KINEMATICS AND STRESS FIELD ANALYSIS FROM A MAJOR STRIKE-SLIP FAULT ON THE NORTHERN ANDES: THE PALESTINA FAULT SYSTEM

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ABSTRACT

The Palestina Fault System (PFS) corresponds to a poorly known series of correlative structures located on the eastern flank of the Central Cordillera (CC) of Colombia. It is originated in its southern segment as a transtensive system derived from the San Jerónimo Fault, then it continues for more than 500 km to the north until it ends in the San Lucas Range transpressive system. The nowadays active volcanism and major regional gold deposits present in the CC are related to these structures. The main Palestina fault trace is characterized by a NE strike along its southern portion, which becomes N-S in its northern end, influenced by the intrusion of the Cretaceous Antioquia Batholith. Different studies carried out along its main trace have shown different kinematics (left-lateral and right-lateral) that are thought to have been caused by a NW-SE stress field established since mid-Miocene. However, structural data collected along the study area, support recent theories that the actual stress regime established for the last 1-2 Ma correspond to an ENE-WSW maximum direction of compression. The data presented here indicate that the main Palestina Fault is an active, right-lateral strike-slip structure. The present observations also support that the left-lateral kinematics, previously reported, may have not been produced by an NW-SE stress field, but by the interaction between the convergence vectors (here presented) and the high sinuosity along the vertical fault plane of the main trace and the local influence of transversal faults.

Keywords: Palestina Fault System, Northern Andean Block, tectonics, fault kinematics, strike-slip tectonics, right-dihedra, paleo-stress tensor.

Author statement

Mónica Saldarriaga: Conceptualization, Investigation, Methodology, Writing - Original Draft, Visualization. **José Fernando Duque-Trujillo:** Conceptualization, Investigation, Methodology, Writing - Original Draft.

1. INTRODUCTION

The Northern Andean Block is the result of the interaction between the Nazca, South American and Caribbean plates, and the Costa Rica-Panamá microplate (Fig. 1), resulting in a complex transpressive tectonics dominated by tectonic blocks connected by strike-slip fault systems (Kroonenberg et al., 1990; Taboada et al., 2000; Syracuse et al., 2016; León et al., 2018; Mora-Páez et al., 2019).

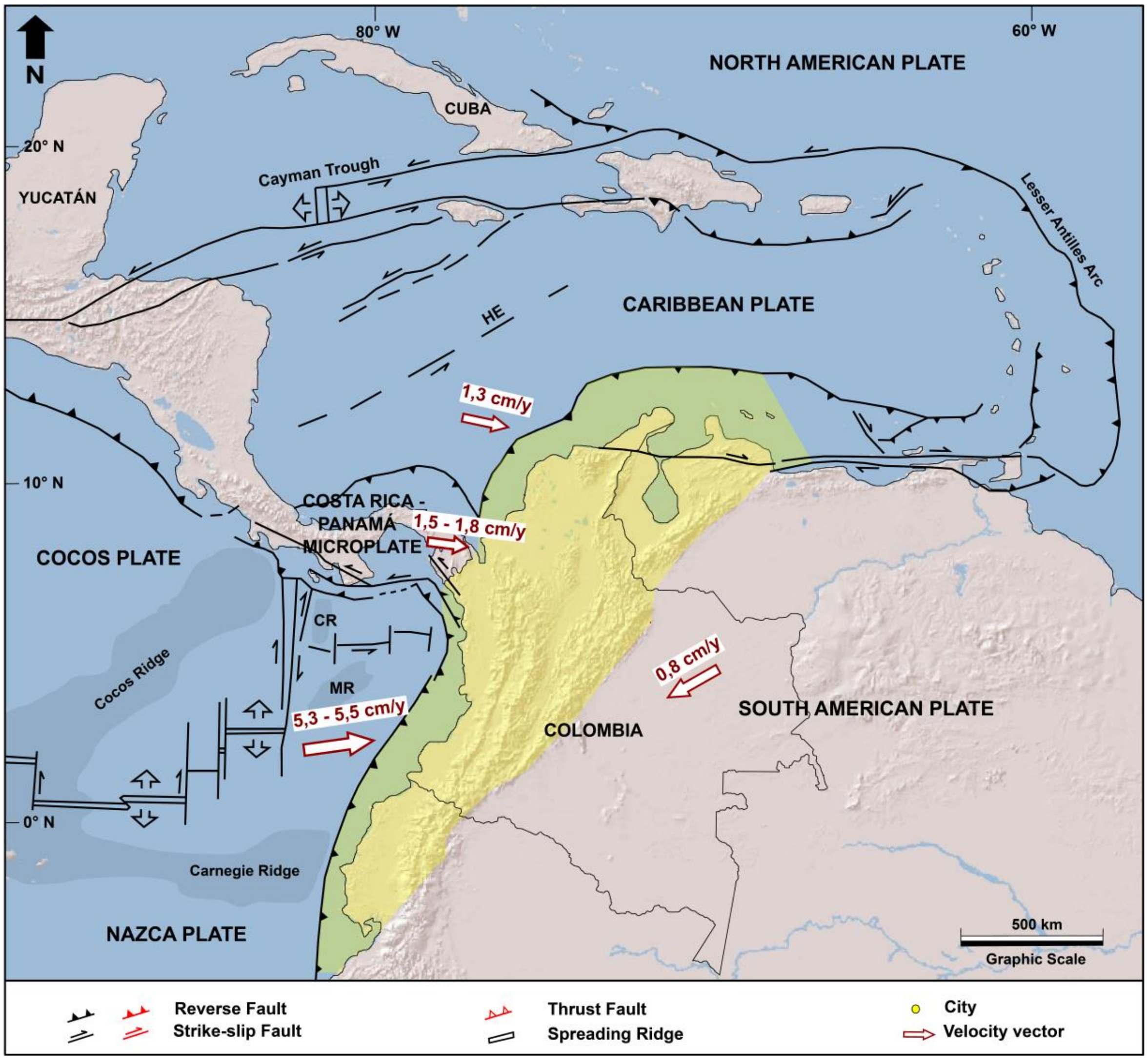

Figure 1. Regional tectonic plate setting for northwestern South America illustrating the Northern Andean Block (highlight in yellow). CR: Coiba Ridge, MR: Malpelo Ridge, HE: Hess Escarpment, Modified from Taboada et al. (2000); Cediel et al. (2003); Mora-Páez et al. (2019).

One of the main strike-slip structures along the Northern Andean Block in Colombia is the Palestina Fault System (PFS) (Fig. 2). Even though the PFS is recognized as an important fault system, it is not considered as a well-known structure and there is still a matter of debate regarding its latest kinematics and recent activity.

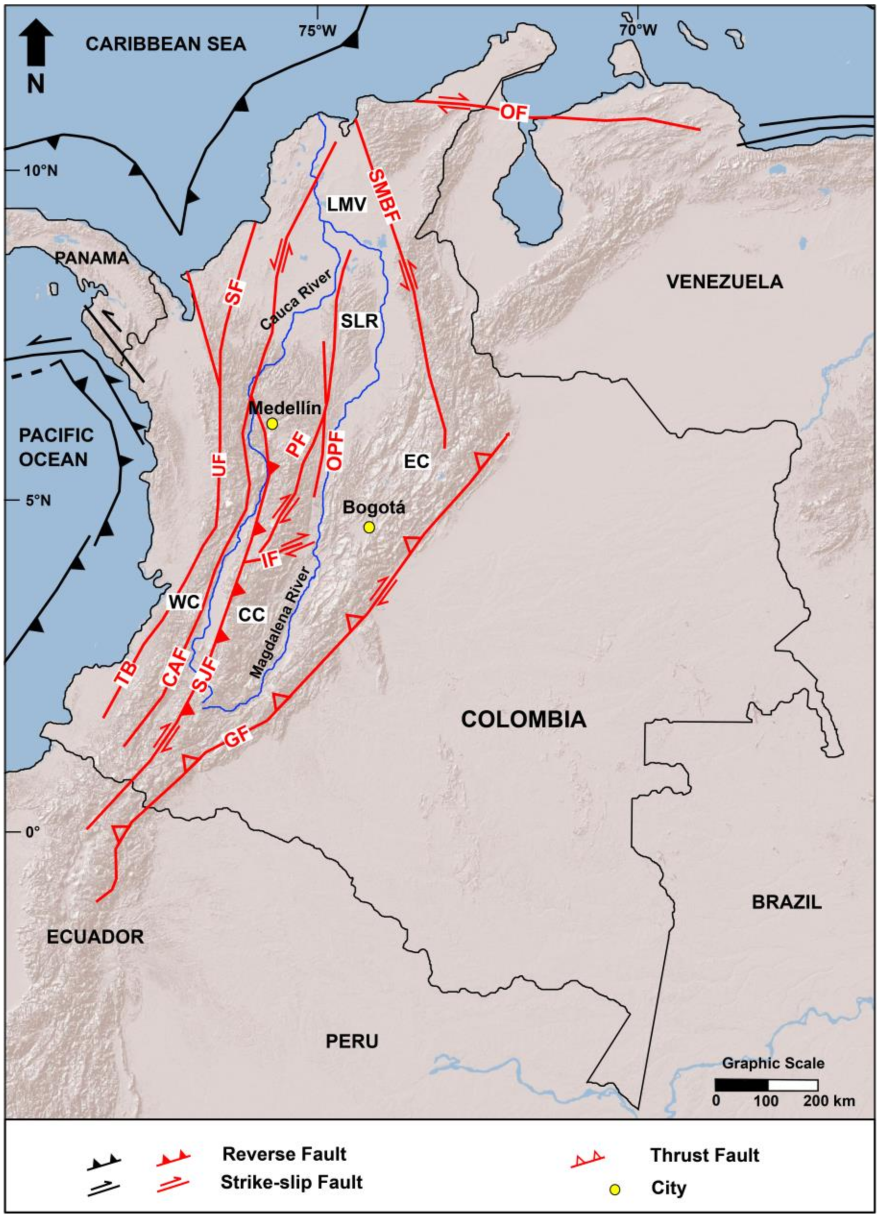

Figure 2. Main tectonic features of Colombia. WC: Western Cordillera, CC: Central Cordillera, EC: Eastern Cordillera, SLR: San Lucas Range, LMV: Lower Magdalena Valley. OF: Oca Fault, SMBF: Santa Marta-Bucaramanga Fault, GF: Guaicaramo Fault, IF: Ibagué Fault, PF: Palestina Fault, OPF: Otú-Pericos Fault, SJF: San Jerónimo Fault, CAF: Cauca-Almaguer Fault, TB: El Tambor Fault, UF: Uramita Fault, SF: Sinú Fault. Modified from Restrepo and Toussaint (1988); Taboada et al. (2000); Restrepo et al. (2011).

