Chapter 12

The Algeciras Fault System of the Upper Magdalena Valley, Huila Department

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Abstract The Algeciras Fault System, of predominant dextral strike–slip displacement, is part of the major interplate transform fault system, known in Ecuador, Colombia, and Venezuela as the Eastern Frontal Fault System. This unique transform deformation belt connects the Nazca Plate in the Gulf of Guayaquil in Ecuador with the Caribbean Plate along the coast of Venezuela. Its dextral strike–slip displacement along the eastern boundary of the North Andean Block facilitates tectonic escape of this microplate in a NNE direction. The Algeciras Fault System constitutes the southern half of this transform belt in Colombia, the northern half runs along the foothills of the Eastern Cordillera and is known as the Guaicáramo Thrust Fault System that connects to the Boconó Fault in Venezuela. This relation underlines the significance of the Algeciras Fault System as the major active fault system in continental Colombia that plays a fundamental role in the geodynamics of the northern Andes. So far, the study of this fault system has established a notable degree of fault activity which has been corroborated by data of historic seismicity and velocity vector data of satellite geodesy obtained in recent years by the Grupo de Investigación en Geodesia Satelital of Servicio Geológico Colombiano. The presence of a series of pull–apart basins and the occurrence of monogenetic alkali basaltic volcanism within the realm of the Algeciras Fault System point to transtensional stress regimes that could possibly relate to mantle processes. Knowledge of this fault system has also important implications for seismic hazards that affect considerable parts of the country and pose a particular threat to the capital city. This chapter narrates the history of the actual state of knowledge that reflects the initial stage of a more profound study of the active tectonics of this great and important fault system.

Keywords: *Algeciras Fault System, North Andean Block, pull–apart basin, transform deformation belt, tectonic escape.*

Resumen El Sistema de Fallas de Algeciras, que presenta predominante desplazamiento dextral, hace parte de un sistema interplaca mayor de fallas transformantes, conocido en Ecuador, Colombia y Venezuela como el Sistema de Fallas del Frente Oriental. Este cinturón de deformación transformante conecta la Placa de Nazca en el golfo de Guayaquil en Ecuador con la Placa del Caribe a lo largo de la costa de Venezuela. Su desplazamiento dextral a lo largo del límite oriental del bloque norte de los Andes

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facilita el escape tectónico de esta microplaca en dirección NNE. El Sistema de Fallas de Algeciras constituye la mitad sur de este cinturón transformante en Colombia, la mitad norte corre a lo largo de las estribaciones de la cordillera Oriental y es conocido como el Sistema de Fallas de Guaicáramo que se conecta con la Falla de Boconó en Venezuela. Esta relación subraya la importancia del Sistema de Fallas de Algeciras como el principal sistema de fallas activas en la parte continental de Colombia que juega un papel fundamental en la geodinámica del norte de los Andes. Hasta el momento, el estudio de este sistema de fallas ha establecido un alto grado de actividad que ha sido corroborado por datos de sismicidad histórica y datos de vector de velocidad de geodesia satelital obtenidos recientemente por el Grupo de Investigación en Geodesia Satelital del Servicio Geológico Colombiano. La presencia de una serie de cuencas de tracción y la ocurrencia de volcanismo monogenético basáltico alcalino en el Sistema de Fallas de Algeciras apuntan a regímenes de esfuerzo transtensional que podrían estar relacionados con procesos mantélicos. El conocimiento de este sistema de fallas también tiene importantes implicaciones para la amenaza sísmica que afecta considerables partes del país y supone una amenaza para la ciudad capital. Este capítulo narra la historia del estado actual de conocimiento que refleja la etapa inicial de un estudio más profundo de la actividad tectónica de este importante sistema de fallas.
Palabras clave: *Sistema de Fallas de Algeciras, bloque norte de los Andes, cuenca de tracción, cinturón de deformación transformante, escape tectónico.*

1. Introduction

The entire territory of the Andean region of northwestern South America, covering Ecuador, Colombia, and Venezuela, bears the imprint of the interaction of three converging major tectonic plates of Nazca, Caribbean, and South America together with the microplates of Cocos and Panamá, that has resulted in the particular trident shape of three divergent cordilleras, each with its own particular evolutionary history and orogenic signature (Costa et al., 2006; Taboada et al., 1998, 2000). The contact zone between the three major plates is diffuse and covers almost the entire Andean mountain region, which has been referred to as a "wide plate margin" by Trenkamp et al. (2002) but more frequently as the North Andean Block (NAB) and sometimes as a sliver (Nocquet et al., 2014), that presently is in the process of tectonic escape towards the NNE with respect to a stable South America (Figure 1; Audemard, 1993, 1998, 2008, 2014; Egbue & Kellogg, 2010; Freymueller et al., 1993; Kellogg & Vega, 1995; Mora–Páez et al., 2019; Pennington, 1981; Taboada et al., 2000; Trenkamp et al., 2002; Witt et al., 2006). The crust of the NAB is highly tectonized and characterized by a dense network of predominantly strike–slip faults (Acosta et al., 2007), a large proportion of which has to be considered as active or potentially active that collectively accommodates the relative motion of the NAB with respect to the adjoining crustal plates (Egbue & Kellogg, 2010; Freymueller et al., 1993; Kellogg & Vega, 1995; Mora–Páez et al., 2016; Nocquet et al., 2014; Paris et al., 2000; Taboada et al., 2000; Trenkamp et al., 2002; Witt et al., 2006). The eastern boundary of the NAB is defined by a wide and complex composite deformation belt, generally referred to as the Eastern Frontal Fault System in Colombia and Ecuador. This is a mayor fault system that runs in a northeasterly direction from the Jambelí Graben in the Gulf of Guayaquil in Ecuador (Audemard, 1993; Gutscher et al., 1999; Witt et al., 2006) to the Caribbean coast in Venezuela covering a distance of approximately 2000 km. It connects the Nazca Plate with the Caribbean Plate, and on that basis, should be considered as a transform fault belt (Sylvester, 1988; Woodcock, 1986; Yeats et al., 1997), that is similar to the well–known San Andreas Fault System in California (Crowell, 1962, 1973; Sylvester, 1988). In Colombia, this transform belt can be divided in two halves with the division occurring more or less at the latitude 4° N close to the town of Villavicencio (Figure 2; Gómez et al., 2007). The northern half of the belt is predominantly a belt of east verging thrust faults forming the border of the Eastern Cordillera and generally known as the Guaicáramo Fault System, whereas the southern half is characterized predominantly by dextral strike–slip faults, of which the most well–known are, from south to north: The Afiladores, Pitalito, Garzón, and Algeciras Faults (Chorowicz et al., 1996; Velandia et al., 2005). The Afiladores Fault connects to a system of echelon strike–slip faults that end in the Gulf of Guayaquil (Alvarado et al., 2016; Audemard, 1993; Baize et al., 2014; Ferrari & Tibaldi, 1992; Tibaldi & Ferrari, 1991; Tibaldi et al., 2007). The present chapter deals with the central part of the southern half which is known as the Algeciras Fault System (AFS), named after the village of that name, located in the center of a pull–apart basin that has created a deep valley along a gentle releasing bend of the main fault branch.

Using traditional methods of geologic cartographic practice, a neotectonic survey has been carried out in recent years,

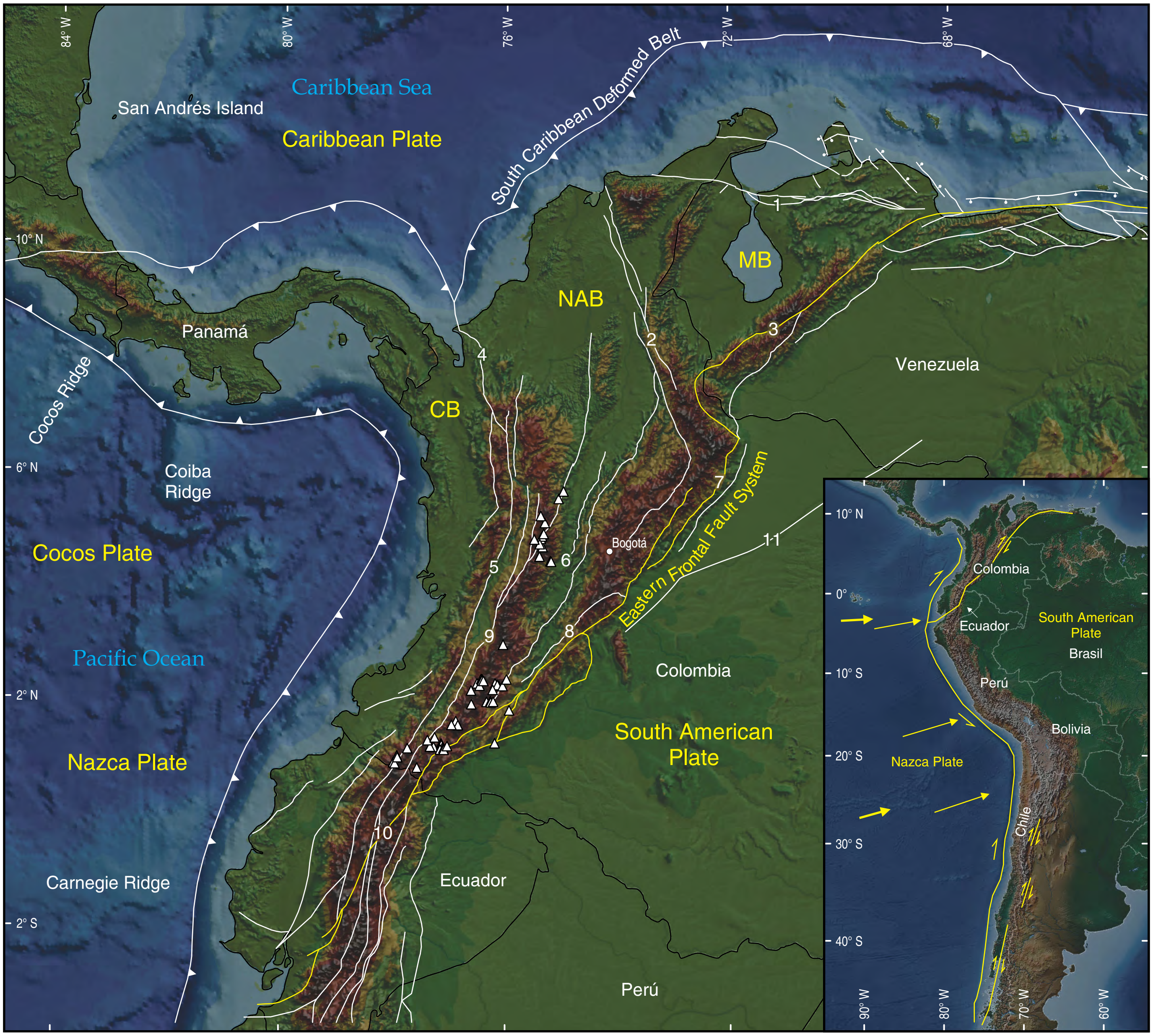

Figure 1. The North Andean Block (NAB) within the setting of the three converging major plates of Nazca, Caribbean, and South America and the Panamá Arc. The eastern boundary of the NAB has been marked as the Eastern Frontal Fault System or Great North Andean Boundary Fault that runs from the Gulf of Guayaquil in Ecuador to the caribbean coast in Venezuela. Source: Audemard & Audemard, 2002. (NAB) North Andean Block; (MB) Maracaibo Triangular Block; (CB) Panamá–Chocó Block. The figure also shows 11 major faults: (1) Oca Fault; (2) Santa Marta–Bucaramanga Fault; (3) Boconó Fault; (4) Uramita Fault; (5) Cauca–Patía Fault; (6) Cambao Fault; (7) Guaicáramo Fault; (8) Altamira Fault; (9) Cauca–Almaguer Fault; (10) Pallatanga–Chingual–La Sofía Fault; and (11) Meta Fault.

that focused on the identification of geomorphic markers, and morphotectonic indicators, by means of interpretation of aerial photos and digital elevation models (DEM) complemented by field surveys, in an intent to establish the degree of activity of faulting, including the selection of sites for in situ paleoseismologic studies in artificial fault outcrops known as trenches (McCalpin, 2009; Yeats et al., 1997). So far, in one particular case, this has led to a paleoseismologic study in trench outcrop. On the basis of these methods of study we describe indications of the latest Pleistocene – Holocene activity of the faults that form part of the Algeciras system in the study area with emphasis on the main branch of the system, the Algeciras Fault proper. Together with a literature review of instrumental and historic seismicity, this has enabled us to define the AFS to be probably the largest and most important active fault structure in Colombia that has profound implications for the associated seismic hazard (Dimaté et al., 2005; Paris et al., 2000).

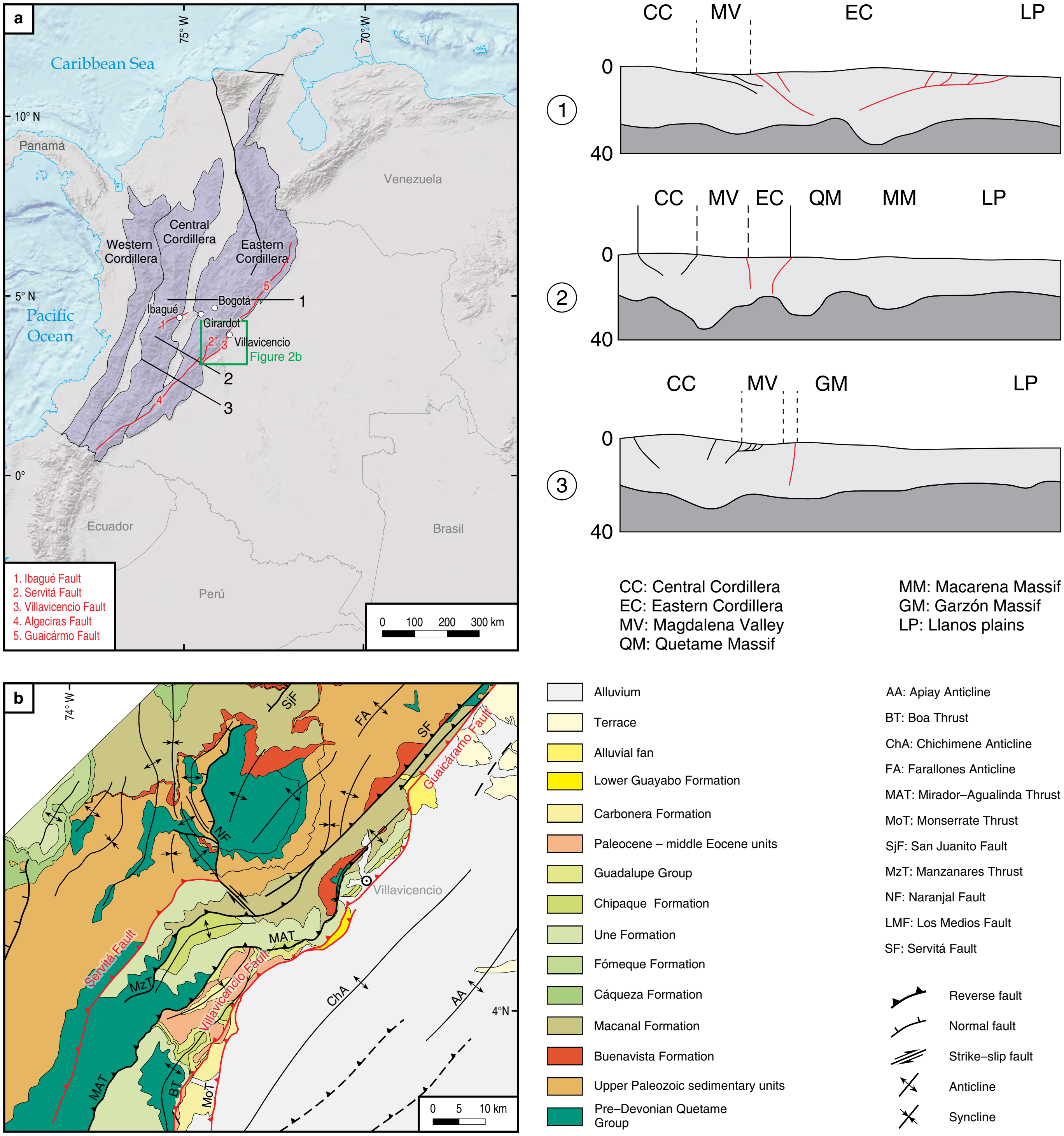

Figure 2. (a) Sections across the Eastern Cordillera show the change–over along the Eastern Frontal Fault System from east verging thrusting (1) to almost vertical strike–slip displacement (3). **(b)** Geological map showing the transverse tectonic structure with almost NW–SE orientation along a line running from Ibagué in the west to Villavicencio in the east that marks the change–over in the Eastern Frontal Fault System from thrusting in the Guaicáramo Fault System in the north to right lateral strike–slip Algeciras segment in the South. Source: Guillande (1988).

