSM block. In the same manner the Oca Fault must have had a WSW orientation prior to the rotation, different again from the present E–W orientation. This seems difficult to reconcile with the present–day extension and NNW strike of the SMBF all the way from the axis of the Eastern Cordillera to the Caribbean and can only have been possible by assuming that the SMF initially was not part of the SMBF system but was different and did not connect to the BF and that its present–day continuity with the BF is fortuitous or apparent. The vertical axis rotation of the Santa Marta Block and Lower Magdalena Valley must have pivoted at a hinge point at the south point of the uplifted block (Montes et al., 2010). On the basis of their model they have calculated a 45 km of left lateral displacement of the SMF only (Montes et al., 2010), different from the 113 km proposed by Mora et al. (2017), based on across fault correlation of litho–stratigraphic units, but again referring to the SMF only. Laubscher (1987) claims a 100 km displacement for the BF as well as for the E–W running right lateral strike–slip Oca Fault, based on kinematic analysis related to the SE directed convergence of the Caribbean Plate with the MTB.

Previous authors have suggested that movement of the BF was reverse and caused the uplift of the Santander Massif (Julivert, 1970; Ward et al., 1973) and others have stated that the fault was presently inactive (Boinet et al., 1989; Julivert, 1958, 1959; Ujueta, 2003). Field studies (Diederix et al. 2009a; Jiménez et al., 2015) have found abundant morphotectonic evidence of active left lateral fault displacement, while Holocene activity was confirmed by means of paleoseismologic studies (Diederix et al., 2009a). Slip rate of the fault was established by Jiménez et al. (2015) as max. 3 mm/y based on paleomagnetic dating, taking as reference the north–westward horizontal displacement of 2.5 km of the erstwhile feeder river of the Bucaramanga fan, the Suratá River. The details of both dating methods varies widely however as the paleoseismologic slip rate of 2.5 mm/y, based on the recognition of 8 prehistoric events, covers a time range of only 8500 years (Holocene), whereas the slip rate of 3 mm/y based on paleomagnetic dating method covers a time range of 0.8 Ma and refers to the Brunhes–Matuyama chron transition of the Pliocene – Pleistocene magnetic polarity time–scale. These are really large differences in temporal resolution. Another time perspective can be found in the strong geomorphic expression of the fault trace and the remarkable preservation of the flat and undissected proximal part of the Bucaramanga fan surface that until now has survived the attack of rapid badland erosion that has affected the distal and mid fan part. Compared to this, a slip rate of 2.5 mm/y or 3 mm/y seems rather low and suggests a higher slip rate during most part of the Pleistocene followed by a possible slowdown during the late Pleistocene – Holocene. This slow down also seems to be reflected in the actual low level of seismic activity of the BF as indicated by instrumental seismicity data. There is a possibility however that this low level of activity might be caused by fault locking in the large Ocaña duplex structure where seismic stress could actually be building up as a result.

GPS data of the GeoRED project have yielded velocity fields of displacement vectors that demonstrate that the NAB is moving to the NNE at a velocity of 8.6 mm/y (Mora–Páez et al., 2016, 2019; Trenkamp et al., 2002). The MTB constitutes the northeastern corner of the NAB but moves semi–independently from it to the northeast (Arnaiz–Rodríguez & Audemard, 2014) while it shares the Boconó Fault in Venezuela as its southeastern boundary that has a displacement of ±11 mm/y. The displacement of the western boundary of the MTB along the SMBF relative to the NAB is 2.5 mm/y. This of course represents a differential movement and added to the 8.6 mm/y of movement of the NAB this amounts to 10.5 mm/y total displacement, effectively the same rate as the Boconó Fault movement with respect to the South American continent.

8. Conclusions

The SMBF is one continuous and important tectonic feature of the northern half of the Andes of Colombia today. This might not always have been the case, as it is possible that this feature already existed during the Proterozoic as suggested by some (Cediel et al., 2003) and that it was reactivated during the Late Cretaceous when the process of tectonic inversion marked the end of the period of Triassic – Jurassic continental rifting (Mora et al., 2017; Sarmiento–Rojas, 2001,) .After this, the fault passed through different phases of reactivation during the Cenozoic (Mora et al., 2017). The present–day activity and configuration of the SMBF is certainly an expression of the Andean orogeny that culminated between 5 to 3 Ma. Presently its activity is largely influenced by the Caribbean Plate subduction and Panamá Arc indenter collision that take place in an E–W and ESE– direction. Subduction of the Caribbean Plate underneath the continental margin of South America is of the flat slab kind. The NNW strike direction and left lateral displacement of the SMBF is in accordance with the convergence direction of the Caribbean Plate, while at the same time this NNW directed displacement facilitates the escape of the MTB, or micro–plate, to the NE.

The orientation and sense of displacement of the SMBF marks a break with the dominant tectonic grain of the southern half of northern Colombian Andes that has a dominant NE to NNE orientation south of latitude 6.5° N. This change–over takes place more or less along the parallel of 5° N that has been defined by Vargas & Mann (2013) as the Caldas Tear and that separates the northern flat subduction slab, referred to as the Bucaramanga segment by Pennington (1981), and the normal dipping subducting and volcanic Cauca slab (Pennington, 1981; Vargas & Mann, 2013) in the south. In all probability this is a deep seated structure that seems to displace dextrally the intermediate depth seismicity swarm of the Bucaramanga nest from the Caldas/Cauca seismicity swarm according to Vargas & Mann (2013).