The PSF is a fault trace with at least 500 km in length, which runs almost along the whole Colombian Andes from Cajamarca town in the south to the San Lucas Range (SLR), before it is buried under the Cenozoic sedimentation of the Lower Magdalena Valley (LMV). This fault system mostly affects rocks from de Cajamarca Complex along the eastern flank of the Central Cordillera (CC), exhibiting a close relationship with the active volcanism and the presence of gold deposits.

Feininger (1970) defined the PFS as a wrench inactive fault with an almost vertical attitude and a right-lateral displacement of 27,7 km. The beginning of this fault system is a matter of debate.

Cortés et al. (2006) propose that it is originated as a transtensive system derived from the San Jerónimo Fault, a fault from the Romeral Fault System (RFS), slightly north of a major crustal structure known as the Ibagué Fault, also originated from the San Jerónimo fault.

The sense of the latest movements of the Palestina Fault is still a matter of debate, since different studies carried out along its trace have shown evidences of whether left-lateral and right-lateral, with normal and inverse components (Collins et al., 1981; Page, 1986; Cortes, 1990; Paris et al., 2000; González, 2001; Mantilla et al., 2006; Mejía, 2012; Naranjo et al., 2018; García-Delgado and Velandia, 2019), which are supported on two different theories about the actual stress regime that governs the Northern Andes (Ego et al., 1996; Taboada et al., 2000; Colmenares and Zoback, 2003; Corredor, 2003; Acosta et al., 2004; Mora-Páez et al.; 2019).

The present work use fault kinematics, morphotectonic features and compilation of existing information to reconstruct the paleostress-tensor and kinematics of the main trace of the PFS and associated structures at two different sectors located in the central and north segments of de system, at the Antioquia Department.

2. GEOLOGICAL SETTING

The Northern Andean Block in Colombia is constituted by three independent mountain ranges named, from west to east, as Western Cordillera (WC), Central Cordillera (CC) and Eastern Cordillera (EC), each one separated by intermontane valleys. The Cauca river separates the WC from the CC, meanwhile the Magdalena river separates the CC from the EC (Fig. 2). Each cordillera has been affected by different geologic and tectonic processes since Mesozoic times.

The EC is a bivergent fold-thrust system (Mora et al., 2010) formed by a Proterozoic continental basement (Restrepo-Pace et al., 1997; Cordani et al., 2005; Ordóñez-Carmona et al., 2006; Mora et al., 2010), that is unconformably overlain by Paleozoic continental rocks, clastic sedimentary rocks and thick shallow-marine deposits that were accumulated on a wide extensional basin since Jurassic until late Cretaceous times (Dengo and Covey, 1993; Sarmiento-Rojas et al., 2006; Ramirez-Arias et al., 2012).

The WC consists of an allochthonous Cretaceous oceanic plateau and island arc-related basement (Kerr et al., 1997; Kerr et al., 1998) consisting of ultramafic and mafic rocks along with volcano-sedimentary sequences (Marriner and Millward, 1984; McCourt et al., 1984; Millward et al., 1984; Duque-Caro, 1990; Restrepo and Toussaint, 1990; Nivia, 1996; Spadea and Espinosa, 1996; Kerr et al., 1997; Kerr et al., 1998; Kerr et al., 2004; Villagómez et al., 2011; Villagómez and Spikings, 2013; Spikings et al., 2015) that are locally covered by early Cretaceous continental sedimentary rocks (Abejorral Fm.) (González, 1980), and intruded by late Cretaceous to Cenozoic plutons that are subduction-related (Villagómez et al., 2011; Villagómez and Spikings, 2013). This allochthonous rocks have been accreted onto the western margin of South America since late Cretaceous (~75 Ma) (Aspden et al., 1987; Kerr et al., 2002; Villagómez and Spikings, 2013; Spikings et al., 2015) through the Miocene (~15 Ma) (Duque-Caro, 1990; Montes et al., 2015; Spikings et al., 2015; León et al., 2018).

The CC is located between the WC and EC, and so between the Cauca and Magdalena rivers (Fig. 3). It is formed by a Proterozoic (González, 2001) and Paleozoic basement (González, 2001; Ordoñez et al., 2002). This last one is mainly represented by the undifferentiated metamorphic rocks of the Cajamarca Complex (Maya and Gonzalez, 1995). Current magmatic activity related to the present subduction of the Nazca plate beneath South American plate is concentrated along the axis of the CC (Marriner and Millward, 1984; Taboada et al., 2000; Bohórquez et al., 2005; Monsalve et al., 2019), displaying important active volcanoes such as Galeras, Ruiz, Machín, Santa Isabel and Tolima.

The western flank of the CC corresponds to the widely deformed zone of the Romeral Fault System (RFS) which represents a Permo-Triassic paleo-margin that experienced repeated episodes of extension and compression through times (Vinasco, 2019), and now comprises major structures such as San Jerónimo, Silvia–Pijao, Romeral and Cauca-Almaguer Faults, all striking subparallel and intersecting with each other (Chicangana, 2005; Villagómez et al., 2011; Spikings et al., 2015). The Romeral Shear Zone (RSZ) is characterized by a tectonic mélange of autochhtonous to para-autochthonous rocks from both, continental and oceanic affinity (Page, 1986; Vinasco, 2019), that are mostly grouped into the volcano-sedimentary Quebradagrande Complex (Maya and Gonzalez, 1995; Nivia et al., 2006; Villagómez et al., 2011; Vinasco, 2019) and the metamorphic Arquía Complex (Restrepo and Toussaint, 1976; Bustamante et al., 2011; Bustamante et al., 2012; Villagómez and Spikings, 2013; Vinasco, 2019). It also includes the Tertiary Amagá and Combia Formations (González, 1980; Sierra et al., 2005; Sierra and Marín-Cerón, 2011; Vinasco, 2019).

Permo-Triassic granitic gneisses associated to the formation and break-up of Pangea (Vinasco et al., 2006; Villagómez et al., 2011; Cochrane et al., 2014; Spikings et al., 2015; Rodriguez et al., 2017) are dispersed throughout the cordillera, as well as several Jurassic to Paleogene continental arc-related plutons (Aspden et al., 1987; Bustamante et al., 2010; Leal-Mejía, 2011; Villagómez et al., 2011; Cochrane, 2013; Bustamante et al., 2017a; Bustamante et al., 2017b; Rodríguez et al., 2018; Duque et al., 2019; Bayona et al., 2020) and co-genetic volcanic components (Bayona et al., 1994; Bayona et al., 2020). Late Jurassic metamorphic rocks of oceanic affinity, previously classified as part of the Cajamarca Complex, have been identified in this flank of the CC (Blanco-Quintero et al., 2014; Bustamante et al., 2017a).

Among the main faults present in the CC, The Palestina Fault System (PFS), the object of interest of this study, is a poorly known strike-slip structure that is related to the nowadays active volcanism (González and Jaramillo, 2001 *in* Cárdenas et al., 2004; Acosta et al., 2007) and that has been considered by some authors, as part of an ancient suture (Restrepo and Toussaint, 1988; Toussaint et al., 1992; Cediel et al., 2003; Kennan and Pindell, 2009; Martens et al., 2014; Bustamante et al., 2017a; Cediel and Shaw, 2019).