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 DEM 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), and the European satellite radar system (SENTINEL) with spatial resolution of 30 and 12.5 m, respectively. 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 without 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 results 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 on either side of the fault trace. These maps are produced at a scale of 1:25 000 and therefore have not been reproduced for this chapter. The ultimate objective 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 includes visible evidence of fault displacement in sediments that can be dated geochronologically (McCalpin, 2009). This is the field of paleoseismology that, in combination with quantified displacement data, serve to calculate slip rate of the fault, recurrence intervals of major seismic events, and date of the last such one (McCalpin, 2009; Yeats et al., 1997).

Another aspect of fieldwork includes the selection of sites for the establishment of geodetic stations as part of the Grupo de Investigación en Geodesia Satelital (GeoRED; Mora–Páez et al., 2019). 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, 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 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 that occurs when crustal deformation reaches the elasticity limit, that is: An instantaneous return to the original state in the form of an earthquake.

3. Regional Tectonic Setting

Almost the entire Andean terrain of the northwestern corner of South America, including Ecuador, Colombia, and Venezuela, constitutes the so–called NAB, crustal block, microplate, or sliver (Audemard, 1993, 2014; Egbue & Kellogg, 2010; Freymueller et al., 1993; Kellogg & Vega, 1995; Nocquet et al., 2014; Pennington, 1981; Taboada et al., 2000; Witt et al., 2006) that has also been described as a "wide plate margin" by Trenkamp et al. (2002). This crustal block is in the process of tectonic escape to the NNE as first suggested by Pennington (1981) and later by others like Audemard (1993), Egbue & Kellogg (2010), Freymueller et al. (1993), Kellogg & Vega, 1995, Taboada et al. (2000), Tibaldi & Ferrari (1991), Trenkamp et al. (2002), and Witt et al. (2006). This escape movement has been demonstrated in the plots of Global Position System (GPS) velocity vectors established during the CASA project (Freymueller et al., 1993; Kellogg & Vega, 1995) and, more recently, has been corroborated by the densified network of permanent GPS/GNSS stations of the GeoRED project, which firmly has established a NNE movement of 8.6 mm/y (Figure 3; Mora–Páez et al., 2002, 2016, 2019). The crustal block escape is the result of the interaction of the three major tectonic plates of Nazca, Caribbean, and South America, complemented by the collision of the Panamá–Baudó Arc (Figure 1). The main driving force for this tectonic escape is considered to be the motion of oblique convergence of the Nazca Plate with the South American continent together with the shallowly subducting Carnegie Oceanic Ridge in the border area of Ecuador and Colombia (Audemard, 1993, 2014; Audemard & Audemard, 2002; Egbue & Kellogg, 2010; Gutscher et al., 1999; Tibaldi et al., 2007; Witt et al., 2006) that functions as the push of a rigid indenter rather like the Arabian Block pushes into the Eurasian Plate and causes the sideways escape of the Anatolian Block (Turkey) (Aydin & Nur, 1982; Sengör et al., 1985). Another force considered to have effect on the tectonic escape of the NAB is the collision, initiated during the middle Miocene, of the Panamá–Baudó Arc (Audemard, 2014; Kellogg & Vega, 1995). However, the effect of this collision is more of a sideways push of the NAB north of the 7° N latitude, as demonstrated quite well in the pattern of GPS velocity vectors established by the GeoRED project (Figure 3; Mora–Páez et al., 2019). The eastern boundary of the NAB is well established and is formed by the transform belt, known as the Eastern Frontal Fault System in Ecuador and Colombia (Audemard, 1993, 2014; Audemard & Audemard, 2002; Egbue & Kellogg, 2010; Kellogg & Vega, 1995; Pennington, 1981; Taboada et al., 2000). The movement along this transform fault belt that facilitates the tectonic escape of the NAB is predominantly of the dextral strike–slip type, but from the latitude 4° N at the town of Villavicencio, north to latitude 7° N at the town of Tame in Arauca, the movement is predominantly of dip–slip thrusting along a fault system known as the Guaicáramo Fault that runs along the eastern foothills of the Eastern Cordillera (Bayona et al., 2008; Diederix et al., 2010; García et al., 2011; Mora et al., 2010). Nevertheless, the up–to date pattern of velocity vectors established during the GeoRED project points universally to movement of the block in a NNE

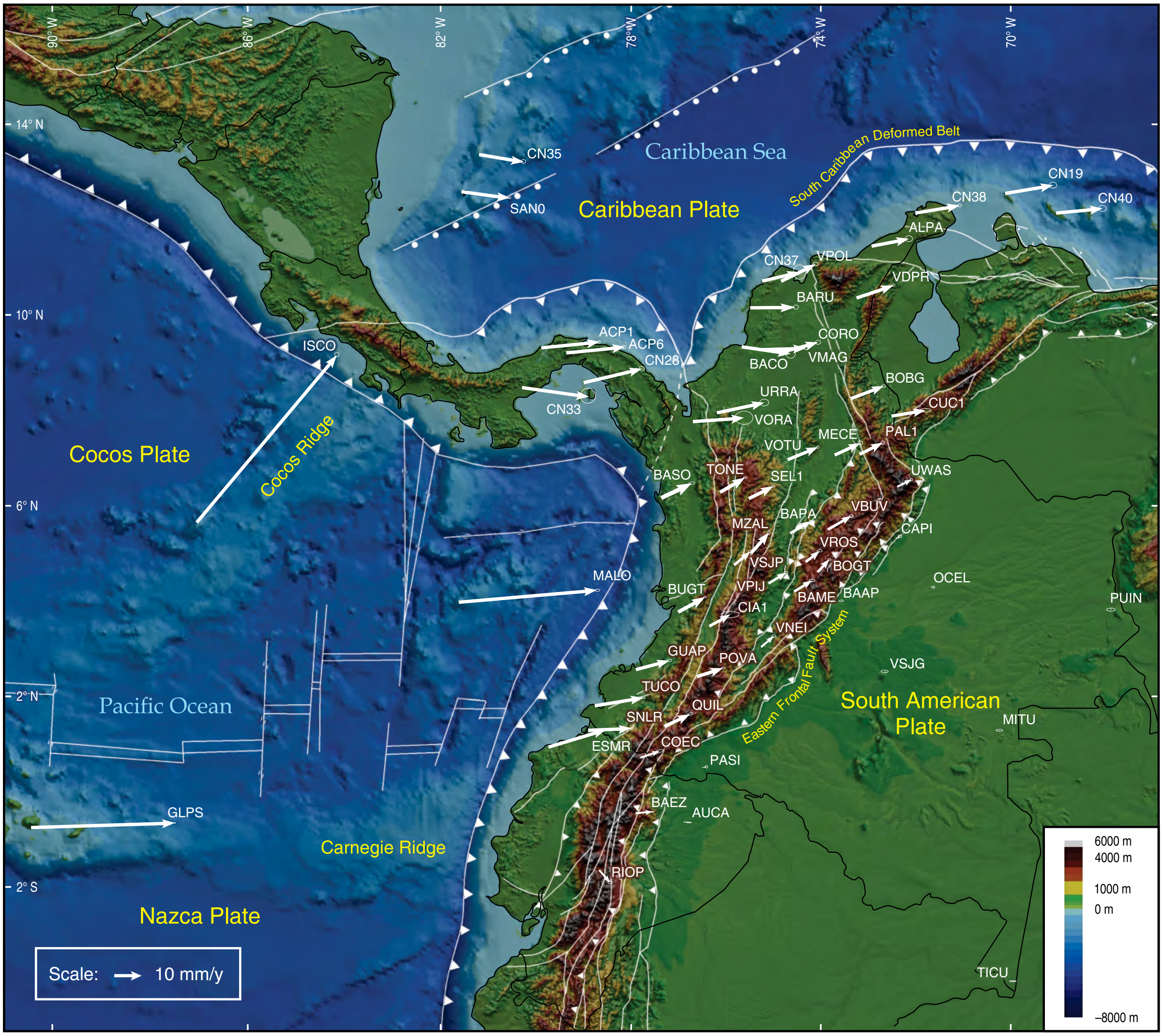

Figure 3. Plot of GPS vectors relative to stable South America. Source: GeoRED project of SGC.

direction at a velocity of 8.6 mm/y (Figure 3; Mora–Páez et al., 2016, 2019). The Guaicáramo system runs along the foothills of the Eastern Cordillera and consists predominantly of east verging thrust and stacked thrust systems that are the mark of a foreland fold and thrust belt (Bayona et al., 2008; Diederix et al., 2010; García et al., 2011; Mora et al., 2010), but always maintains a dextral strike–slip component as has been observed in the field (Diederix et al., 2010) and is also evident in the pattern of GPS velocity vectors established during the GeoRED project (Figure 3; Mora–Páez et al., 2002, 2016, 2019). The Guaicáramo Fault System makes an abrupt double right angle bend north of the town of Tame in the northeast over a distance of 150 km to resume its NE strike at the town of Cúcuta and continues as the Boconó Fault that follows the length of the Mérida Andes in Venezuela (Audemard & Audemard, 2002; Audemard et al., 2005, 2006). This abrupt double bending over a distance of 150 km is known as the "Pamplona Indenter" (Audemard, 2014; Audemard et al., 2006; Bayona et al., 2008; Boinet et al., 1985; Mora et al., 2010; Rodríguez et al., 2018) but has not been defined yet kinematically. It might even be a large left hand restraining step–over in the system (Christie–Blick & Biddle, 1985; Dooley & McClay, 1997; Mann, 2007; Rodríguez et al., 2018; Sylvester, 1988; Woodcock & Schubert, 1994). The imaginary E–W line Girardot–Villavicencio at 4° N latitude marks a transverse zone that has caused rather abrupt westward bending of the Guaicáramo system where it enters the Eastern Cordillera and is best expressed in the geometry of the Servitá Fault, which belongs to the Guaicáramo system (Figure

2; Guillande, 1988; Chorowicz et al., 1996), and the NW–SE oriented Naranjal Fault (Mora et al., 2010). This transverse zone, that also marks the widening of the Eastern Cordillera to the north of it, has its origin in the Central Cordillera and relates to the ENE striking dextral strike–slip Ibagué Fault that has displaced the Central Cordillera and the Ibagué Batholith over a horizontal distance of 30 km (Acosta et al., 2004; Audemard, 2014; Diederix et al., 2006, 2009; Montes et al., 2005; Osorio et al., 2008). It is considered, together with the similarly oriented Garrapatas Fault running from Buenaventura NE–ward in the Western Cordillera, as an effect of the eastward indentation caused by the collision of the Panamá–Baudó Arc with continental South America (Acosta et al., 2004; Audemard, 2014; Egbue & Kellogg, 2010; Kellogg & Vega, 1995).

4. The Algeciras Fault System

The Algeciras Fault System constitutes the main part of the southern half of the transform belt system in Colombia and covers the length of the system between the village of La Uribe in the northeast, where the main branch of the system enters the Eastern Cordillera (Figure 4; Gómez et al., 2015), and the town of Sibundoy in the southwest not far from the town of Mocoa, (Gómez et al., 2015; Ingeominas & Geoestudios, 2000) on the way passing the towns of Garzón, Timaná, and Pitalito. South of the town of Sibundoy the fault continues as the Afiladores Fault that continues into Ecuador (Alvarado et al., 2016; Baize et al., 2014; Eguez et al., 2003; Ferrari & Tibaldi, 1992; Ingeominas & Geoestudios, 2000; Soulas et al., 1991; Tibaldi & Ferrari, 1991; Tibaldi et al., 2007). This is the part of the transform fault system in Colombia that will be described in more detail as it has been the subject of study in recent years.

The AFS in this stretch of the transform belt in Colombia covers a distance of 330 km and constitutes a belt of interconnecting and anastomosing faults, the central and most important branch of which is the Algeciras Fault proper (Figure 4). Particularly in the sector between the village of Algeciras in the north and Pitalito in the south, most of the movement of the fault system is concentrated along this main branch. This has resulted in an outstanding morphological expression on the DEM imagery and also on aerial photos that compare with the well–known and well–studied Boconó Fault in Venezuela (e.g., Audemard, 2016; Audemard & Audemard, 2002; Audemard et al., 2005, 2006; Pousse–Beltran et al., 2017). The width of the fault belt of the AFS varies in this sector between 25 and 40 km. The entire system between La Uribe (Gómez et al., 2015), where the main branch of Algeciras Fault enters the Eastern Cordillera coming in from the Llanos Orientales, to Pitalito, the fault traverses obliquely the entire width of the Eastern Cordillera to the point where this merges with the Central Cordillera (Figure 5; Butler & Schamel, 1988). In this sector, the fault constitutes a large part of the western boundary of the Neoproterozoic Garzón Massif (Butler & Schamel, 1988; Diederix & Gómez, 1991; Saeid et al., 2017; van der Wiel, 1991). At the valley of Balsillas, located at 2.45° N latitude (Gómez et al., 2015), the fault system, coming from the southwest, starts to branch out northeastward into several branches, the westernmost of which proceeds in the direction of Bogotá, whereas the easternmost branch follows the front of the cordillera to emerge just beyond the north end of the serranía de La Macarena to continue in the direction of the Meta Fault (Figure 4; Gómez et al., 2015), but there its trace is lost under the thick accumulation of large alluvial fan deposits that descend from the cordillera towards the Llanos Orientales Basin. In between these two branches, the Paleozoic Quetame Massif has been wedged in (Gómez et al., 2015). The AFS in the sector between Algeciras and the Ecuadorian border consists of a number of branch faults; the most important of these will be described in some more detail. The westernmost of these branches is the San Agustín–Agrado–Hobo branch that connects at its northern end to the main branch near the village of El Paraíso located 10 km north of the town of Algeciras. The eastern branch of the system is the Suaza–Acevedo branch that connects to the main branch near the village of Zuluaga in the north, whereas southward it follows the valley of the Suaza River to come out near Mocoa to eventually connect to the main strand at the valley of Sibundoy. Another prominent branch runs from the town of Timaná to the southwest also to converge with the main system near the valley of Sibundoy, on the way passing through the villages of Yunguillo and San Francisco (Figure 5; Ingeominas & Geoestudios, 2000).