Figures for total accumulated left lateral fault displacement along the SMBF range between 45 and 115 km, but these figures have been obtained from the northern or Santa Marta segment only and were based on across fault correlations of older rock units, whereas Laubscher (1987) calculated a 100 km displacement based on kinematic analysis. Similar figures of total accumulated displacement for the BF proper do not exist in spite of the abundant evidence of Quaternary to recent fault activity that is available along almost the entire length of the fault. On the other hand recently conducted paleoseismologic and paleomagnetic studies have yielded figures for slip–rate of the BF of 2.5 and 3.0 mm/y respectively. The first figure has been obtained by means of paleoseismology study and covers only the last 8500 years of the Holocene epoch indicating an average recurrence interval of 8 seismic events of 1000 years (Diederix et al., 2009a), whereas the second figure applies to a paleomagnetic study and covers a time interval of 800 000 years and is based on the distance of 2.5 km horizontal offset of the erstwhile feeder stream of the Bucaramanga alluvial fan. Both study methods are very different of course, and cover widely different time ranges that lead to different results and interpretations. It is probably more relevant to consider them to be complementary. Purely qualitative approaches to the age aspect of fault activity is provided by the geomorphology and more in particular by the morphotectonic appearance of the fault both in aerospace imagery as well as in the field and suggest a significantly higher fault slip rate during the Late Pleistocene.

Present–day seismic activity on the other hand is low and there are no records of historic seismic events that can be related directly to the BF. This appears to confirm the hypothesis of a recent reduction in slip rate, but it could well be that the Ocaña duplex structure is the cause of a blockage in fault movement that could result in the existence of a temporal seismic gap.

Further urgent paleoseismologic studies and GNSS space geodesy observations and and monitoring are required in order to achieve a better and more reliable definition of fault slip rate and degree of activity of the BF, an active tectonic structure that crosses the dense urban conurbation of over one million of inhabitants. In particular future fault instrumentations have to adopt a policy of extending the coverage with GPS stations that are further removed from the fault trace in a pattern of orthogonal transects or traverses that could reach to beyond the fault shear zone. Additional methods would have to include paleomagnetic sampling in the same areas of instrumentation to obtain a clearer picture of block rotation in the fault shear zone, and regional InSAR surveys over more extensive areas on both sides of a fault that will facilitate the visualization of the elastic deformation related to fault movement.

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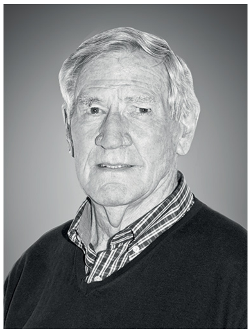
Explanation of Acronyms, Abbreviations, and Symbols:

BF	Bucaramanga Fault
DEMs	Digital elevation models
GeoRED	Grupo de Trabajo Investigaciones Geodésicas Espaciales
GPS	Global Positioning System
InSAR	Interferometric synthetic aperture radar
JAXA	Japan Aerospace Exploration Agency
MTB	Maracaibo Tectonic Block
NAB	North Andean Block
NASA	National Aeronautics and Space Administration
RSNC	Red Sismológica Nacional de Colombia
SGC	Servicio Geológico Colombiano
Sentinel	European satellite radar
SMBF	Santa Marta–Bucaramanga Fault
SMF	Santa Marta Fault
SNSM	Sierra Nevada de Santa Marta
SRTM	Satellite Radar Topographic Mission

Authors' Biographical Notes



Hans DIEDERIX graduated from the State University of Leiden, the Netherlands with a MS Hon Degree in 1965, and worked thereafter during 14 years until 1978 in the field of diamond and base metal exploration and mining in South, East, and Central Africa. From 1979 until 1985 he worked as a lecturer in photogeology, remote sensing, structural geology, and the geology of mineral deposits at the Centro Interamericano de Fotointerpretación (CIAF) in Bogotá, Colombia. The same activities were carried out by him from 1986 to 1998 at the International Institute of Aerospace Surveys and Earth Sciences in Enschede, the Netherlands, where also he was active in the field in project formulation and acquisition. After retirement he developed special training courses in morphotectonic terrain analysis for the study of active tectonics that were given in many occasions in Colombia, the Netherlands, and India in the period until 2002. During the last 16 years he has worked in an advisory capacity, heading a working group in active tectonics, in close cooperation with the GeoRED project of space geodesy research of the Servicio Geológico Colombiano, which he continues doing to this day.

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Fredy DÍAZ–MILA is member of the Space Geodesy Research Group (GIGE) of the Servicio Geológico Colombiano. His current research is on the application of imaging geodesy techniques for determining movements of the Earth's crust related to geodynamic phenomena, especially interferometric synthetic aperture radar (InSAR). He graduated as a cadastral and geodetic engineer from the Universidad Distrital Francisco José de Caldas and later specialized in geographic information systems at the Universidad Antonio Nariño in Bogotá, Colombia. He obtained a master's in environmental management from the Universidad Internacional Iberoamericana de Puerto Rico. He has coauthored several publications on the use of spatial geodetic technology to analyze the Earth's deformation under the auspices of GIGE.