The PFS begins near the town of Cajamarca (Tolima Department, located on the eastern flank of the CC), where it merges with the RFS (Cediel et al., 2003; Cárdenas et al., 2004; Kennan and Pindell, 2009); then it continues for more than 500 km to the north until it ends as a positive flower structure in the San Lucas Range (Bolivar Department)

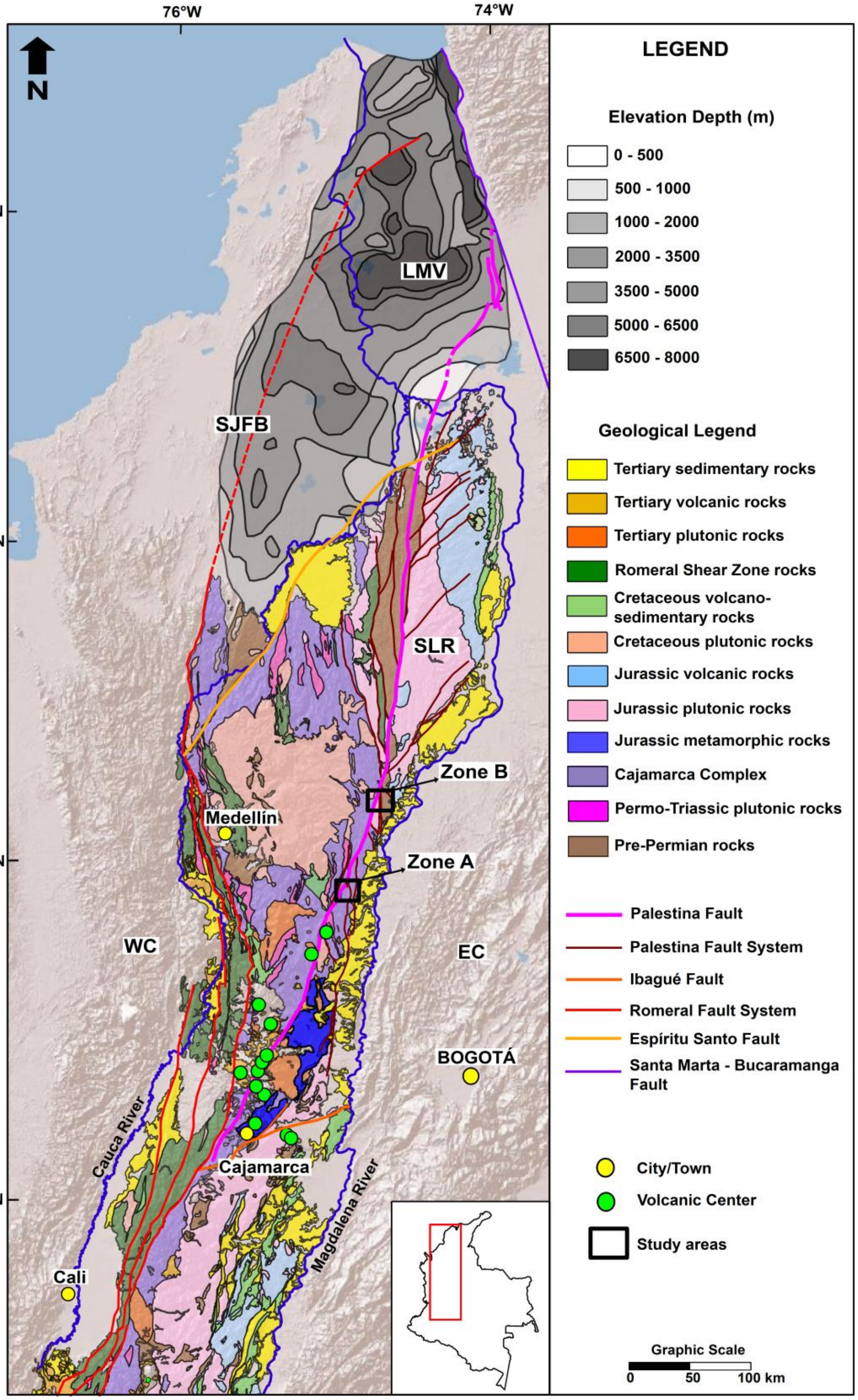

Figure 3. Simplified geology of the Central Cordillera of Colombia, the San Lucas Range (SLR) and the structural depth-model (elevation in meters) of the top of the basement of the Lower Magdalena Valley (LMV) and San Jacinto fold belt (SJFB). WC: Western Cordillera; EC: Eastern Cordillera. Modified from Gómez et al. (2015); Mora-Bohórquez et al. (2017) and Bustamante et al., 2017a.

(Feininger, 1970; Cárdenas et al., 2004; García-Delgado and Velandia, 2019); an isolated block that forms the northern termination of the CC.

The first studies regarding the Palestina main Fault and associated structures were carried out by Feininger (1970); Feininger et al. (1972) and Page, (1986) in the Antioquia Department. Recent studies are concentrated mostly in the south portion and the PFS and the SLR (Mantilla et al., 2006; Mejía, 2012; Naranjo et al., 2018; García-Delgado and Velandia, 2019), leaving the central segment with a lack of updated information.

In the Antioquia Department the influence of the PFS represented to SUMICOL S.A.S. (and its *spin-off* IACOL AGREGADOS S.A.S.) a challenge in the marble and schists mining project, which led to a series of private studies regarding this fault system. As part of that initiative, that zone was first defined as the study area. Due to difficulties in finding structural data, another zone was incorporated (Fig. 3). Therefore, the study area comprises two different zones (Fig. 4). The Zone A, locally known as Rio Claro sector, is where SUMICOL S.A.S. operates. It is located on the southeast corner of Antioquia, at 160 km from Medellín city. The Zone B, or Puerto Berrío sector, is located to the north, near the town of Puerto Berrío, at 180 km from Medellín city. In the Zone B is included the "Palestina stream", the original location where Feininger (1970) described the Palestina Fault.

The Rio Claro sector (Fig. 4A) is characterized by the presence of different metamorphic rock types that have been grouped as the Cajamarca Complex (González, 1980; Maya and Gonzalez, 1995; González, 2001). Here, these rocks include light grey to black marble; quartz, sericite, chlorite, feldespatic and graphite schists and gneisses; quartzites and amphibolites (Feininger et al., 1972; Gonzalez, 2001). A Paleozoic quartz-dioritic instrusive gneiss is present at the northwestern margin of the study area in faulted contact along the Cocorná Sur Fault with the Cajamarca Complex (González, 1980; Maya and Gonzalez, 1995; González, 2001). Cretaceous (?) quartz-feldespatic muscovite and garnet bearing pegmatitic intrusions have been identified mostly thanks to the drilling programs executed by SUMICOL S.A.S. in the southwest of the sector. Alluvial and colluvial Quaternary deposits are present mostly along the Claro river and Las Mercedes stream. In terms of structures, this sector has important faults associated to the PFS, such as Cocorná Sur, Mulato and Jetudo faults.

The Puerto Berrío sector (Fig. 4B) exhibits a more diverse geology. To the east of the main trace of the Palestina Fault, the Cajamarca Complex is represented by quartz and feldespatic gneisses, quartzites, amphibolites and small marble lenses (Maya and Gonzalez, 1995; González, 2001). These rocks are intruded by the Cretaceous quartz-diorite Antioquia Batholith (Duque et al., 2019). To the west of the main trace there are no rocks associated to the Cajamarca Complex. Bounded among the Palestina, Nus and El Bagre faults are a Jurassic dioritic intrusion and a Cretaceous volcano-sedimentary sequence composed by black shales, sandstones and conglomerates. Ordovician sandstones of La Cristalina Formation and the Proterozoic quartz-feldespatic San Lucas Gneiss are present in the eastern part of the sector (Feininger et al., 1972; Gonzalez, 2001; Fonseca et al., 2011).