5. Geomorphic Expression of the Algeciras Fault System Main Branch Fault

The geomorphic expression of the main branch of Algeciras Fault, as seen on the DEM imagery, is particularly strong along the stretch between the village of La Uribe in the northeast and the town of Garzón in the south, where the fault trace is remarkably straight and has been accentuated by deeply incised rivers that have produced V–shaped valleys that make for maximum visibility of the fault trace on aerospace imagery (Figure 4). Quite notable, particularly in the vicinity of the village of Zuluaga and further to the southwest, close to the town of Timaná, is the presence of numerous synthetic and antithetic Riedel shears (Figure 6a; Dooley & McClay, 1997; Sylvester, 1988; Tchalenko & Ambraseys, 1970; Wilcox et al., 1973) that fit perfectly in the model of simple shear for the generation of strike–slip faults (Sylvester, 1988; Wilcox et al., 1973). Most of these are short and reach no more than 2 km in length, but some are considerably longer and reach lengths of 10 km, e.g., the Timaná Fault (Figure 6a; Cárdenas et al., 1998; Ingeominas & Geoestudios, 1998).

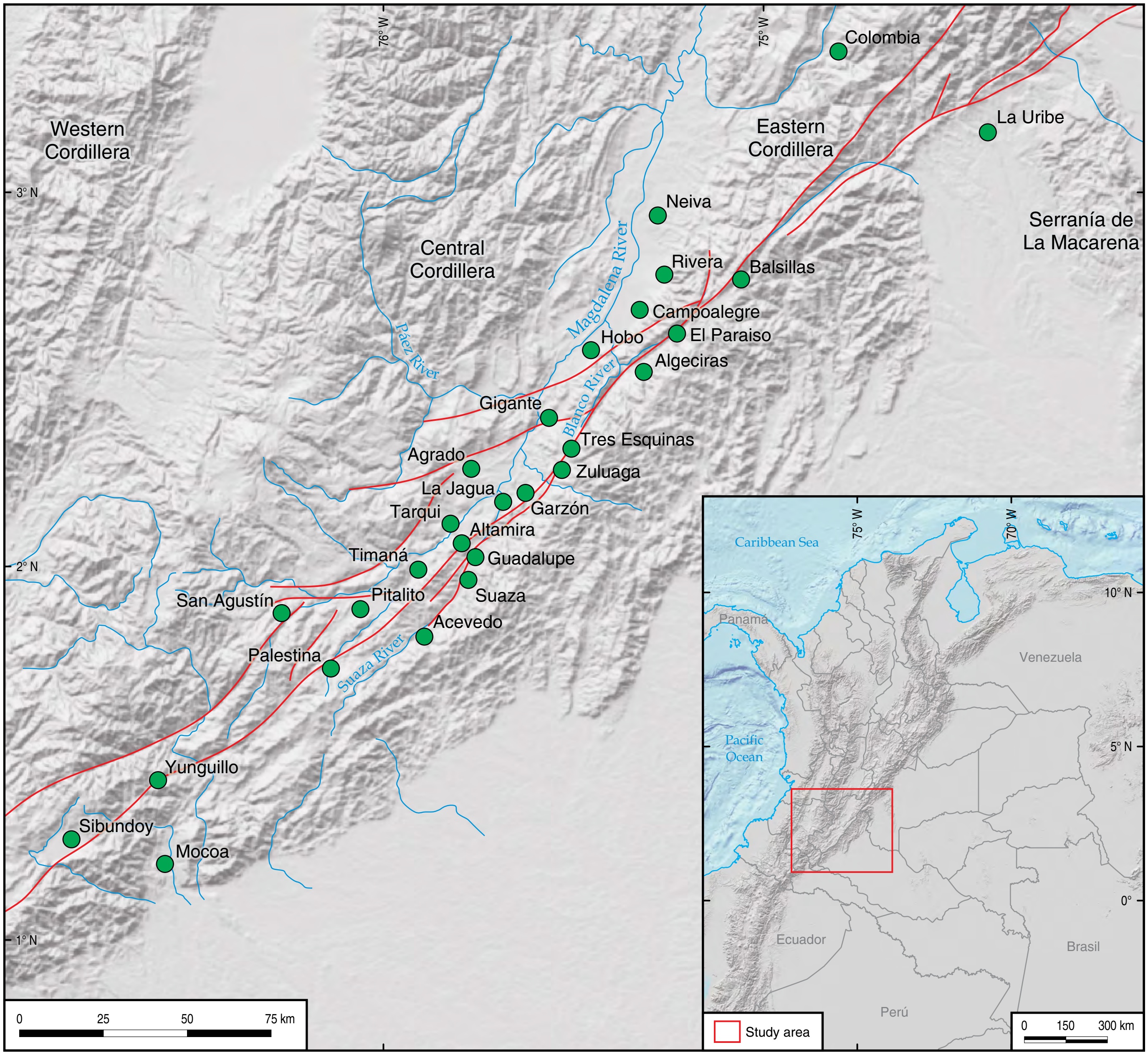

Figure 4. DEM of part of the Eastern Cordillera that displays the pronounced geomorphic expression of the Algeciras Fault System with the main branch fault being the Algeciras and Afiladores Faults, and the satellite branch faults of Agrado Fault and Suaza Fault. Names of the municipalities have been indicated for referencing.

Drainage offsets and deflections as well as stream length control together with features such as fault saddles, triangular facets, offset ridges, shutterridges, and normal and uphill facing scarps are common morphotectonic indicators which, when occurring in an aligned array, can be taken as convincing geomorphic evidence for recent (Quaternary) fault activity. In this sense, the mention of morphotectonic indicators in this text has to be taken as evidence of fault activity observed along the entire length of the main branch. In some cases across fault linear geomorphic markers constitute piercing points when they cross the fault trace. These, when observed to have been offset, can serve as valuable reference for the establishment and quantification of lateral fault displacement provided that these features can be reliably dated. An example of this is the case of the Suaza River having been offset, halfway between Altamira and Garzón, for at least 4 km by right lateral displacement of a longitudinal ridge of resistant conglomerates and sandstones of the Gualanday Formation of Eocene age that has acted as a shutterridge. Unfortunately, no geochronologic dates could be obtained that would have permitted to establish the slip rate of the fault in that particular sector. Another notable feature typically associated with strike–slip faults is the presence of at least

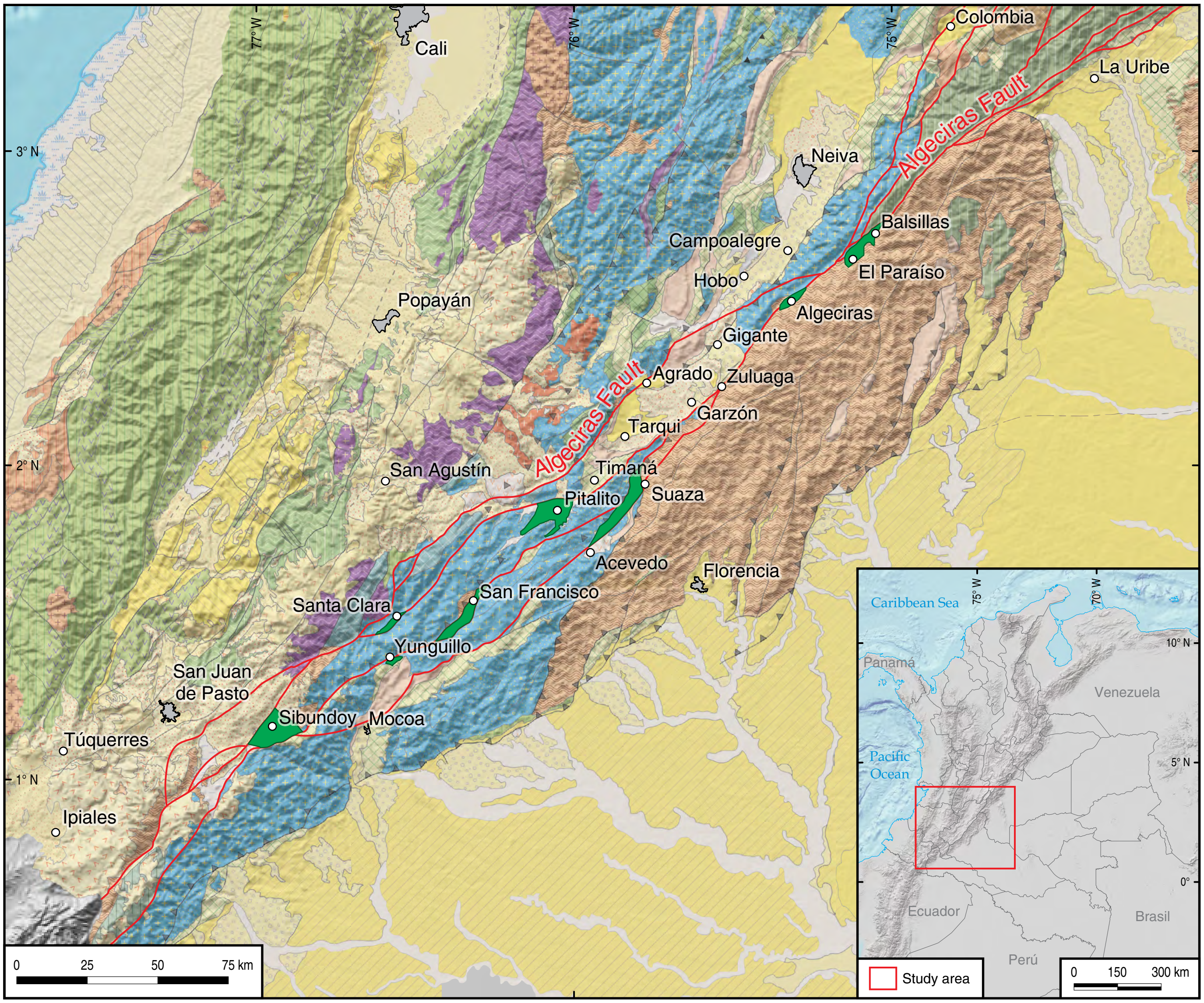

Figure 5. Map of the Algeciras Fault System between La Uribe in the northeast and the Ecuadorian border in the southwest. Tectonic basins are indicated in green. Principal municipalities have been indicated. Modified from Gómez et al. (2015).

6 tectonic basins developed along the fault trace, known until now as pull–apart basins, that normally are the result of the interaction of fault geometry and the sense of fault displacement (Aydin & Nur, 1982; Christie–Blick & Biddle, 1985; Crowell, 1973; Cunningham & Mann, 2007; Dooley & McClay, 1997; Mann, 2007; Storti et al., 2003; Sylvester, 1988; Wilcox et al., 1973). These have been developed in so–called releasing bends or releasing step–overs along the fault trace (Christie–Blick & Biddle, 1985; Cunningham & Mann, 2007). The following basins have been identified and will be treated in some more detail later (Figure 5): (1) Sibundoy Basin at the convergence of the San Francisco–Yunguillo branch and the northern extension of the Afiladores Fault (Gómez et al., 2015; Ingeominas & Geoestudios, 2000, 1999); (2) San Francisco–Yunguillo Basin (Ingeominas & Geoestudios, 1999), situated in a gentle bend of the Villalobos Fault branch, described by Velandia et al. (2005) as a lazy–S–shaped pull–apart basin; (3) the Pitalito Basin, developed along a releasing bend of the main branch of Algeciras Fault near the town of Pitalito (Cárdenas et al., 1998); (4) the Algeciras Basin developed along a gentle releasing bend of the main branch of Algeciras Fault near the village of Algeciras that gave the name to the fault system (Diederix & Romero, 2009; Page, 1986; Vergara, 1996); (5) El Paraíso Basin formed at a small right hand fault step–over along the main branch fault 10 km to the northeast of the Algeciras valley; and (6) Balsillas Basin, situated at the highest elevation along the main branch fault within the Garzón Massif. There are a few other valleys along fault branches of the system (Suaza and Santa Clara Basins) that possibly might respond to the definition of a pull–apart basin but would require more detailed mapping and study. Hereafter fol-

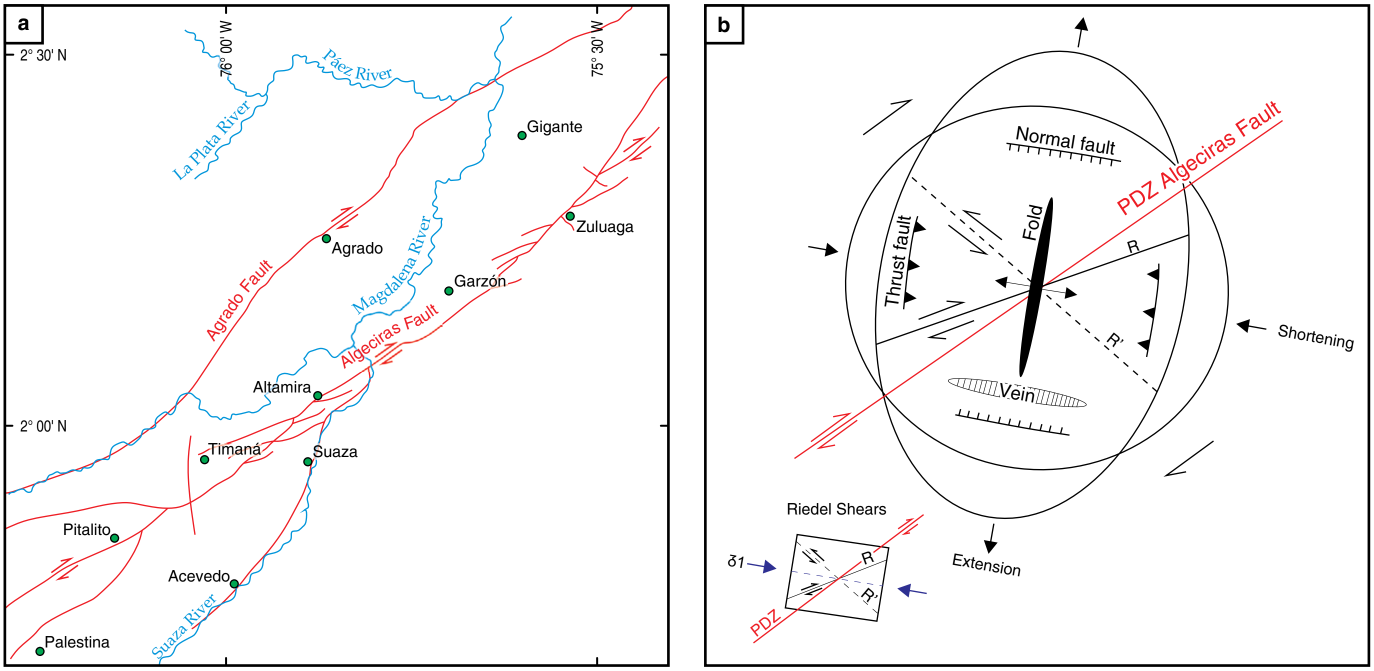

Figure 6. **(a)** Map configurations of synthetic Riedel shears occurring along the main fault branch in the sector between Pitalito in the southwest and Zuluaga in the northeast. Adapted from Bakker (1990). **(b)** Strain ellipse of the simple shear model according to Wilcox (1973), and the related structural features, such as synthetic and antithetic Riedel shears and folding that result from extensional and compressional stress fields. PDZ: Principal Deformation Zone.

lows a more detailed description of these 6 basins, two of which only have been subject to detailed neotectonic study (Figure 7).

5.1. Sibundoy Basin

This basin is situated in the SW sector of the AFS under study and is located at the near convergence of the San Francisco–Yunguillo Fault branch and the Colon Fault, which is the northern extension of the Afiladores Fault, which has its extension to the south in Ecuador (Figure 5; Alvarado et al., 2016; Baize et al., 2014; Ferrari & Tibaldi, 1992; Ingeominas & Geoestudios, 2000; Tibaldi & Ferrari, 1992; Tibaldi et al., 2007; Velandia et al., 2005). These two faults almost converge in the SW corner of the basin and this place is host to a small volcano, the Sibundoy Volcano. Little is known of this volcanism other than that it is part of a field of at least 7 such volcanoes that occupy an area directly to the east and south of La Cocha Lake. This volcanism is of Quaternary age and probably is of the monogenetic type similar to the alkali–basaltic volcanism in the area of San Agustín and Acevedo, to be described later, and all within the realm of the AFS. The basin has a roughly triangular shape with two sides controlled by the two faults just mentioned that have an ENE and NNE direction, respectively (Figure 7). The third side of the triangle closes the valley along a NW–SE line but is not controlled by a fault. The basin has been classified as a pull–apart basin by Velandia et al. (2005) but on the basis of the description just given it appears more likely that the basin, with its thick alluvial fill, corresponds to the description of a "fault wedge basin" (Christie–Blick & Biddle, 1985; Crowell, 1962, 1973; Cunningham & Mann, 2007; Mann, 2007). The basin has a dimension of 20 × 10 km and its southern margin, controlled by the San Francisco–Yunguillo Fault, has a morphotectonic expression in the Quaternary alluvial fill with small counterscarps, best seen on aerial photos. Also, there are some airphoto indications that the basin appears to be diagonally crossed by a shortcut fault. These features suggest fault activity but no detailed neotectonic field studies have as yet been undertaken to assess the degree of activity of its controlling faults.

The area of the Sibundoy Basin has been the scene of the 1834 M ≥ 7 earthquake that caused extensive regional destruction (Dimaté et al., 2005; Ramírez, 2004).

5.2. San Francisco–Yunguillo Basin

An elongated gently curved valley with a longitudinal axis of 20 km and a maximum width of 4 km, along the San Francisco–Yunguillo branch fault (Ingeominas & Geoestudios, 1999), has been classified by Velandia et al. (2005) as a lazy–S shaped pull–apart basin (Figure 7). However, the curvature of the controlling faults is to the left and in combination with right lateral fault movement it should act as a restraining bend, and that could not explain the generation of the basin with its alluvial fill (Ingeominas & Geoestudios, 1999). This alluvial fill occurs

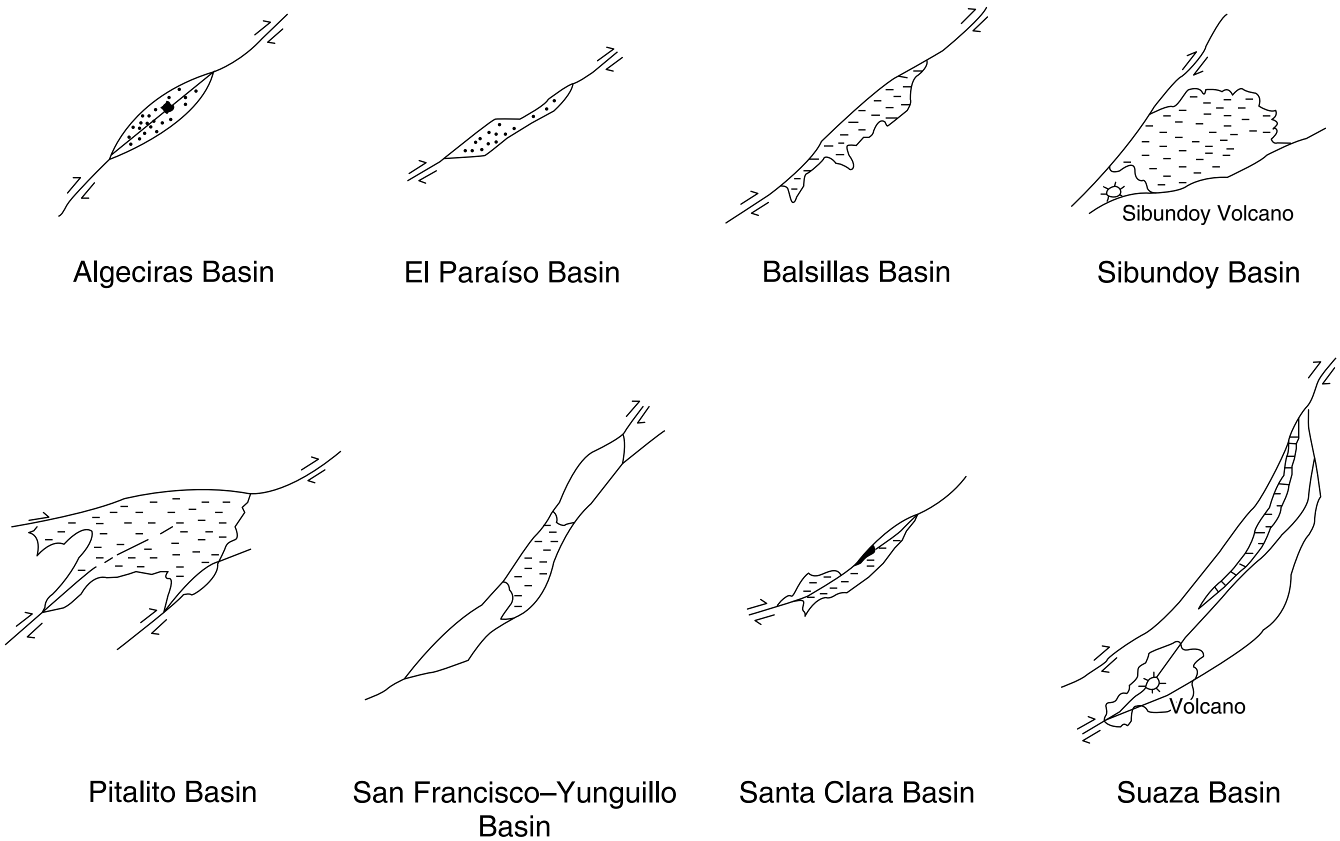

Figure 7. Schematic outline (not at uniform scale) of the tectonic basins of the Algeciras Fault System.

in two separate depocenters within the valley and this suggests that a different kinematic model has to be constructed of a composite basin that probably involves two connected pull–apart basins (Figure 7; Dooley & McClay, 1997).

5.3. Pitalito Basin

The continuation to the SW of the main branch of Algeciras Fault beyond the town of Timaná shows a distinct curvature that functions as a releasing bend along a right lateral strike–slip fault. The result of this configuration is the fairly large Pitalito pull–apart basin in the center of which is the town of Pitalito that gave it its name. The basin has a longitudinal axis of 18 km and a maximum width of 8 km and has a flat surface of its alluvial fill. Its well defined northern boundary is controlled by the Algeciras Fault that locally bears the name of Granadillo Fault, which has an excellent morphotectonic expression with offset and deflected streams, offset ridges and alluvial fans, shutterridges, and uphill facing scarps (counterscarps) all well aligned and clearly marking the fault trace. Tectonic control of the southern margin is difficult to establish. The two faults that enter the basin from the southwest, and that control the courses of the Guachicos and Guarapas Rivers, lose their morphologic expression when entering the basin perimeter. A direct link with the main trace of the Algeciras Fault in the NE corner of the basin might exist but cannot be detected on aerial photos or in the field (Figure 8).

The detailed study by Bakker (1990) has established an alluvial basin fill with sediment supply mainly by the Guachicos and Guarapas Rivers entering the basin from the southwest. Gravimetric and geo–electric subsurface soundings carried out by him established a maximum depth of the basin in the NE corner of 1200 m, clearly an indication of the tectonic origin of the basin. The same author also established a shallow depth of the basin in the southwest corner, separated from the deep NE part by a an abrupt break, interpreted to be a normal fault with a NW strike that seems to be the result of the simple shear deformation model of a dextral strike–slip Algeciras Fault with tensional stress in the direction of the longitudinal axis of the deformation ellipse (Figure 6b; Christie–Blick & Biddle, 1985; Sylvester, 1988; Wilcox et al., 1973). Peculiarly, the present–day drainage pattern in the basin shows an abrupt 120° change in the direction of the courses of the two main rivers, Guachicos and Guarapas, entering the basin from the southwest running towards the NE, abruptly assuming a flow direction to the west contrary to the depth division of the basin. The explanation of this anomalous stream behavior we have assumed to be recent stream piracy by the Magdalena River that passes close to the southwest corner of the basin (Figure 8).

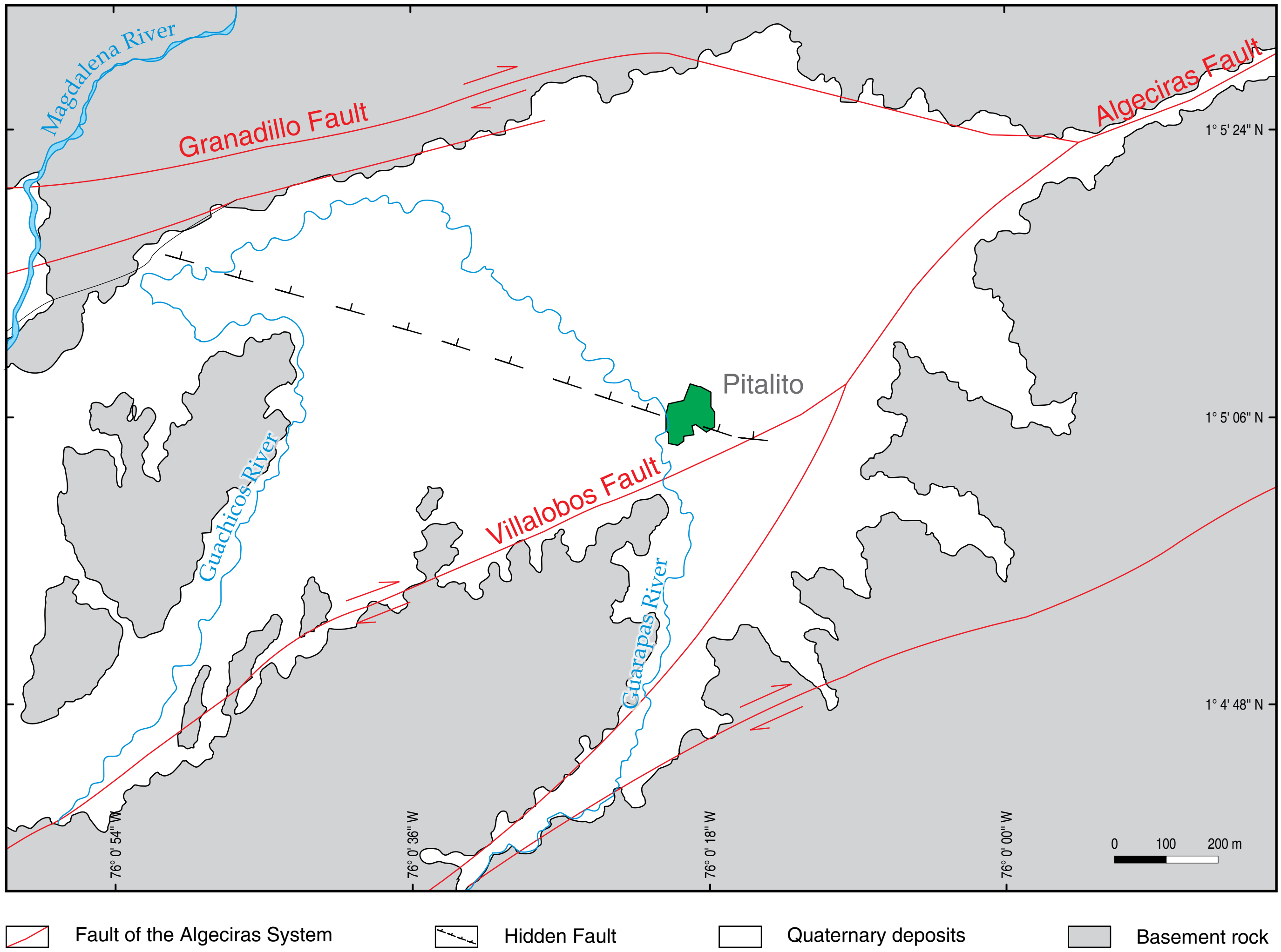

Figure 8. Map of Pitalito Basin with the main controlling faults the curvature of which constitute a releasing bend being a condition for creating the pull–apart basin. Adapted from Bakker (1990).