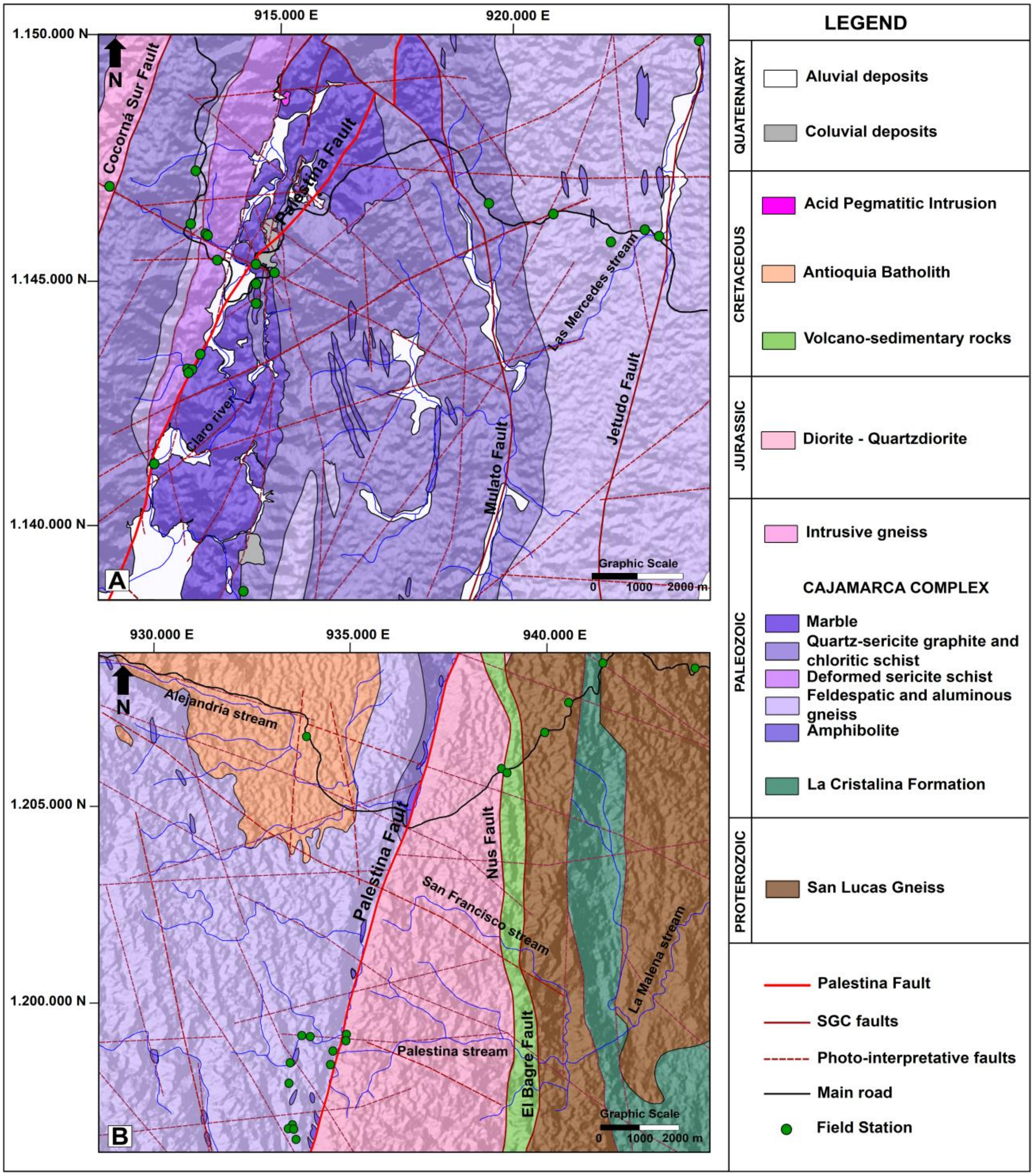

Figure 4. Geology of the Rio Claro **(A)** and Puerto Berrío **(B)** sectors. Modified from Feininger et al. (1970); Feininger et al. (1975); Fonseca et al. (2011).

3. METHODS

The first phase of this work consisted on the review of existing information regarding the PFS, regional geology, the different kinematic models of the Northern Andes and methodologies applied to determine the paleo-tensors and the stress field.

Between 2012 and 2016, SUMICOL S.A.S. conducted different private studies and drilling programs at the Rio Claro sector to produce detailed cartographic and morphotectonic information for the marble and schists mining project of IACOL AGREGADOS S.A.S. This information is part of the present work.

A photointerpretation of DEM and the subsequent hillshade images obtained from the SAR Datasets/ALOS-1 PALSAR; using satellite images with spatial resolution of 12,5 meters (NASA – Alaska Satellite Facility, 2019) was accomplished to identify features and local structures that are not contained in the official SGC (*Servicio Geológico Colombiano*) maps, although those are of great importance in the analysis of the Palestina Fault and its related structures.

A total of 174 fault plane data associated with the PFS was collected at outcrop scale in rocks older than Cretaceous during different field campaigns at Rio Claro and Puerto Berrío sectors. At the Rio Claro sector, the fault-slip data was mostly measure in schists and gneisses from the Cajamarca Complex; only a few were taken in the marble unit, since fault-slip data could be confused with dissolution marks in this type of rocks. Collected measurements consist on trend and plunge of slickenside kinematic indicators and the attitude of the fault plane containing them. The sense of shear was determined in many fault-planes using kinematic criteria described by Doblas (1998), resulting in 115 slickenside measured where the most common kinematic indicator were crescentic markings. Although many of the measurements were done on weathered rocks, the fault-slip data was well preserved and most of the data has good quality.

Fault kinematic tendency analysis was conducted based on the fault plane dip and slickenside plunge graphics (Duque-Trujillo et al., 2014). This plots are constructed based on the relationship between the fault plane dip and the striae plunge contained on each fault plane. The first step is to consider that a fault dip could be associated with a primary deformational regime (normal, inverse, or strike-slip) based on Anderson's classification of tectonic stress (Anderson, 1951). Then, the striae plunge is analyzed in order to constrain the fault slip direction along the striae containing plane. Striae structures which its plunge values are close to the maximum value in a plane (the dip value of each plane) are associated with vertical displacement faults (reverse or normal faults). Meanwhile, striae structures which have plunge values considerable lower compared to the plane dipping value are considered as faults with displacements mainly occurred along the fault-plane strike or close to it (strike-slip to oblique faults).

The data was graphed, analyzed and corrected using *Stereo 32* (Röller and Trepmann, 2003) and *TectonicsFP* software (Ortner et al., 2002) to produce rose diagrams, fault-slip data plots and dihedra density plot and stereogram (Fig. 5). Only three data were eliminated as the lineation differed more than 10° from the fault plane where those were measured.

The fault-slip data is used for stress inversion procedures to partly reconstruct the direction of the maximum resolved shear stress and inversely, the stress state that produced the kinematic indicator registered on a plane. The striae inversion process defines the reduced stress tensor associated to the principal stress axes ($\sigma1$, $\sigma2$ and $\sigma3$) (Delvaux and Sperner, 2003), here obtained by the right-dihedra method (Angelier 1979, 1984).

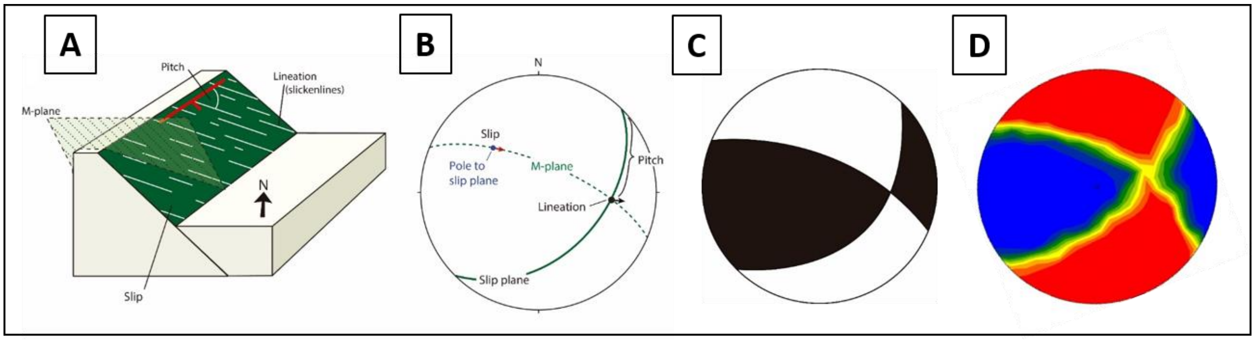

Figure 5. illustration of paleo-stress analysis **A:** schematic of fault-slip data measurements; **B:** Fault-slip data plotted in a steronet (*ej. Stereo32*); **C:** Right-dihedra stereogram figure; **D:** Dihedral density plot. Modified from Fossen (2010).

This method segments the fault plane into four dihedrals, where the boundaries correspond to the fault plane itself. The maximum stress (σ1) is contained inside one of the two compressive dihedrals, while the minimum stress (σ3) is contained inside one of the extensive dihedrals (Casas-Sainz et al., 1990). The resulting compression and tension areas are illustrated in a stereogram figure, called right-dihedral. The premise of this method is that if the same stress regime generates different fault planes, the σ1 and the σ3 should be common for all of them (Angelier, 1994).

4. THE PALESTINA FAULT SYSTEM

The Palestina Fault System (PFS) corresponds to a series of correlative structures located on the eastern flank of the CC of Colombia. The main Palestina Fault was first described by Feininger (1970), who defines it as a wrench inactive fault with an approximately N20°E strike, an almost vertical attitude and a right-lateral displacement of 27,7 km. It begins in the south, near the town of Cajamarca (Tolima Department) (Fig. 6) and continues to the northeast towards Caldas Department; together including other active faults, controls Pleistocene to present magmatic activity in the CC (González and Jaramillo, 2001 *in* Cárdenas et al., 2004; Acosta et al., 2007). Then, it goes through Antioquia and Bolivar Departments, where it has a northern vergence, forming the San Lucas Range transpressive system (Acosta et al., 2007; García-Delgado and Velandia, 2019). To its northern end, in the LMV, the PFS is covered by Quaternary deposits associated with La Mojana´s alluvial fan in the Momposina Depression, near the Mono and Violo streams (Feininger 1970; González et al. 2015). The presence of the PFS under these recent sediments has been interpreted by different geophysical methods (Mantilla et al., 2006; Mora-Bohórquez et al., 2017). Mora-Bohórquez et al. (2017) define the Palestina Fault as one of the southeast limits of the LMV, claiming that it separates two basements with different lithologies, ages and structural tendencies (Fig. 3).