5.4. Algeciras Basin

The best known pull–apart basin is the valley of Algeciras with the small town of Algeciras in the middle that gave the valley as well as the fault system its name. The basin has evolved in a gentle releasing bend of the main Algeciras Fault. The present valley has a spindle shape with a longitudinal axis stretching over 12 km. The actual width is 3 km at its widest (Figure 9; Page 1986; Paris et al., 2000; Vergara, 1996). The sector of the Algeciras Fault between Tres Esquinas in the southwest and the valley of Balsillas in the northeast and beyond has a strong morphologic expression best seen on the DEM imagery as it is accentuated by deep V–shaped valleys of the Blanco River coming in from the SW and the Neiva River coming in from the NE, the two rivers converging just outside the central section of the western rim of the valley. The valley is symmetrically spindle or lozenge shaped in plan but asymmetric in cross section because of the difference in altitude of the southeast flank situated entirely within the Garzón Massif and the lower altitude of the northwest flank in intrusive rocks of the Jurassic (Figure 10). The result of this is that the alluvial fill of debris flows has its origin exclusively in the Garzón Massif (Figure 10). Another result of this is that the flow of sediments has forced both rivers to shift their course to the western fault controlled rim of the valley. This has kept remarkable freshness of the fault trace that therefore is marked by an abundance of triangular facets, which in this particular case presents no conclusive evidence for recent activity of the fault (Figure 11; Diederix & Romero, 2009). Through a process of kinematic adjustment a new recent shortcut fault formed that runs precisely along the longitudinal diagonal axis of the basin (Diederix & Romero, 2009; Reijs & McClay, 2003). This shortcut fault cuts across the valley alluvium displacing its topography by horizontal strike–slip movement, creating well marked uphill and downhill facing scarps with so–called scissor or hinge effect in the process (Figure 11; Diederix & Romero, 2009). The total displacement since the initiation of the shortcut fault has been 3.5 km during the upper Pleistocene. Figure 9 shows the great similarity in the distance of displacement at both extreme ends of the

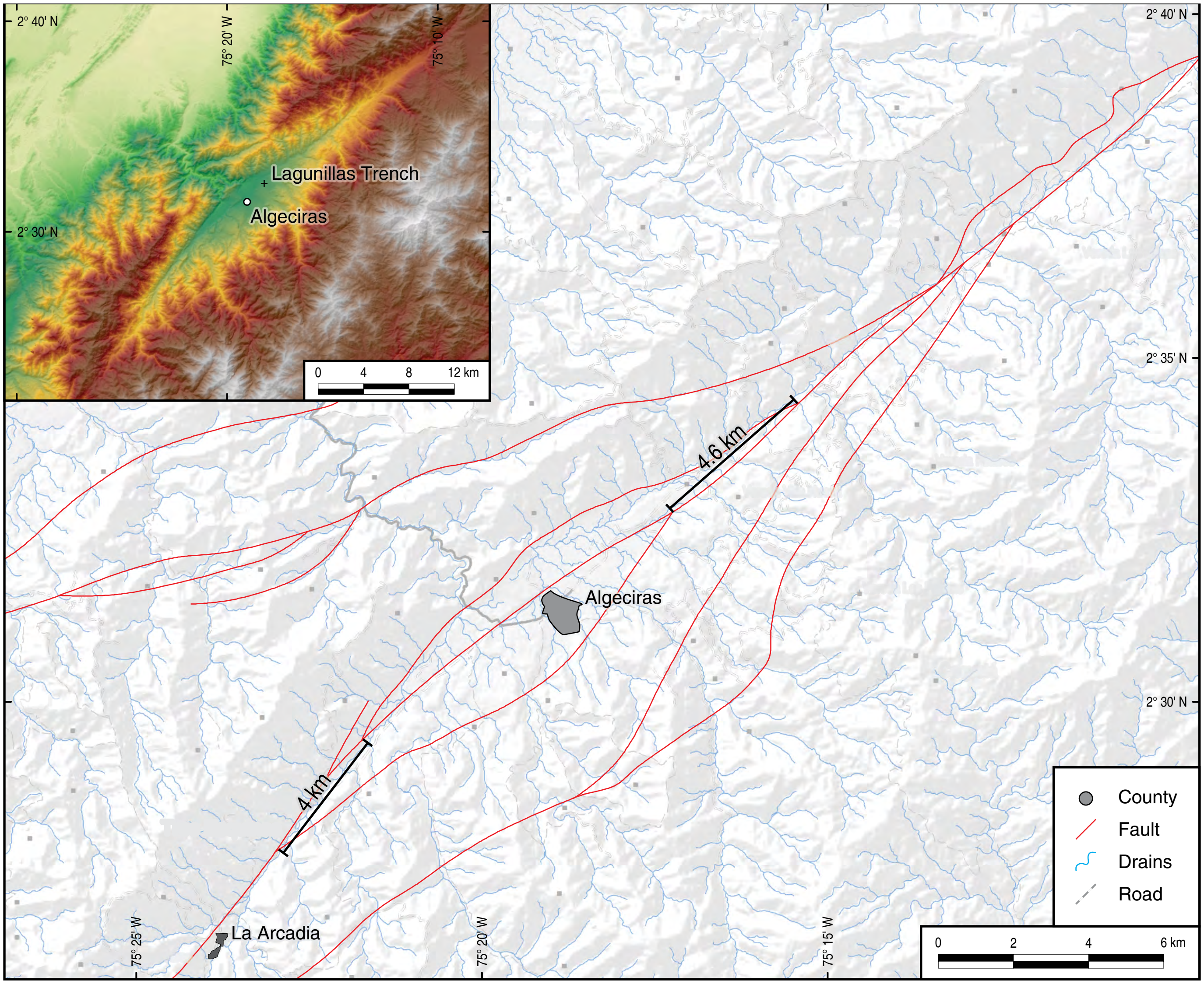

Figure 9. DEM and map of the Algeciras pull–apart basin that show the evolution in size reduction of the basin and the kinematic straightening of the controlling fault by development of the cross basin shortcut fault. The approximate 3.5 km displacement of the lozenge shaped pull–apart basin is indicated by the identical offsets at both extremes of the basin.

spindle–shaped basin which are almost of the same magnitude. The absence of reliable dating possibilities of these offset features unfortunately has prevented the establishment of a time frame for this displacement and therefore has not permitted the calculation of fault slip rate. Another such feature that might have provided a possibility of establishing fault slip rate is the presence of an abandoned and beheaded stream bed in the distal part of the alluvial fan where the access road to the Algeciras valley passes through. This dry river bed can be matched with a stream 800 m to the south that probably is the original stream that has been offset by the short cut fault (Figures 9, 11). Unfortunately, there was no way that the soil samples taken in the beds of both branches could be reliably matched and thus would have permitted the dating of the initiation of the stream offset and therefore precluded the quantification of fault slip rate for the shortcut fault. Another case of a piercing point was encountered along the main branch fault approximately 6 km further to the north where the distance of offset was much smaller, no more than 50 m, but the extreme roughness of the terrain made trench excavation impossible.

The evolution of the pull–apart basin has been registered in the alluvial valley fill of successive debris flow fans coming down from the Garzón Massif that shows a higher degree of dissection in the southwestern part of the valley, indicating a younging towards the northeast that reflects the progradation of the basin as it opened up in that direction (Diederix & Romero, 2009). The basin evolution however must have a longer history than the present–day configuration suggests, because outside the perimeter of the fault controlled valley as we know it today (Figure 9) on the valley slopes at both sides, remnants of degraded terraces occur that are limited on the uphill side by abrupt slope changes

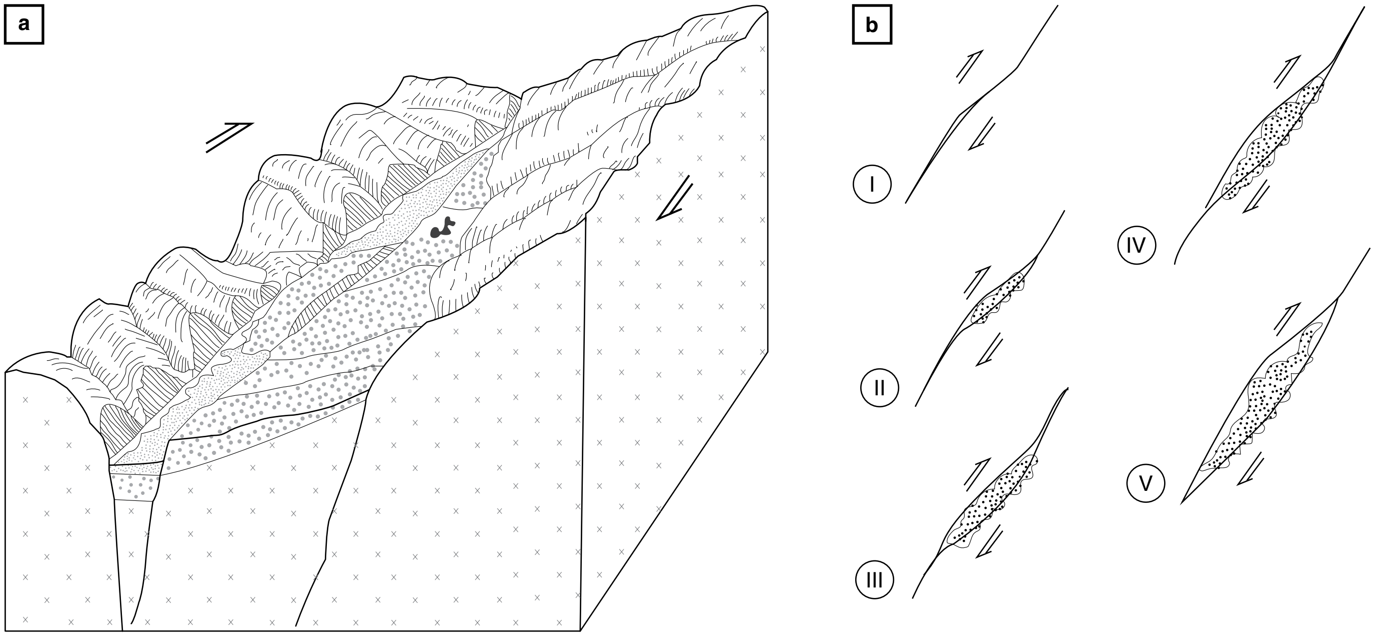

Figure 10. (a) Block diagram of the Algeciras pull–apart basin. **(b)** Plan view of the simplified tectono–sedimentary evolution of the basin.

that indicate fault control by a fault that is not active any longer (Figure 12). The remnant terraces consist of fine grained slope debris with occasional boulders or blocks that probably indicate that the terrace remnants represent ancient valley floors. Our interpretation is that, contrary to the progressive evolution of pull–apart basins towards basin widening over time (Aydin & Nur, 1982; Dooley & McClay, 1997), the Algeciras Basin shows the opposite evolution as it apparently has been much wider during an earlier stage of evolution and that it subsequently narrowed down to smaller dimensions in a kind of telescoping process. These processes of diminution or size reduction and the subsequent development of shortcut faulting might probably terminate in a total straightening of the main fault branch. This could lead to an eventual total disappearance of the pull–apart basin in the future (Reijs & McClay, 2003).

5.4.1. Paleoseismology of the Algeciras Basin

Recent paleoseismologic studies have been carried out in two small manually excavated trenches dug across the uphill facing scarp of the shortcut fault in the center of the Algeciras valley at the Lagunillas farm and another one across a larger uphill facing scarp of the main branch of Algeciras Fault 5 km to the northeast at the Santa Elena farm. Organic rich black clay deposits were encountered at the foot of the scarps that inter–digitate with weakly developed colluvial wedges made up of detrital material derived from crystalline basement of the high ground of the scarps. In the trench walls, no actual fault traces could be detected in spite of the certainty of having intersected the real fault trace (Figure 13). The explanation for this must be sought in the high plasticity of the black clay deposits that effectively lead to concealment of the fault trace in the vertical walls cut by strike–slip fault with horizontal displacement which generally leads to reduced visibility (McCalpin, 2009). This non–visibility of the fault trace also created difficulty in the proper siting of sample collection for ^{14}C dating. Ten samples were taken, and their ages ranged from 8950 y BP in the bottom clays of the trench to present–day age in the upper clay soils. In between these two levels in the central part of the trench that is supposed to be the location of the fault trace, a 2 m wide and 0.5 m thick V shaped red patch of oxidation (Figure 13) is considered to represent surface exposure conditions which have been interpreted to represent a so–called “open crack” generated by a major seismic event. Sample results from below and above this patch yielded a time window of 1340 years between 2540 and 1200 y BP, far from a precise enough paleoseismologic result. Another possibility that could explain the non–visibility of the fault trace in the trench walls could be the a–seismic displacement of the fault along the shortcut branch. Supporting evidence for this is thought to be the widespread occurrence of fractures and cracks in the buildings and grounds of a college and the town hospital, which are situated at a distance of no more than 100 m from the fault trace, well within the fault shear zone. These cracks and fractures have an orientation orthogonal to the fault trace and can reach lengths of at least 50 m. These features might well be a manifestation of fault creep and have necessitated the recent relocation of the hospital to a position further removed from the fault trace.

At a distance of approximately 7 km along the road north to the village of El Paraíso, a road outcrop revealed exposure of the main branch of Algeciras Fault that displays a vertical fault plane that puts into contact Proterozoic gneisses of the Garzón

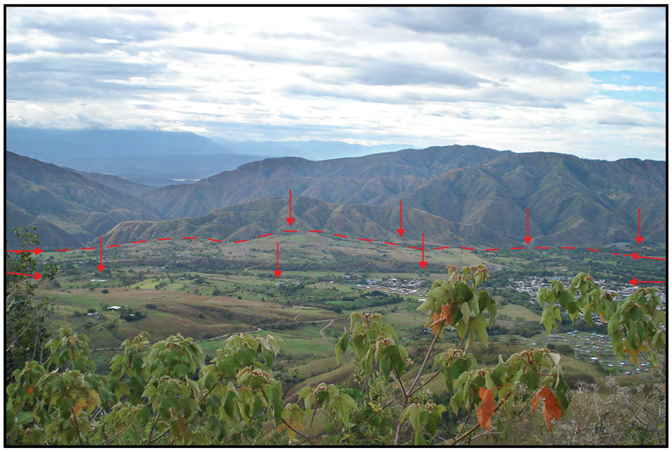

Figure 11. Westward view of the Algeciras valley showing the trace of the western border fault marked by triangular facets, and the uphill facing scarp (counterscarp) of the shortcut fault traversing the central part of the valley.

Figure 12. Fault controlled remnants of the paleo valley bottom seen as a dissected terrace that indicates that the basin originally was wider. View to the south.

Massif on the east with upper Pleistocene gravels on the west. A few centimeters thickness of fault gouge mark the fault plane but no kinematic indicators could be detected and neither any systematic fracturing of clasts (Figure 14).

5.5. El Paraíso Basin

Some kilometers northeast of the outcrop, following the main road, just beyond the village of El Paraíso, the V–shaped fault valley widens to give room to El Paraíso pull–apart basin with a length of 5 km and a maximum width of 1.5 km (Figure 15). This pull–apart basin is a composite one as it developed at a double right hand releasing step–over (Figure 7). The place where the two originally overlapping basins meet shows a narrowing of the elongate valley. Two small pressure ridges within the valley bottleneck are interpreted to be the expression of local transpression build–up (Figure 7).

5.6. Balsillas Basin

From El Paraíso Basin, the road climbs up steeply in a NE direction following a deep canyon eroded along the trace of the main fault to reach an altitude of 2400 masl, where a wide valley opens along the trace of the fault. This is the Balsillas Basin that has a longitude of 22 km and a width of 5 km. The basin has a well–marked NW margin that is controlled by the main branch of Algeciras Fault but its SE boundary is not well marked, rather similar to the situation of the Pitalito Basin described above, and neither are the closures at both extremes of the valley (Figure 7). A kinematic model of basin evolution along either a releasing bend or a releasing step–over has yet to be established. Quite remarkable is the fine grained nature of the sedimentary valley fill that is also manifested in the gravels in the stream bed of the Balsillas River that runs the length of the valley from SW to NE, which are dominated by the pebble size fraction. This contrasts strongly with the very coarse nature of the debris flow fill of the Algeciras Basin. The reason for this must be sought in the high degree of saprolitization of the surrounding basement rocks of the Precambrian Garzón Massif that has so far escaped exhumation and yields only fine grained and clay fraction sediments.

Ramification of the AFS towards the northeast starts at the Balsillas Basin where two branches splay off the main Algeciras Fault on the NW side of the valley (Figures 4, 5). The western one of these appears to continue further to the north in the direction of Bogotá. More ramifications of the system occur further to the northeast with the main branch continuing straight towards the northeast where, on emerging from the mountain front, it disappears apparently under a thick cover of large alluvial fans. Another branch continues to the NE to eventually emerge from the mountain front north of the town of Villavicencio, where it starts to control the abrupt slope break that marks the limit between the piedmont and cordilleran belt of the Eastern Cordillera and where it is known as the Guaicáramo Fault that has dominant reverse and thrust fault characteristics.

6. The Agrado–Hobo Western Branch Fault

Between the municipality of San Agustín, situated 23 km to the west of Pitalito, and the village of El Paraíso to the northeast of the Algeciras valley, stretches the western branch of

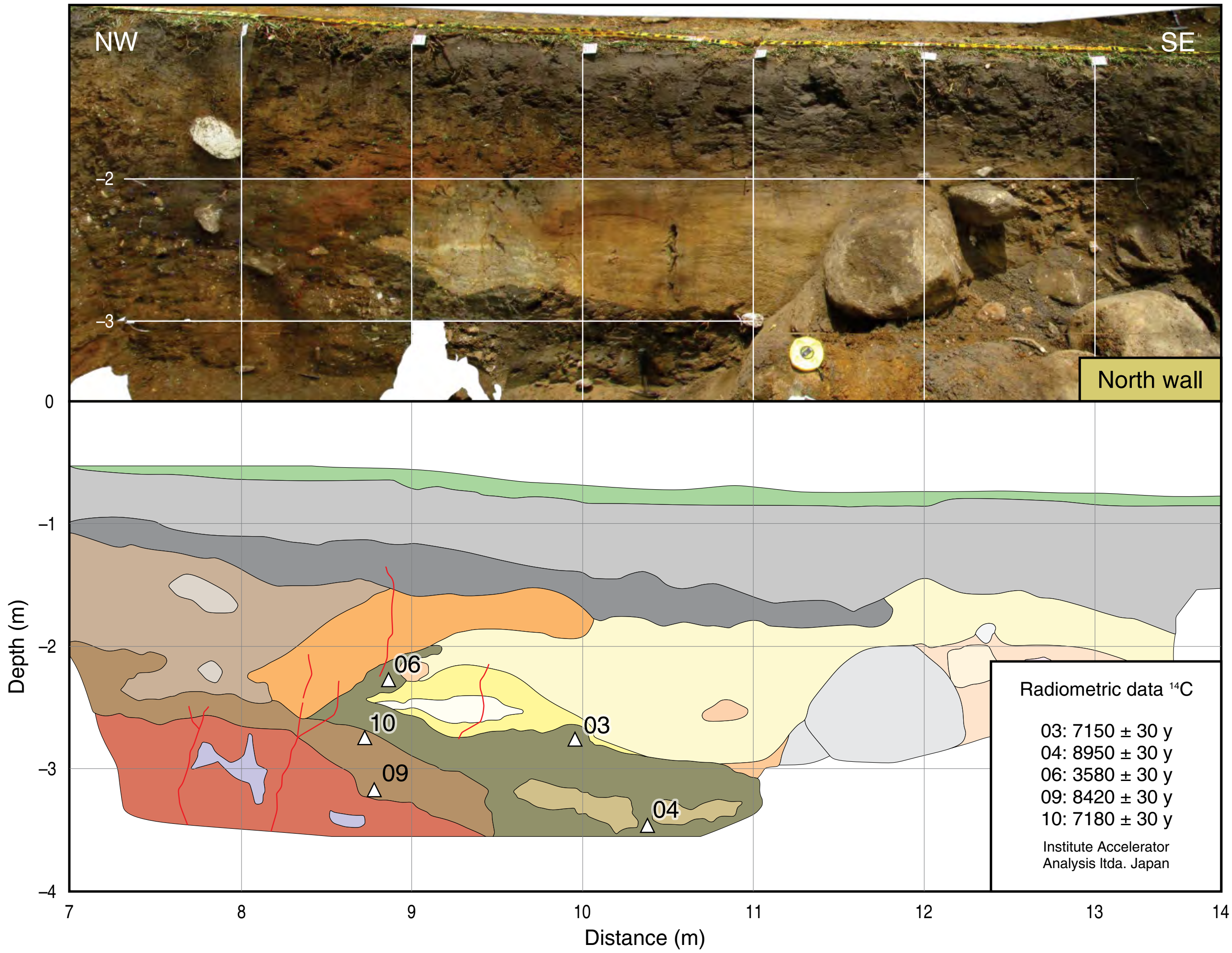

Figure 13. Photo and log of the north wall of the Lagunillas trench. The approximate position of the fault trace is marked by the red oxidation zone that indicates the presence of an open crack produced by fault activity. No fault trace has been identified. Numbers refer to sample positions with age dating analyses of ^{14}C indicated.

the AFS. It branches off from the main Algeciras Fault at San Agustín and converges again 170 km to the northeast with the main fault near the village of El Paraíso (Figure 5). This branch fault passes close to the town of Agrado, where a small sag pond has been observed along its trace. Further to the northeast the fault passes 2 km south of the town of Hobo, where it has been identified by Guillande (1988) as a left lateral strike–slip fault (Chorowicz et al., 1996; Guillande, 1988) although that is not certain (Figure 5) because morphotectonic and geological evidence encountered along the fault trace further to the southwest, between the towns of Tarqui and Agrado, bears witness to right lateral fault. Along its southwestern extension it has a pronounced morphologic expression on aerospace imagery, as it follows the course of the Magdalena River of which it controls straight stream segments. Emerging from the Magdalena River valley, west of the small town of Tarqui, the fault displays numerous morphotectonic features such as stream offsets and deflections, stream control and rake–like drainage patterns, aligned fault saddles, uphill facing scarps in Quaternary terrace deposits, and triangular facets (Figure 16), all of which combined provide evidence of recent or at least Quaternary activity of this fault. A remarkable extensive and resistant ridge of Eocene Gualanday Conglomerates and sandstones running in a N–S direction west of the town of Tarqui, has been offset right laterally over a distance of 10 km where its continuation crops out near the town of Agrado. Close to the village of El Paraíso at its northeastern extreme the fault trace acquires strong visibility on aerospace imagery because of the alignment of deeply incised V–shaped longitudinal valleys. Near the confluence of the Páez River with the Magdalena River the fault passes practically across the footprint of the dam wall of El Quimbo hydroelectric scheme, where horizontally striated slickenside

Figure 14. Road outcrop of the vertical fault plane of the main branch of Algeciras Fault that puts in contact Proterozoic gneisses of the Garzón Massif on the left with coarse Pleistocene gravels on the right. View to the south.

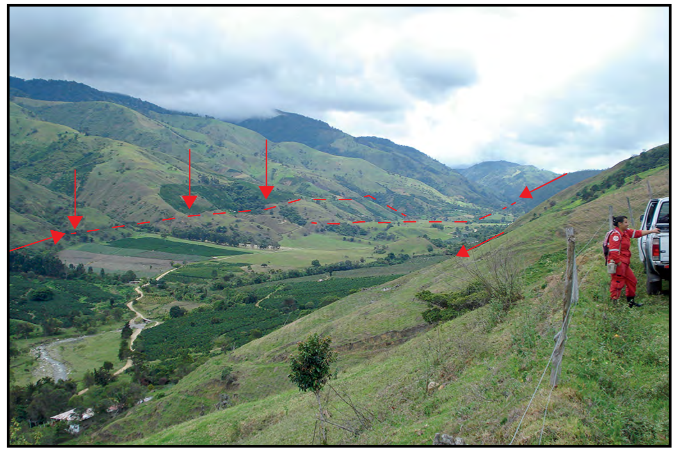

Figure 15. View to the north of El Paraíso pull–apart basin. Position of controlling fault has been indicated.

surfaces are rather abundantly visible in road outcrops of the conglomerates and sandstones of the Eocene Gualanday Formation, marking the passage of the fault (Figure 17). The actual slip rate of this fault could not yet be established, but judging by its morphologic expression, and comparing it with that of the main branch of Algeciras Fault it must be considerably less than that and probably be in the order of 1–2 mm/y.

7. The Suaza Fault System Eastern Branch Fault

The valley of the Suaza River is a narrow one that extends in a NNE–SSW direction over a distance of 40 km from the small town of Acevedo in the south to the village of Suaza in the north (Figure 5). It is controlled by the Suaza Fault and its satellites, a fault system that stretches from its convergence with the main branch of Algeciras Fault near the village of Zuluaga in the north (Figure 5) to the area of Mocoa town in the south where it merges again with the main branch of Algeciras Fault, locally known as the Aucuyaco Fault, near the valley of Sibundoy, covering a total distance of 225 km. The nature and genesis of the Suaza valley and its control by the eastern branch system of the AFS is still a puzzle. Some authors have referred to it as being a pull–apart basin with greatest depth of 3 km at its northern end (van der Wiel, 1991), but such extreme depth seems highly unlikely. However, to the north of the Suaza village the wide valley of the town of Guadalupe could be the result of pull apart processes along a wide right hand releasing bend of the Suaza Fault before it enters the canyon that abuts against a large shutterridge along the main branch of Algeciras Fault that displaces the fault and the canyon dextrally over a distance of 4.4 km. Beyond this shutterridge the Suaza River resumes its northward course to its confluence with the Magdalena River at the village of La Jagua. As the Algeciras Fault has a much higher slip rate than the Suaza Fault this situation might have provoked a kinematic readjustment of the north end of the Suaza Fault that took an easterly trajectory to come out at the village of Zuluaga where it now joins the main branch of Algeciras Fault (Figure 5).

Both margins of the Suaza valley appear to be controlled by faults of the eastern branch system: The Acevedo Fault in the west and the east Suaza Fault in the east. In the center of the valley, and in large part following the streambed of the Suaza River, is the Suaza Fault proper. Furthermore, within the confines of the bounding faults, the Cenozoic deposits of the Gualanday, Gigante, Picuma, and Las Vueltas Formations (van der Wiel, 1991) are dipping steeply to the west on the west bank and to the east on the east bank forming a narrow anticlinal structure with a total width in the order of 7 km with the central part of the anticline having been eroded. What we see at present is a situation of inverted relief of an anticlinal valley in which the alluvial floodplain belt is very restricted in width. Although the Suaza valley stands out well morphologically on DEM imagery, the same cannot be said of the controlling faults that have a rather weak morphologic expression, due, in the case of the Suaza Fault proper, to the fact that its trace follows for the greater part the stream course of the Suaza River, thus reducing its visibility on imagery. Evidence of strike–slip displacement along the Suaza Fault was found north of Suaza village in a road cut in Quaternary deposits (Figure 18) and further to the south a few kilometers before reaching the town of Acevedo in outcrops of the Picuma Formation sandstones and conglomerates (van der Wiel, 1991) that display slightly oblique fault striae. No slip rate could be established so far as no reference

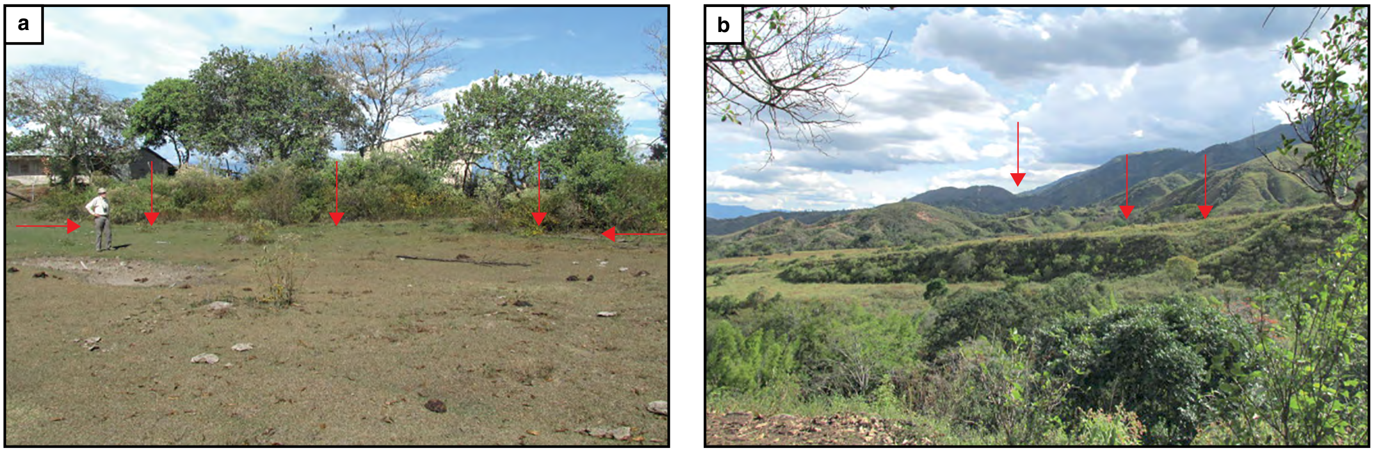

Figure 16. Morphotectonic expression of the Agrado Fault with **(a)** small uphill facing scarp in alluvial fan deposits in westward view, and **(b)** fault saddle, triangular facets, and alluvial fan in southward view.

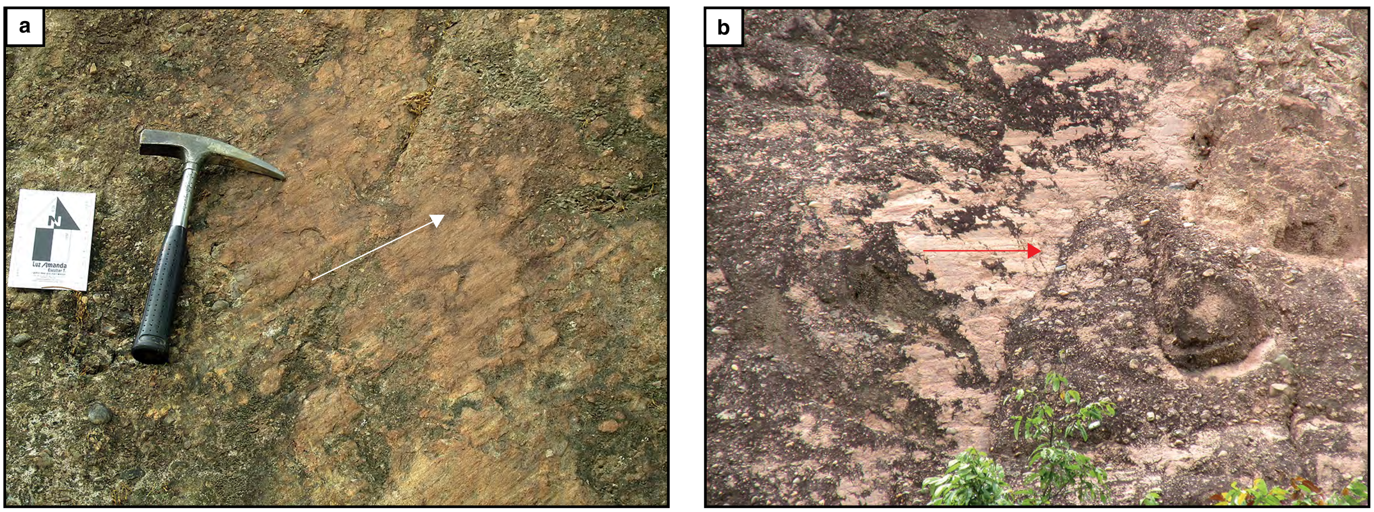

Figure 17. (a, b) Slickenside surfaces with oblique to horizontal striae in conglomeratic sandstones of the Eocene Gualanday Formation along the Agrado Fault, close to El Quimbo dam wall.

geomorphic or morphotectonic markers could be identified for measuring displacement distances, and no ages for the dating of relevant alluvial deposits are available.