Regional gold deposits are dispersed along the PFS main trace and associated faults (Fig. 6), which had control the precipitation of ore-forming minerals since early Jurassic times (Leal-Mejía 2011; Naranjo et al. 2018). Marble deposits associated with the Cajamarca Complex (González, 1980; Maya and Gonzalez, 1995; González, 2001), have been dismembered and displaced (Feininger, 1970; Feininger et al., 1972), allowing de juxtaposition of schists and gneisses with marble of

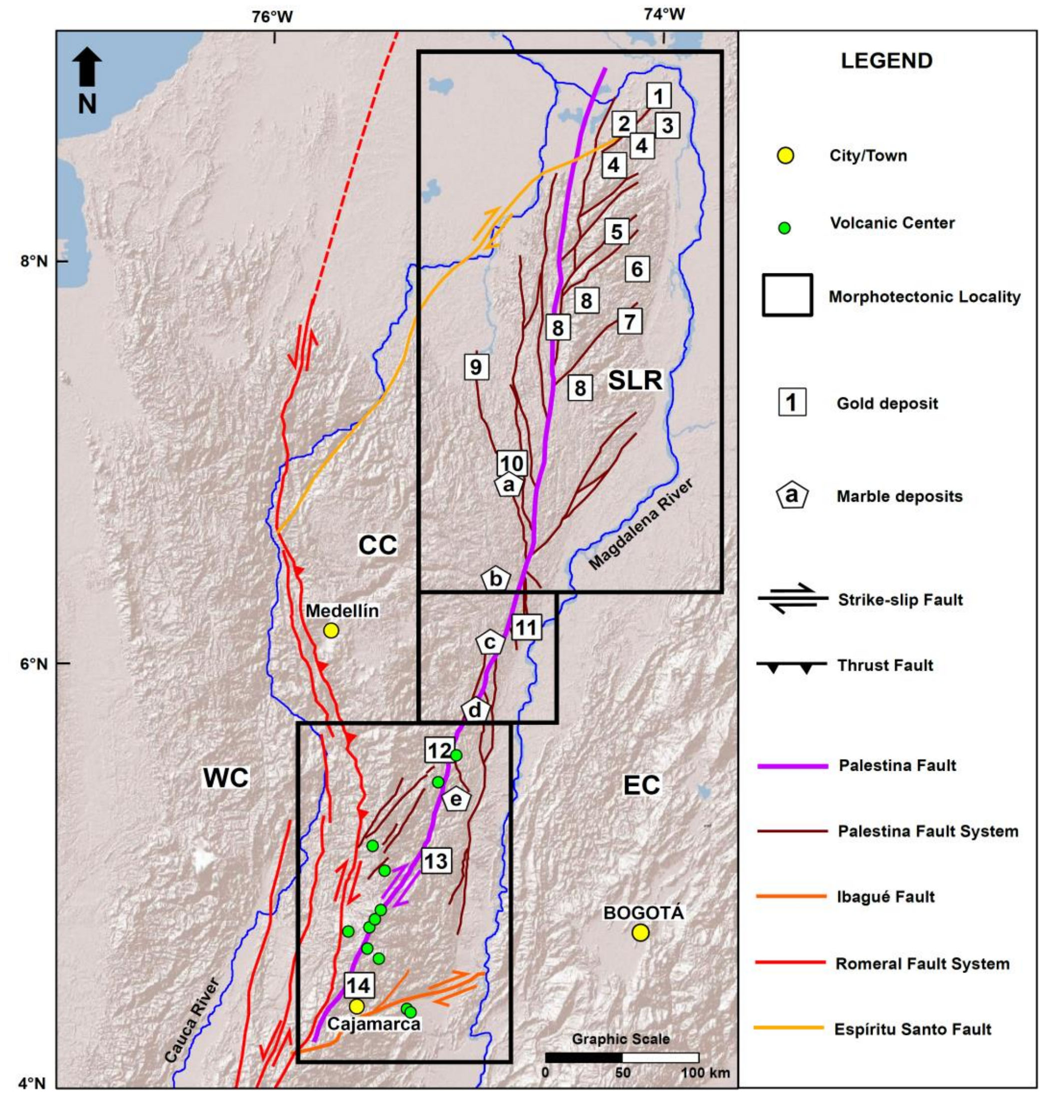

Figure 6. Morphotectonic Localities according to Cárdenas et al. (2014); and gold and marble deposits located along the PFS. 1) San Martín de Loba-Juana Sánchez; 2) Santa Cruz; 3) El Pinal; 4) La Cabaña-Cerro San Carlos; 5) San Pedro Frio; 6) Santa Rosa del Sur; 7) Cerro Pelado; 8) Guamoco; 9) El Bagre; 10) Segovia-Remedios; 11) El Vapor; 12) Río Dulce; 13) Santa Isabel-Líbano; 14) Cajamarca-Salento. a) Segovia-Remedios; b) Maceo-El Bagre; c) El Jordán-El Prodigio; d) Río Claro-La Danta; e) Samaná-La Victoria. Modified from Leal-Mejía (2011) and Luengas et al. (2017).

different qualities and purity, factors that are of great importance for the ceramic, paper, lime, clinker and agro industries present at the study area.

Based on superficial deformations and changes in the geometry of the main fault trace, Cárdenas et al. (2004) divide the PFS into three different segments or Morphotectonic Localities: Southern, Central and Northern (Figs. 6 and 7).

The Southern Morphotectonic Locality (SML) (Fig. 7A) begins near the town of Cajamarca (Tolima Department), where the Palestina Fault is originated as a transtensive system derived from the San Jerónimo Fault (part of the RFS), just to the north of a major crustal structure known as the

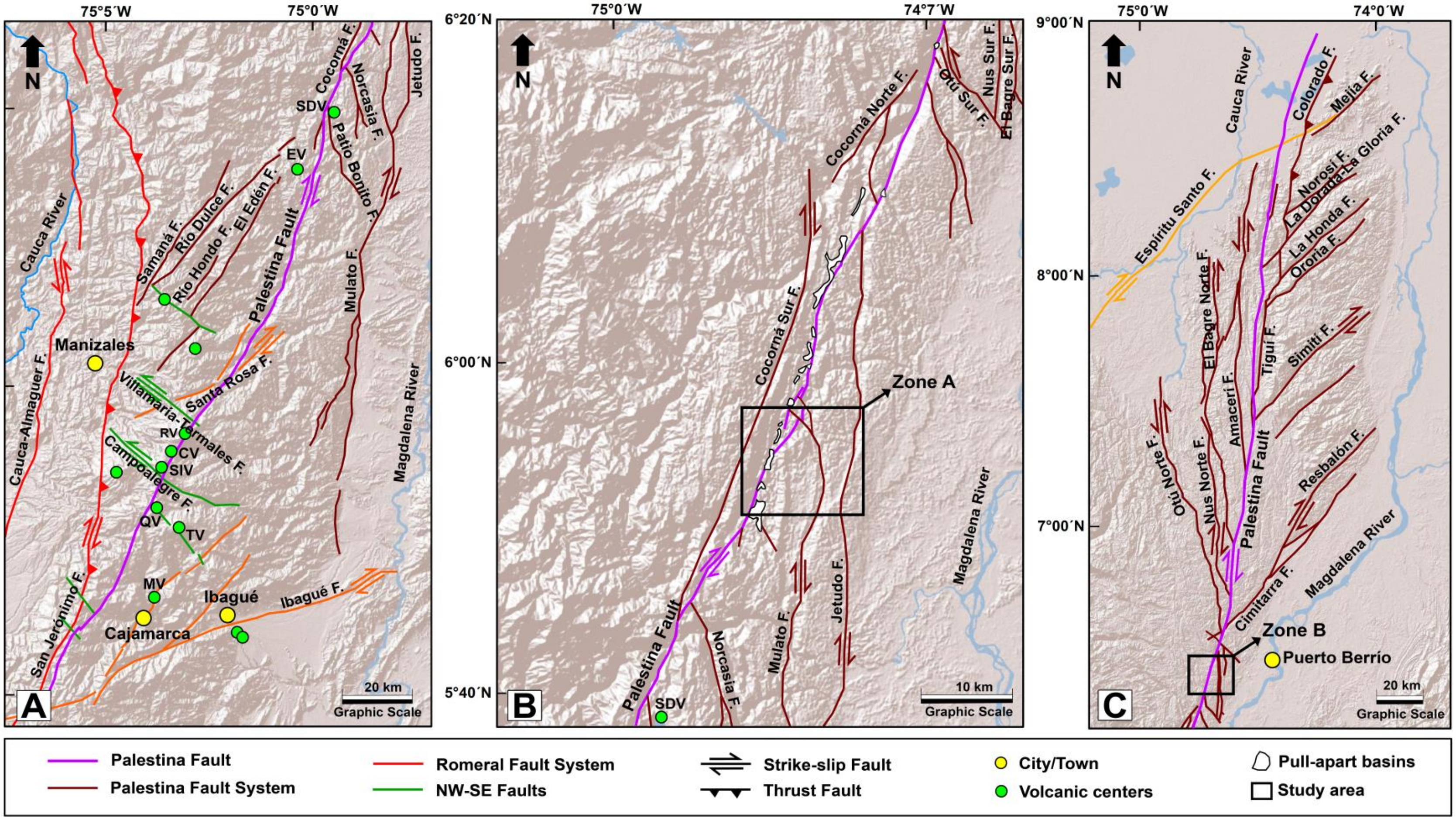

Figure 7. Morphotectonic Localities of the PFS, according to Cárdenas et al. (2004). **A:** Southern Morphotectonic Locality; **B:** Central Morphotectonic Locality; **C:** Northern Morphotectonic Locality. SDV: San Diego Volcano, EV: Escondido Volcano; RV: Ruiz Volcano, CV: Cisne Volcano, SIV: Santa Isabel Volcano, QV: Quindío Volcano, TV: Tolima Volcano, MV: Machín Volcano. Modified from Feininget et al. (1970); Feininger et al. (1975); Fonseca et al. (2011); Mejia (2012); Gómez et al. (2015).

Ibagué Fault (Cortés et al., 2006). To the north, this locality ends where the Cocorná Sur Fault overlaps the main trace, north to the San Diego volcano. This locality is characterized by: a) the NE-SW direction of the main trace; b) the presence of a *horse-tail splay* formed by the SW faults of El Edén, Río Dulce, Río Hondo, and Samaná; c) transversal (*R´Riedel*) NW-SE faults such as Campoalegre and Villamaría-Termales; d) the alignment of the Quindío, Santa Isabel, Cisne, Ruiz, Escondido and San Diego volcanic centers along the main Palestina Fault trace.