8. Tectonic Aspects

The AFS, together with the Guaicáramo Thrust Fault System along the Llanos border of the Eastern Cordillera, the Boconó Fault System of the Mérida Andes in Venezuela, and the more fragmented Pallatanga–Chingual–La Sofía Fault System in Ecuador (Tibaldi et al., 2007), constitute the North Andean transform belt along which the North Andean Block is being displaced to the NNE at a rate of 8.6 mm/y in a process of tectonic escape (Alvarado et al., 2016; Audemard, 1993, 2014; Baize et al., 2014; Egbue & Kellogg, 2010; Eguez et al., 2003; Mora–Páez et al., 2016, 2019; Nocquet et al., 2014; Pennington, 1981; Sengör et al., 1985; Sylvester, 1988; Tibaldi & Ferrari, 1992). It is the most important active intraplate, or probably better defined as an interplate, fault system in Colombia and along its southern half responsible for the most damaging historic earthquakes during the last 250 years (Cifuentes & Sarabia, 2009; Dimaté et al., 2005; Ramírez, 2004; Sarabia et al., 2006; Velandia et al., 2005). The history of activity of this fault system goes back much further, possibly to 20 Ma. Evidence of early activity is related principally to episodes of cordilleran uplift. Thus the Precambrian Garzón Massif whose western margin is situated along the Algeciras Fault, has been uplifted since 20 Ma, with two notorious phases of accelerated uplift dated at 12.5 and 6.4 Ma (Anderson et al., 2016; Egbue & Kellogg, 2010; Gregory–Wodzicki, 2000; Kroonenberg et al., 1990; Ramírez et al., 2015; Saeid et al., 2017; van der Wiel, 1991). Saeid et al. (2017) postulate a phase of considerable range–normal shortening in this sector of the Central and Eastern Cordillera of 45 km that caused major uplift of the Garzón

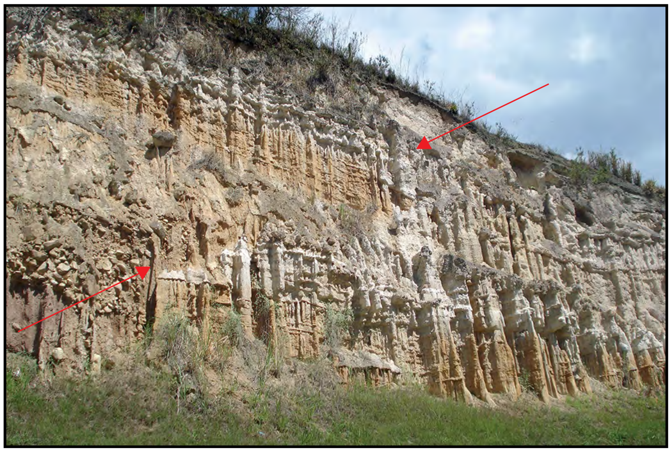

Figure 18. Road cut in Pleistocene fan deposit in the Suaza valley cut obliquely by the Suaza Fault. View to the south.

Massif along a low angle (12–17°) thrust plane. Others, like Butler & Schamel (1988), Diederix & Gómez (1991), Ramírez et al. (2015), and Velandia et al. (2005) suggest high angle reverse faulting. The low angle thrusting reported by Saeid et al. (2017) is based on seismic profiles and an exploratory borehole that has pierced rocks of the Garzón Massif and reached cretaceous formations underneath. They refer to this thrust fault as being the Garzón Fault, first mentioned as such by Chorowicz et al. (1996) and Guillande (1988), but this fault is the same as the Algeciras Fault main branch described by Diederix & Romero (2009), Velandia et al. (2005), and Vergara (1996). In fact all fault names refer to one and the same fault. It seems difficult to reconcile this Miocene low angle thrusting with the present strike–slip horizontal displacement along the subvertical main branch of Algeciras Fault of which there is abundant, geological, geomorphological, seismological, and satellite geodesic evidence. It would mean a process of extreme thrust fault verticalization during or shortly after a phase of orogen normal shortening. We therefore think that the Garzón Thrust and the main branch of Algeciras Fault are not the same, but happen to coincide at surface where there is only one almost straight fault trace running over a considerable distance. Arguments for this could be the re–interpretation of the seismic line, used by Saeid et al. (2017), that shows a possible vertical discontinuity to great depth that might well represent the Algeciras Fault. Furthermore, at surface, there is a divergence of fault traces south of the municipality of Garzón where the Suaza River breaches the fault trace of the main branch of Algeciras Fault. The trace of the main fault branch is seen to continue in the same southwest direction, whereas the thrust faulted limit of the Garzón Massif takes a turn to the south (Figure 5; Diederix & Gómez, 1991). The only alternative would be a strike–slip Garzón/Algeciras Fault with a high angle reverse component. van der Wiel (1991) reports a strong uplift phase of 6.5 km and exhumation of the massif that occurred between 6.4 and 3.3 Ma. She supports this by the sudden appearance of clasts of Precambrian metamorphic rocks in gravels of the upper Gigante Formation and the upper Pliocene Las Vueltas Formation (van der Wiel, 1991) that was deposited along the western rim of the massif in the Upper Magdalena Valley. Strike–slip displacement of the Algeciras Fault seems to have initiated 4.5 Ma before present according to Bakker (1990) who took this date as the beginning of the opening of the Pitalito Basin as a pull–apart structure along a releasing bend of the main branch of Algeciras Fault. This agrees quite well with the suggestion of Audemard (1993) that the opening of the Jambelí Graben in the Gulf of Guayaquil could well have been the initiation of the tectonic escape of the NAB. Other authors, who have worked in the area of the Gulf of Guayaquil in Ecuador, suggest even younger ages of 2.0–1.5 Ma for the initiation of movement of the AFS (Alvarado et al., 2016; Anderson et al., 2016; Audemard, 2014; Baize et al., 2014; Ferrari & Tibaldi, 1992; Gutscher et al., 1999; Nocquet et al., 2014; Tibaldi & Ferrari, 1991; Witt et al., 2006). They relate the initiation to the opening of the Jambelí Graben in the Gulf of Guayaquil as the start of the fault movement and the NNE tectonic escape of the NAB (Audemard, 1993). They consider this opening of the gulf to be the result of shallow low angle subduction of the Carnegie Ridge below the Andean mainland of Ecuador and southern Colombia acting as a rigid indenter that impulsed this tectonic escape of the NAB with right lateral movement along the Eastern Frontal Fault System of which the AFS is such an important element (Alvarado et al., 2016; Anderson et al., 2016; Audemard, 2014; Baize et al., 2014; Gutscher et al., 1999; Velandia et al., 2005).

Collision of the Panamá–Baudó Arc indenter is considered to have occurred in middle Miocene times, approximately 12 Ma ago, that has produced a strong push in easterly or NNE direction that caused the main shortening and uplift of the Eastern Cordillera (Audemard, 1993, 2014; Kellogg & Vega, 1995; Vargas & Mann, 2013) and has been indicated as the main pulse for promoting the escape of the NAB or at least a contributing force to that process (Audemard, 2014). The slightly more ENE orientation of the velocity field of GPS vectors that can be observed north of latitude 7° N, suggests the influence of a W–E push that add an E–W component to the NNE movement of the NAB (Figure 3; Mora–Páez et al., 2019). The consensus opinion is that the oblique Nazca Plate convergence with South America is the controlling factor for slip partitioning and the escape of the NAB and whatever the precise date for the beginning of the displacement of the NAB by means of movement of the fault system, a fact is that the AFS in all its morphological characteristics provides us with convincing evidence of recent and ongoing dextral strike–slip movement, that until now has not been possible to be quantified, but could well be in the range of 10 mm/y in analogy to the values for slip rate obtained of its trajectories in Ecuador (Alvarado et al., 2016; Baize et al., 2014; Ego et al., 1996; Nocquet et al., 2014; Tibaldi & Ferrari, 1992; Tibaldi et al., 2007) and Venezuela (Audemard, 2014, 2016; Pousse–Beltran et al., 2017).

The presence of a number of at least 6 tectonic basins or pull–apart basins along the main branch of Algeciras Fault distributed over a distance of 220 km suggests a local transtensive stress regime in a setting of a generally E–W oriented compressive stress field, that is a consequence of the oblique convergence of the Nazca Plate. These pull–apart basins could thus be interpreted to represent the negative flower structures associated with releasing bends or releasing step–overs along the fault as certainly is the case of the Algeciras Basin. On the other hand, it is also feasible that the geometry of a crustal wedge or microplate, in this case the NAB, in a process of tectonic expulsion by transcurrent slip movement along a crustal transform fault belt, the Eastern Frontal Fault System (Alvarado et al., 2016; Audemard, 2014; Baize et al., 2014; Egbue & Kellogg, 2010; Mora–Páez et al., 2016, 2019; Nocquet et al., 2014), creates local transtensional regimes that can lead to the formation of pull–apart basins, as seems to be the case with the North Anatolian Fault in Turkey (Aydin & Nur, 1982; Sengör et al., 1985).

Another phenomenon possibly related to these transtensional environments is the presence of an alkali–basaltic volcanic province. Volcanic fields of this type occur along the western rim of the fault system in the vicinity of the town of San Agustín and the village of San José de Isnos, where a number of small volcanic cones and lava flows cover a surface area of approximately 200 km^2 (Kroonenberg & Diederix, 1982; Kroonenberg et al., 1982, 1987). Further to the south along the western rim of the fault system between the southwest point of the Sibundoy Basin and the eastern margin of La Cocha Lake a similar field of probably the same type of monogenetic volcanism is present in which 7 volcanic cones have been identified so far in a field covering 100 km^2. Along the eastern rim of the AFS in the valley of the Suaza River close to the town of Acevedo, where the trace of the Suaza Fault locally follows the stream bed of the river, a large area of alkali olivine basalt crops out (Kroonenberg & Diederix, 1982; Kroonenberg et al., 1982, 1987). No eruption centers have been identified until Monsalve–Bustamante et al. (2020). These basalt flows cover a surface area of 50 km^2. This type of monogenetic alkali–basaltic volcanism points to a possible source in the mantle (Kroonenberg et al., 1982, 1987). The same transtensional stress environment that is associated with the AFS as part of a deep reaching transform fault belt that acts as a facilitator of escape movement of the crustal wedge of the NAB, could also create the space for the rise of magma from mantle sources. Another explanation for the mantle origin of this ultrabasic volcanism is suggested also by Kroonenberg et al. (1987), and recently worked out in more depth by Idárraga–García et al. (2016), is the possibility of subduction of the fossil Malpelo spreading ridge in this sector of the cordilleras. A real possibility exists that more occurrences of this type of volcanism will be discovered in the future and be associated with the Algeciras Fault or other strike–slip fault systems. Interestingly, more recently a rather similar type of basic volcanism has been discovered much further to the north close to the dextral strike–slip Ibagué Fault (Diederix et al., 2006; Montes et al., 2005; Osorio et al., 2008) in the east flank of the Central Cordillera in the Tolima Department (Núñez et al., 2001).

It has already been observed that the northward continuation of the AFS starts at latitude 2° 40' N at the Balsillas Basin where a fan like fault branching begins with the westernmost branch connecting northwards with the Bogotá Fault System, the easternmost branch, on leaving the cordillera, seeming to link up to the Meta Fault that obliquely traverses the Llanos Orientales plains to continue in Venezuela and, according to Audemard (2014), in the distant future might be the transform shortcut to the Caribbean. The central branches, beyond the northern limit of the basement highs of the Garzón Massif and the Quetame Massif, connect to the Guaicáramo Fault System. This fault system, product of tectonic rift inversion, is the central structure of the foreland fold and thrust belt that follows the foothills of the Eastern Cordillera and is known as a reverse and thrust fault system. However, there is evidence of strain partitioning into range normal and range parallel deformation indicated by the presence of right lateral fault branches in the system (Diederix et al., 2009; García et al., 2011). This is also corroborated by the NNE oriented velocity field of GPS vectors that confirms a notable strike–slip component along the eastern deformation front of the Eastern Cordillera thus underpinning it to be part of the transform deformation belt that connects the Nazca and Caribbean Plates.

9. Seismicity Associated with the AFS

Historic seismicity of the last 250 years in Colombia shows a register of at least 5 major seismic events: 1785 Putumayo, Mw 6.8; 1827 Altamira, Mw 7.3; 1834 Sibundoy, Mw 6.7; 1917 San Martín, Mw 6.8; 1967 Colombia (Huila), Mw 7.0. All five of these were superficial events of <30 km depth. The strongest one of these events was the 1827 Altamira earthquake of Mw 7.3, with its epicenter in the northern sector of the Suaza valley not far to the east of the small town of Altamira, situated along the main trace of the Algeciras Fault. That event devastated the Huila Department with almost all of its towns and villages suffering major destruction and loss of life. Important secondary effects of this event were large landslides that dammed the Suaza, Mayo, and Honda Rivers which, in the case of the Suaza River, caused disastrous flooding downstream along the Magdalena River all the way down to the towns of Honda and La Dorada as a result of efforts to engineer a passway for draining the dammed valley which had engulfed the town of Guadalupe (Dimaté et al., 2005; Ramírez, 2004; Romero et al., 2009;

Sarabia et al., 2006). More recently, on the 9 February 1967, an earthquake of Mw 7.0 with epicenter near the hamlet of Vega de Oriente, situated close to the trace of the main Algeciras Fault, 15 km SE of the municipality of Colombia (Huila Department), destroyed the villages of Campoalegre, Colombia, Algeciras, and El Paraíso and caused a great deal of damage further afield in the Huila Department, like Neiva, Pitalito, Garzón, and even as far as Bogotá, Capital District of Colombia (Dimaté et al., 2005; Ramírez, 2004; Sarabia et al., 2006). Landslides were very common during this and the 1827 event, and can still be identified on aerial photos of much later date as well as in the field. Other phenomena like surface cracks and liquefaction were abundantly reported (Cifuentes & Sarabia, 2009).

The map of Figure 19 shows the plots of all seismic events registered in the period 1993 to 2017 by the Red Sismológica Nacional de Colombia (RSNC) of the Servicio Geológico Colombiano (SGC), along the AFS and include approximately 8000 events, 95% of which had a depth of less than 30 km and magnitudes Ml less than 3.0. Only 5% had a magnitude of Ml 3.0 to 5.7. These seismic events have a distribution from south to north as follows: Starting at the Ecuadorian frontier it follows towards the north the east flank of the Central Cordillera in the Nariño and Putumayo Departments, to continue in the Upper Magdalena Valley in the Huila Department, passing through the towns of San Agustín, Pitalito, Timaná, Altamira, Garzón, Agrado, and Gigante. Beyond the latter it switches over to the axis of the Cordillera Oriental passing through the towns of Zuluaga, Arcadia, Algeciras, El Paraíso, Balsillas, and the Páramo of Los Picachos to continue to the village of La Uribe in the east and Colombia in the west, indicating its arrival in the zone where the AFS starts to branch out towards the northeast. In the Cundinamarca Department seismicity follows the eastern foothills of the Eastern Cordillera where the system is known as the Guaicáramo Fault System (Bayona et al., 2008; Dimaté et al., 2005; Mora et al., 2010). The maximum width of the seismic belt reaches 100 km and has a total length of 700 km (Figure 19). The location of epicenters has a high degree of reliability as it is based on the signals of 60 permanent stations covering the national territory that permits high accuracy in positioning.

Figure 19 indicates that the distribution of the seismic events within the AFS is clustered in sectors of high and low density that appear to be correlated to the geometry of the trace of the main fault branch with the restraining bends representing zones of transpression with a high density of seismic events, and the releasing bends representing zones of transtension with a low density of seismic events, coinciding with the presence of pull–apart basins described above. The possibility exists that the zones of transtension with relative scarcity of seismic events experience a–seismic fault slip, as appears to be the case of the Algeciras Basin short–cut fault, where areas very close to the fault trace present surface fracturing orthogonal to the fault trace, which could well be the result of fault creep along the short–cut fault which is the product of the kinematic straightening out process of the original fault geometry of this pull–apart basin as described above.

A good example of seismic clustering appears to be the area around the village of Colombia (Figure 19), which in recent years has registered a number of seismic events with a maximum magnitude of Mw 5.7 and that seems to be associated with a western splay fault that branches off the AFS, known as the (wrongly named) Altamira Fault (wrong, because this fault has nothing to do with and is far removed from the small town of Altamira, after which apparently it has been named. A better name should be Rivera Fault, as already was suggested by Vergara (1996), which name refers to the small town that is well–known for its thermal springs that occur along the trace of this fault) that is a high angle reverse fault with a dextral strike–slip component. Figure 19 shows the distribution of epicenters and focal mechanisms as well as tensional stress tensors of some of the major magnitude events. In the lower part of the Figure you can observe the cross profiles and longitudinal profiles that present the concentration of hypocenters at an average depth of approximately 15 km with crustal rooting at a depth of 40 km.

10. Results

The results of the recent studies are rather preliminary as it concerns an ongoing research program of several years duration. Therefore only partial results can be presented here. The study is one of the first attempts to determine the extent and complexity of the AFS in southern Colombia. Field evidence includes the identification of geomorphic markers and morphotectonic indicators that are the basis for detailed neotectonic cartography that permit the characterization of individual faults and gives an indication of their degree of activity and their relation to present–day and historic seismicity. The nature of some of the pull–apart basins that characterize the strike–slip movement of the main fault has been analyzed and modeled. This applies to the Pitalito, Algeciras, and El Paraíso Basins, where the geometric shape of the basins and the outline of the controlling faults conform to the model of a releasing bend or step–over along strike–slip faults, while the presence of diagnostic morphotectonic indicators and geomorphic markers have been inventoried on aerospace imagery and in field observations. A first attempt at paleoseismologic study has been made in the Algeciras valley where two trenches have been excavated, one across the short-cut fault and the other one on the main fault branch. Results of ^{14}C laboratory analysis of 10 samples collected in the first trench have all yielded Holocene ages, but the invisibility of fault traces in the exploratory trenches due to the high plasticity of the clayey sediments that leads to their concealment, has precluded the identification of paleoseismic events and therefore no data on fault slip rate and recurrence intervals could be obtained with the possible exception of one paleoseismic

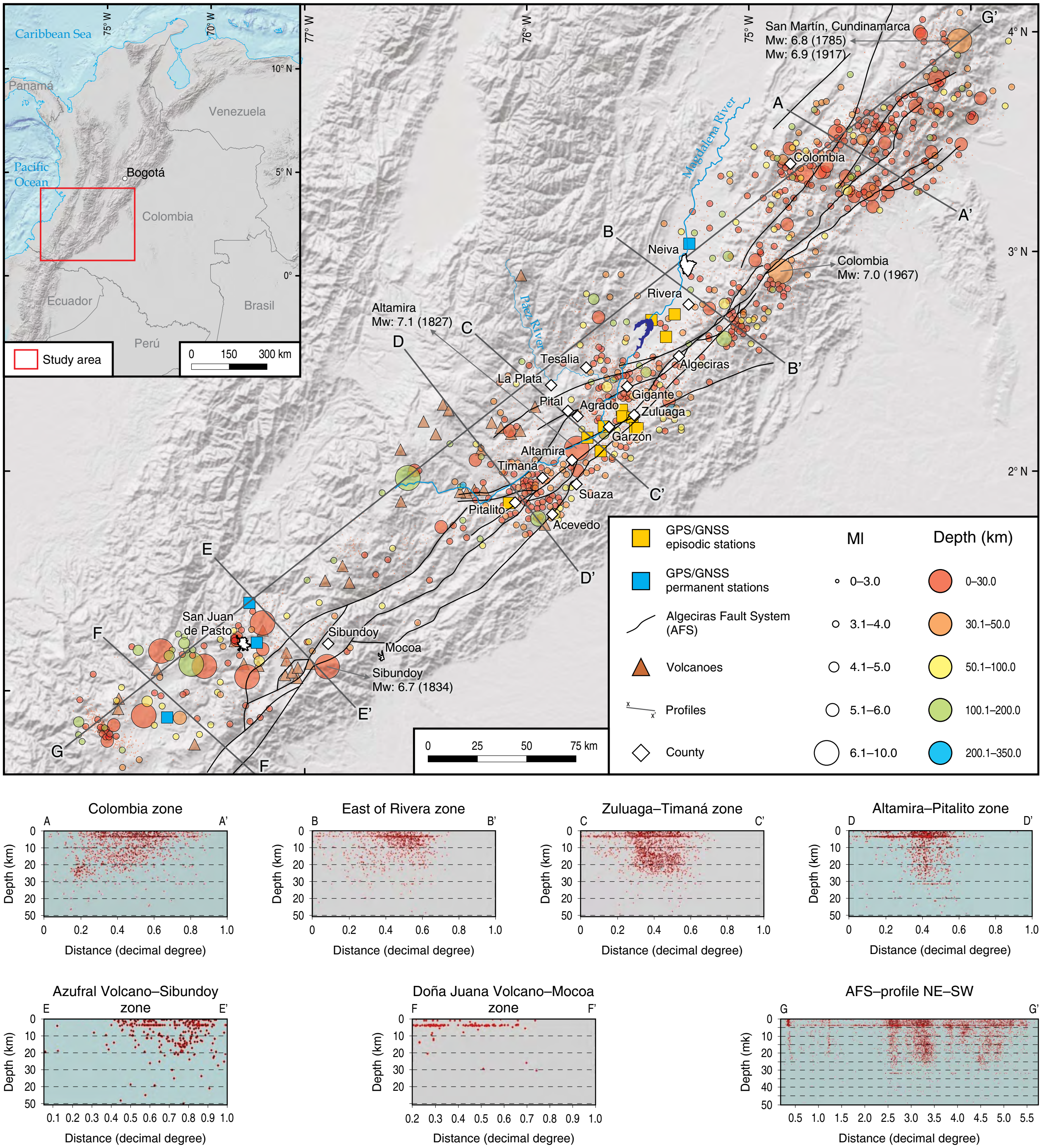

Figure 19. Plot of instrumental seismicity for the period 1993–2017 of the Algeciras Fault System with six cross profiles and one longitudinal profile.

event of an age about 1850 y BP, but with an unworkable time window of 1340 years. An alternative explanation for this has been sought in the possible condition of fault creep along the short cut fault that has some supporting evidence in the common presence of fractures and cracks oriented perpendicular to the fault trace seen at surface and in buildings within the zone of fault shear along the western limit of the town of Algeciras. On the other hand, the morphotectonic expression of the main branch of Algeciras Fault compares with the Boconó Fault in Venezuela that has a well–established slip rate in the order of 10 mm/y (Audemard, 2014, 2016; Audemard et al., 2006; Pousse–Beltran et al., 2017). Likewise, fault slip rate data for faults of the Ecuadorian side of the transform system have yielded similar results (Alvarado et al., 2016; Baize et al., 2014; Ferrari & Tibaldi, 1992; Tibaldi & Ferrari, 1991; Tibaldi et al., 2007). Based on these comparisons and recently obtained space geodesy data of 8.6 mm/y movement rate of the northward escape of the NAB it seems reasonable to postulate a similar slip rate for the Algeciras Fault. This would make the Algeciras Fault potentially the most important one in terms of seismic hazard in the interior of the Colombian territory.

The detailed neotectonic survey of the exact position, geometry, and morphology of the fault system has also facilitated its instrumentation by GPS field stations along cross fault profile swaths that, in a couple of years, will permit the monitoring of crustal elastic deformation resulting from fault movement that in the end will open a panorama of more reliable forecasting of future seismic activity.

11. Discussion

The AFS is a predominantly dextral strike–slip system that represents 500 km of the southern sector in Colombia of the North Andean boundary transform belt that connects the Nazca Plate in coastal Ecuador with the Caribbean Plate in northern Venezuela. This major fault system has been referred to in the literature usually as the Eastern Frontal Fault System. However, it is proposed to rename it the North Andean Boundary Fault, because this expresses better its manifestation in the Mérida Andes of Venezuela in the form of the Boconó Fault which runs more or less along the crest of the Mérida Andes, and also evades the suggestion that it is restricted to the eastern border zone of the Eastern Cordillera in Colombia and Ecuador. Along the part of the southern sector of this transform system in Colombia presently under study, the Proterozoic Garzón Massif has been uplifted in a process of apparently low angle thrusting in Miocene – Pliocene times in two phases: One around 12 Ma ago and a more recent one between 6.4 and 3 Ma (Anderson et al., 2016; Ramírez et al., 2015; Saeid et al., 2017; van der Wiel, 1991). During the Pliocene Epoch, from approximately 3 Ma onwards the major uplift and exhumation phase of the massif slowed down and movement along the main Algeciras Fault changed from low angle thrusting to dextral strike–slip movement along a subvertical fault plane (Anderson et al., 2016; Saeid et al., 2017). This timing of the beginning of strike–slip movement agrees with the opening of the Jambelí Graben in the Gulf of Guayaquil at approximately the same time and is considered to be caused by the obliquity of convergence of the Nazca Plate and the flat subduction of the Carnegie Ridge (Audemard, 1993, 2014; Egbue & Kellogg, 2010; Freymueller et al., 1993; Gutscher et al., 1999; Nocquet et al., 2014; Tibaldi & Ferrari, 1992; Tibaldi et al., 2007; Witt et al., 2006) that set in motion the tectonic escape to the NNE of the NAB, facilitated by right lateral sliding of the crustal block along the transform belt, including the AFS. However, it seems difficult to reconcile the present–day strike–slip fault along a subvertical major fault with the erstwhile low angle (12–17°) thrust movement along the same fault reported by Saeid et al. (2017). Nevertheless, the character of the AFS as a strike–slip fault system since Quaternary time is a well–established fact and abundantly supported by geological and geomorphological aerial photo observation and field evidence (Diederix & Romero, 2009; Page, 1986; Paris et al., 2000; Velandia et al., 2005; Vergara, 1996). We think that the solution to this apparent controversy, apart from accepting a process of extreme fault verticalization, lies in assuming the coincidence of two fault systems: The subvertical dextral strike–slip Algeciras Fault and a low angle Garzón Thrust Fault that upward converge and intersect the surface as one fault with one single fault trace that marks the western boundary of the uplifted Garzón Massif over a distance of 80 km.

The escape of the crustal wedge of the NAB at a velocity of 8.6 mm/y (Egbue & Kellogg, 2010; Freymueller et al., 1993; Mora–Páez et al., 2016, 2019; Pennington, 1981; Trenkamp et al., 2002) can provide an explanation for the creation of zones of transtension and the associated development of pull–apart basins in spite of the overall state of compression as a result of the oblique subduction of the Nazca Plate. The transtension associated with the escape of the crustal wedge could also have created space for the ascent of magma of the upper mantle that explains the occurrence of numerous pull–apart basins and the occurrence of Cenozoic alkali–basaltic to ultrabasic volcanism within the deformed belt of the AFS.

So far, 6 pull–apart basins have been identified along the length of the AFS, but not all six correspond strictly to the definition of pull–apart basin, but certainly have to be considered as being tectonic in origin. Each of these basins is of different shape and size and has a different kinematic and evolutionary history. Only three of these have been subjected to study that permitted its modeling: The Pitalito, Algeciras, and El Paraíso Basins. Of particular interest is the development of the Algeciras pull–apart basin, which originally seems to have occupied a much wider fault controlled valley. This, in subsequent stages narrowed down which eventually led to the complete kinematic straightening out of its original curvature by the development of a perfectly straight shortcut fault along the longitudinal diagonal of the spindle shaped basin and in future could lead to the complete disappearance of the basin (Reijs & McClay, 2003).

12. Conclusions

The main fault branch, and to a lesser extent the satellite faults of the AFS, show abundant morphotectonic evidence of Quaternary and recent activity to be seen both in the field and on aerospace imagery which displays an outstanding morphologic expression, that compares to the well–studied Boconó Fault in Venezuela, which is the northeastern segment of the North Andean transform belt, of which the slip rate has been well established as maximum 11 mm/y. It seems justified therefore to postulate a similar degree of activity and a similar slip rate in the order of 10 mm/y. However, the present state of knowledge of the AFS is still in a rather preliminary phase of study and it has not been possible yet to establish a quantified slip–rate based on unequivocal evidence of paleoseismic events. The occurrence of a number of pull–apart basins and the association of alkali–basaltic and ultrabasic volcanism of possible deep crustal or upper mantle affiliation are likely related to the development of transpressive regimes associated with the combination of fault geometry and sense of strike–slip fault movement, and to the creation of space resulting from the tectonic expulsion of a crustal wedge, the NAB. These are aspects of great interest that require a more detailed and profound study.

Important seismic activity in historic times that is ongoing today lends justice to the consideration that the AFS is probably the most dangerous fault in continental Colombia, capable of causing major magnitude earthquakes in the future. More detailed study is necessary to arrive at a more realistic quantification of slip rate and assessment of its seismic hazard. This will find support in the use of satellite geodesy technology that is being applied and developed by the GeoRED project of the SGC as part of the Dirección de Geoamenazas activities.

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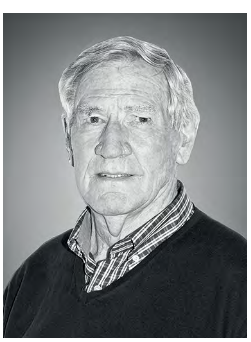
Explanation of Acronyms, Abbreviations, and Symbols:

AFS	Algeciras Fault System
ALOS PALSAR	Satellite radar system
CASA	Central and South America GPS Project
DEM	Digital elevation models
GeoRED	Grupo de Trabajo Investigaciones Geodésicas Espaciales
GPS	Global Position System
GNSS	Global Navigation Satellite System
JAXA	Japan Aerospace Exploration Agency
NAB	North Andean Block
NASA	National Aeronautics and Space Administration
RSNC	Red Sismológica Nacional de Colombia
SGC	Servicio Geológico Colombiano
SENTINEL	European satellite radar
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.

Olga Patricia BOHÓRQUEZ is a geological engineer with a degree from the Universidad Nacional de Colombia, Medellín and has over 30 years of experience in her field. She is also a specialist in land use planning and natural risk management at the Universidad de Caldas, Colombia. She is an expert in the exploration, design, and installation of seismic networks and GNSS stations for multipurpose geodetic investigations, as well as in the processing and analysis of seismological data and analysis of GNSS results. She has participated in the Servicio Geológico Colombiano for monitoring and research at the Observatorio Vulcanológico y Sismológico de Pasto and Manizales, the Red Sismológica Nacional de Colombia, and the Space Geodesy Research Group, under the umbrella of the GeoRED project, with which she is currently affiliated. She has also participated in neotectonic and paleoseismological investigations of several active faults in Colombia, such as the Silvia–Pijao, Villa María–Termales, Ibagué, Bucaramanga–Santa Marta, Aguas Calientes, and Algeciras Faults. She has served as an undergraduate thesis advisor in geology, physics, and geological engineering at Universidad Distrital Francisco José de Caldas and at Facultad de Ingeniería of the Universidad de Antioquia. She has coauthored several national and international scientific publications and is actively involved in the dissemination of scientific knowledge through conferences at various educational centers in Colombia.

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