The Central Morphotectonic Locality (CML) (Fig. 7B), is limited to the south by the SML and ends to the north as a transtensive overlap of the Cocorná Fault. The deformation along this segment is characterized by a sequence of aligned *pull-apart* basins, aligned Quaternary deposits, elongated depressions, lineal valleys and strongly controlled drainages. In this locality, a *horse-tail splay* is formed by a series of SE trending faults as the: Norcasia, Patio Bonito, San Diego, Mulato, Jetudo, Bagre Sur, Nus Sur and Otú Sur. The Rio Claro sector is placed in this locality.

The Northern Morphotectonic Locality (NML) (Fig. 7C) constitutes the more continuous and straighter segment of the main Palestina Fault. It is limited to the south by the CML and it ends to the north as the San Lucas Range transpressive system. The Palestina Fault continues to the north, into the LMV (Fig. 3) covered by Quaternary deposits (Gonzalez et al., 2015; Mora-Bohórquez et al., 2017). The NML is characterized by the N-S direction of the main trace and the presence of *pull-apart* basins and *push-up* ridges, fault scarps, triangular facets, fault saddles and displaced drainage along its trace, all of them indicating a right-lateral movement with a high-grade vertical component (García-Delgado and Velandia, 2019), verging to the west. The Puerto Berrío sector is placed in the southern part of this morphotectonic locality.

4.1. OUTCROPPING CHARACTERISTICS

Local structures or lineaments were photointerpreted from the DEM (Fig. 8). At the Rio Claro sector (Fig. 8A), most of the structures reflect a NE-SW to N-S strike, indicating an association to the PFS. The Palestina main trace branches into at least three NE structures (not including the Cocorná Sur Fault). WNW-ESE lineaments with displacement of scarps and the main Palestina Fault, were also identified. At the Puerto Berrío sector (Fig. 8B) the main Palestina trace has a clear expression and doesn´t seem to branch into secondary structures. In this sector, WNW-ESE structures are cutting the Palestina Fault and seem to be displacing it. NNW-SSE structures are also identified in this sector, probably associated to the PFS. It wasn´t possible to identify El Bagre Fault in the DEM.

At regional scale, the PFS exhibits different features (Fig. 9) and a strong morphological expression characterized by its straightness and a series of lineal depressions such as elongated and aligned valleys, steep scarps, deep fault saddles (Fig. 9A and B) and deflected and rectilinear drainage (Feininger, 1970; Cortés, 1990; Cárdenas et al., 2004; Mejía et al., 2012; García-Delgado, 2019).

Along the main trace of the PFS, it is common to find zones of variable sizes with evidences of a deformation, exhibiting breccias (Fig. 9C and D), faulting at various levels (Fig. 9E and F),

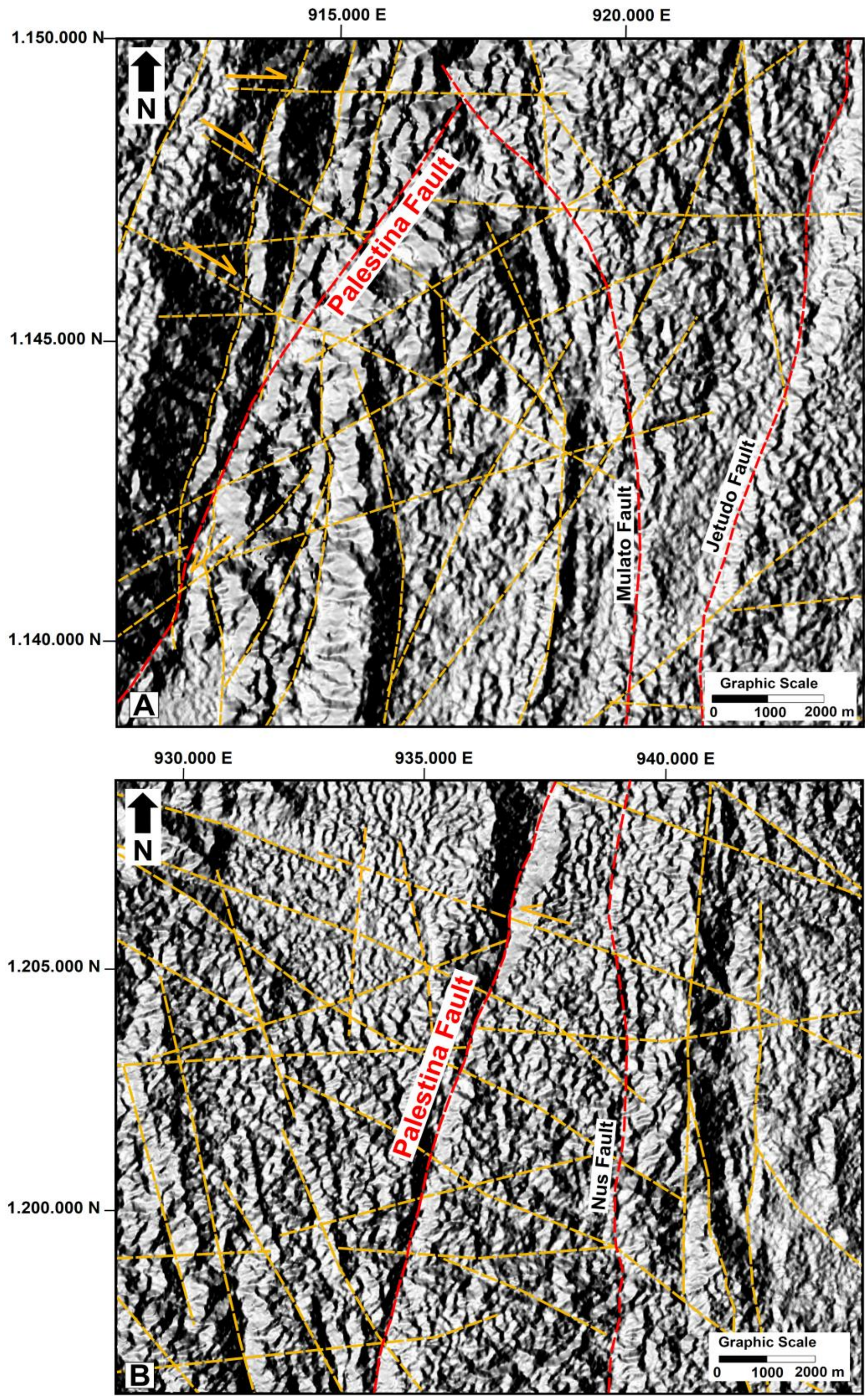

Figure 8. Photointerpretation of structures in the DEM, at the Rio Claro **(A)** and Puerto Berrío **(B)** sectors.

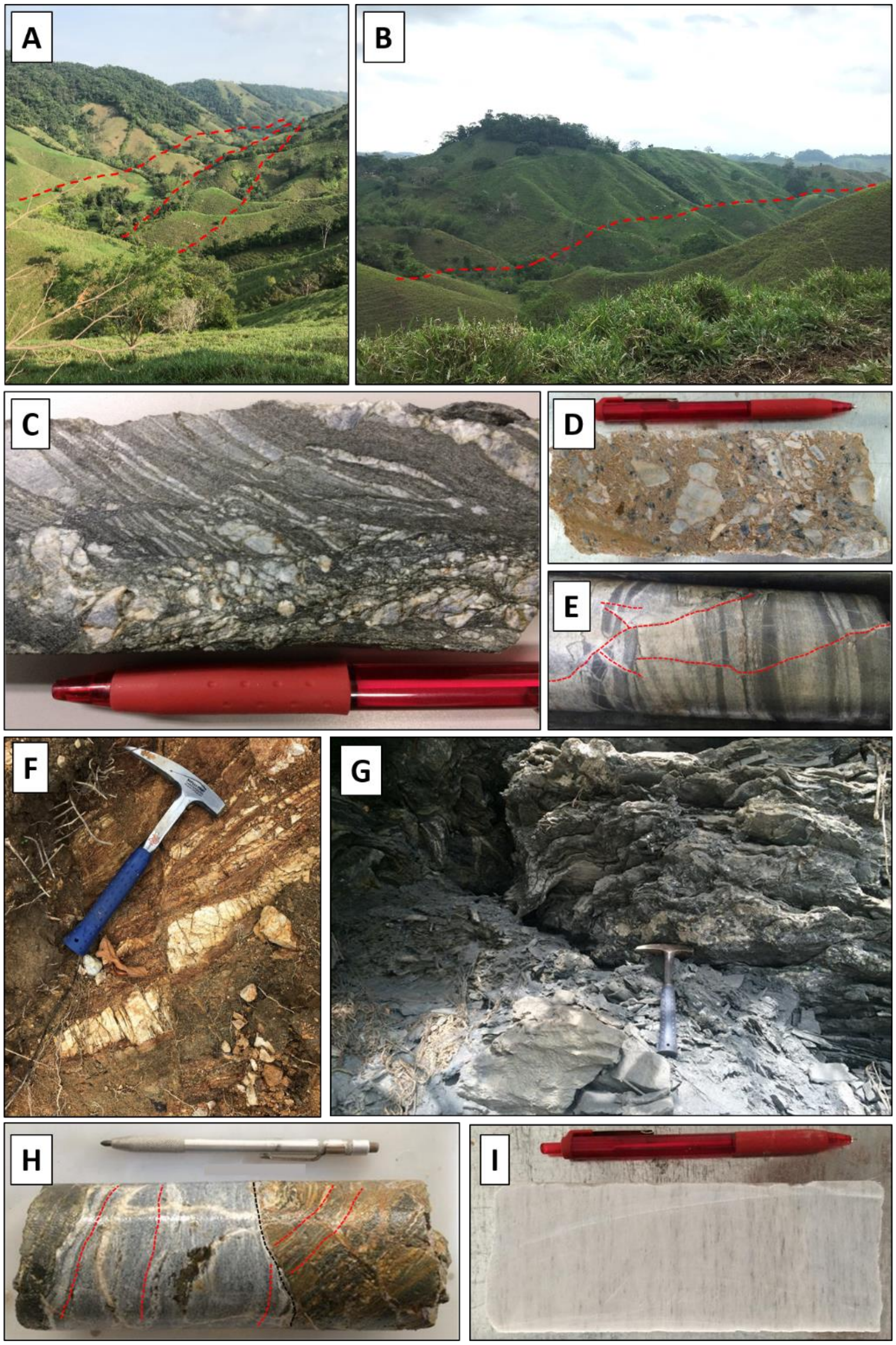

Figure 9. Characteristics associated to the PFS. **A, B:** Fault saddles of the main Palestina Fault in the Puerto Berrío sector; **C, D:** Breccias in schist and marble of the Cajamarca Complex, at the Rio Claro sector; **E, F:** microfaulting in marble and faulting of schist at the Rio Claro sector; **G:** Gouge in marble at the Rio Claro sector; **H:** Faulted contact between marble and schist**; I:** Mylonite in marble at the Rio Claro sector.

cataclastic rocks (Fig. 9G), faulted contacts between marble and schist (Fig. 9H) and mylonites with reduced and elongated calcite crystals (Fig. 9I) (Feininger, 1970; Cortés, 1990; Cárdenas et al., 2004; Mejía, 2012).

Other important regional features are the extensional and contractional duplexes (*pull-apart* and *push-up*) exhibited in the CML and in the SRL (Cárdenas et al., 2004; García-Delgado and Velandia, 2019). These features have been identified at the Rio Claro sector, along the Claro river (Fig. 10), produced on the overlaps between the main trace and associated NE structures, and also as a result of the interaction of blocks that are limited by secondary structures in a *Riedel* fracture pattern. At Puerto Berrío sector, no such features were identified, since the main Palestina trace doesn´t present step-overs in this area. Figure 10 also illustrates the NE-SW elongation of the marble kegels aligned with the structural tendency.

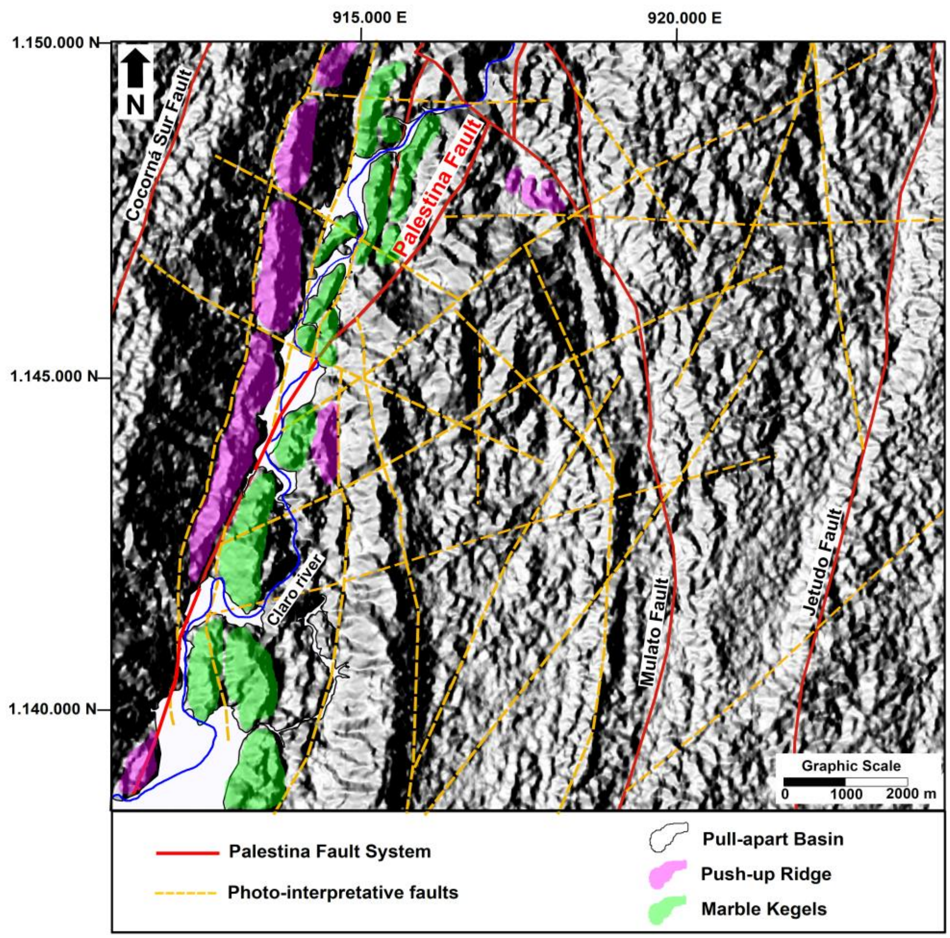

Figure 10. Hillshade image illustrating pull-apart basins, push-up ridges and elongated kegels, associated to the Palestina main trace at the Rio Claro Sector.

4.2. AGE, DISPLACEMENT AND KINEMATICS

The Palestina and Otú faults (PFS associated structures) have been consider by some authors to be part of an early Paleozoic cortical suture (Restrepo and Toussaint, 1988; Toussaint et al., 1992; Cediel et al., 2003; Chicangana, 2005; Kennan and Pindell, 2009; Martens et al., 2014; Cediel and Shaw, 2019). However, recent geological studies performed near Ibagué city (Tolima Department) suggest that during the Jurassic, oblique subduction, contraction, and possible collision took place on what is now the Otú Fault, leading to the development of a strike-slip suture (Bustamante et al., 2017a) that allowed large transcurrent displacements, juxtaposing rocks with different tectonic histories in the CC (Bayona et al., 2006; Kennan and Pindell, 2009; Bustamante et al., 2017a). Although the Palestina main trace is cutting and displacing the Otú Fault, which implies an older age for the latest (Feininger, 1970), the role of the main trace as part of this suture is still unclear, since no detailed studies with this objective have been carried out. Nevertheless, recent findings east of the Palestina Fault, regarding different ages and tectonic events on rocks that were previously classified as the Cajamarca Complex (Blanco-Quitero et al., 2014; Bustamante et al., 2017a) indicate that much more work is needed to understand the relationship between these rocks and the Palestina and Otú faults.

Based on the measurements of ten different lithological units, structural characteristics and changes in the metamorphic isogrades along the Palestina main trace, Feininger (1970) estimated a right-lateral displacement of 27,7 km; however Kennan and Pindell (2009) consider that such offset is much larger although they don't explain on which they base this assumption.

The sense of NW-SE antithetic faults such as Calderas, Bizcocho, Balseadero, Nare and Monteloro (Feininger et al., 1972) that are inside the Antioquia Batholith, suggest a *"mega-augen"* behavior for this large plutonic body and supports a right-lateral displacement during the Cenozoic for the batholith and the surrounding metamorphic units in the CC (Fig. 11) (Rodríguez et al., 2005), including the Cajamarca Complex. This same kinematics is deducted from an important deformation area evidenced in DEM model (Fig. 12), where sigmoidal shapes are formed east of the main trace and a *flower structure* is formed between it and the Cocorná Fault.

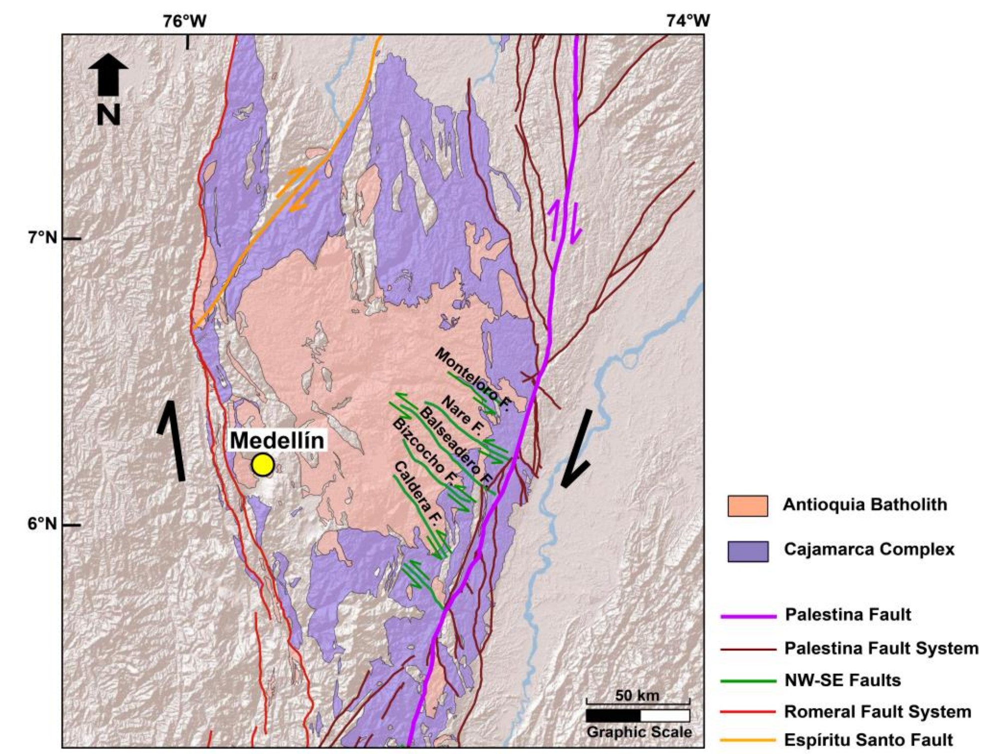

Figure 11. Tectonic model illustrating the *"mega-augen"* behavior of the Antioquia Batholith inside the RFS and PFS. Modified from Rodríguez et al. (2005).

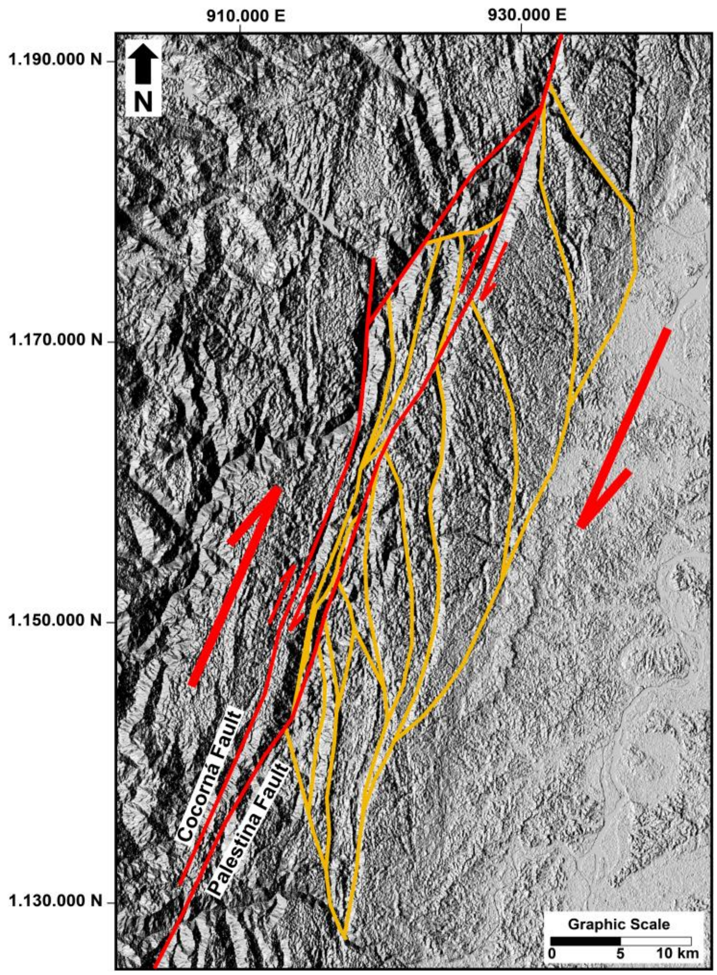

Figure 12. Regional deformation zone exhibiting right-lateral kinematics for the PFS.

Feininger (1970) argues that there is at least 200 meters of vertical normal displacement, based on evidences found in the marble unit of the Cajamarca Complex; while Page (1986) found vertical displacements of 25 to 80 meters in associated faults near the Guatapé river. At the Rio Claro sector, SUMICOL S.A.S. found a vertical movement for the Palestina main trace, evidenced by a vertical displacement in drainage, that is larger on the western margin of the Claro river, reaching up to 25 meters.

Even though Feininger (1970), Cortés (1990) and Mora-Bohórquez et al. (2017) consider that the PFS is actually inactive, the seismicity data indicates low activity (Taboada et al., 1998; Veloza et al., 2012). Features such as displaced Quaternary volcanic deposits from the Ruiz volcanic complex, displaced and aligned drainages, triangular facets, sag ponds, knickpoints, fault saddles, pressure ridges and *pull-apart* basins reported along the three morphotectonic localities, indicate that the Palestina Fault has had activity in recent times (Collinst et al., 1981; Page, 1986; Paris et al, 2000; García-Delgado and Velandia, 2019).

SUMICOL S.A.S. conducted a morphotectonic analysis to find evidences of recent tectonic activity at the Rio Claro sector. Many of the previously documented features were found: horizontal and vertical displaced scarps and drainage, aligned fault saddles, pressure ridges, *pull-apart* basins and various generations of triangular facets. The Mountain Front Analysis (Keller, 1986) calculated for the Palestina main trace and an associated fault in this area, showed Sinuosity Indexes (I_s) between 1,0 and 1,2, that together with the calculated Triangular Facet Slope (Fig. 13) (Wallace, 1978), indicate moderate activity for these faults in the area.

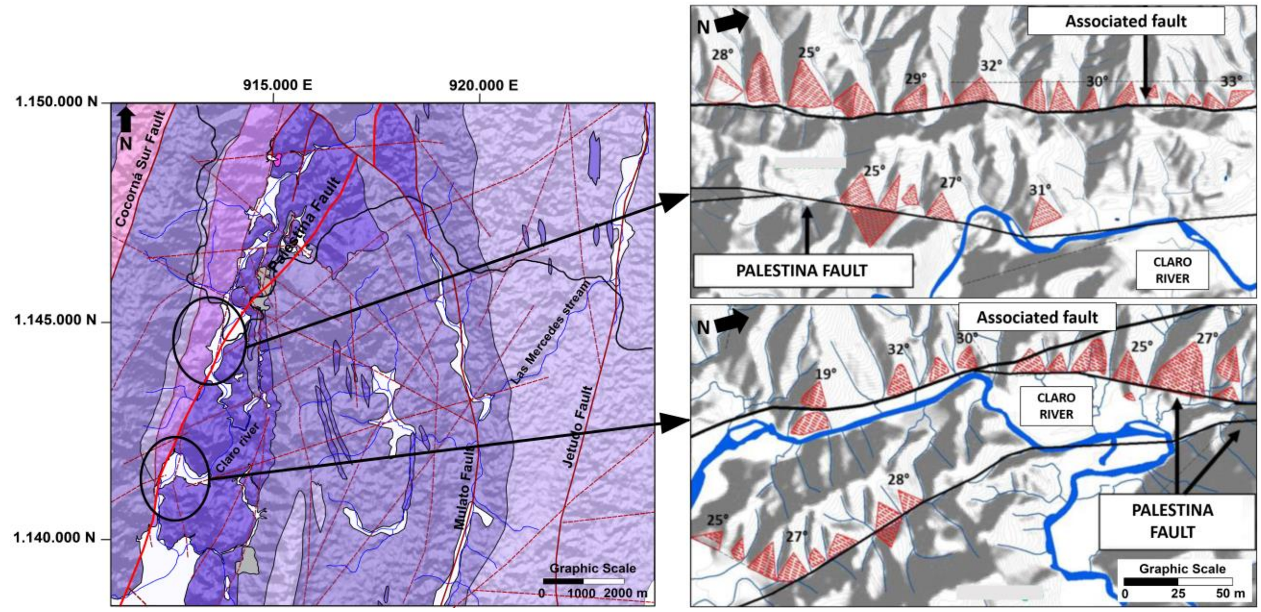

Figure 13. Triangular Facet Slope analysis at the Rio Claro sector. Geological legend as in Figure 4. Modified from Feininger et al. (1970); Feininger et al. (1975).

One of the identified *pull-apart* basins exhibits a clear "*lazy Z*" to rhomboidal shape (Fig. 14), an indication of recent activity and a dextral behavior (Mann et al., 1983); it was drilled by SUMICOL S.A.S., finding an active alluvial deposit of the Claro river of more than 30 meters deep.

Some authors have reported left-lateral movements for the main Palestina trace (Collins et al., 1981; Page, 1986; Paris et al., 2000; González, 2001; Naranjo et al., 2018), some arguing that this corresponds to the actual kinematics of the fault, supported on the theory that since mid-Miocene, a NW-SE stress field was established north of the 4-5°N latitude, causing the differential reactivation and reverse in kinematics of existing right-lateral faults (Ego et al., 1996; Taboada et al., 2000; Colmenares and Zoback, 2003; Corredor, 2003; Acosta et al., 2004; Cárdenas et al., 2004; Cortés and Angelier, 2005; Cortes et al., 2005; Toro and Osorio, 2005; Cortés et al., 2006; Acosta et al., 2007). This NW-SE stress field would have been induced by the accretion of the Chocó-Panamá Block (Duque-Caro, 1990; Taboada et al., 2000; Acosta et al., 2004; Montes et al., 2015) and influenced by the transference of the oblique convergence vector of the Nazca plate to the South American plate (Trenkamp et al., 2002; Toro and Osorio, 2005) and the ESE subduction of the Caribbean plate (Ego et al., 1996; Taboada et al., 2000; Acosta et al., 2004).

However, Mora-Páez et al. (2019) have found that a new ENE-WSW stress regime has been established along the Northern Andean Block since 1-2 Ma, which would favor right-lateral displacements for the strike-slip faults. According to Mora-Páez et al. (2019) this new stress field

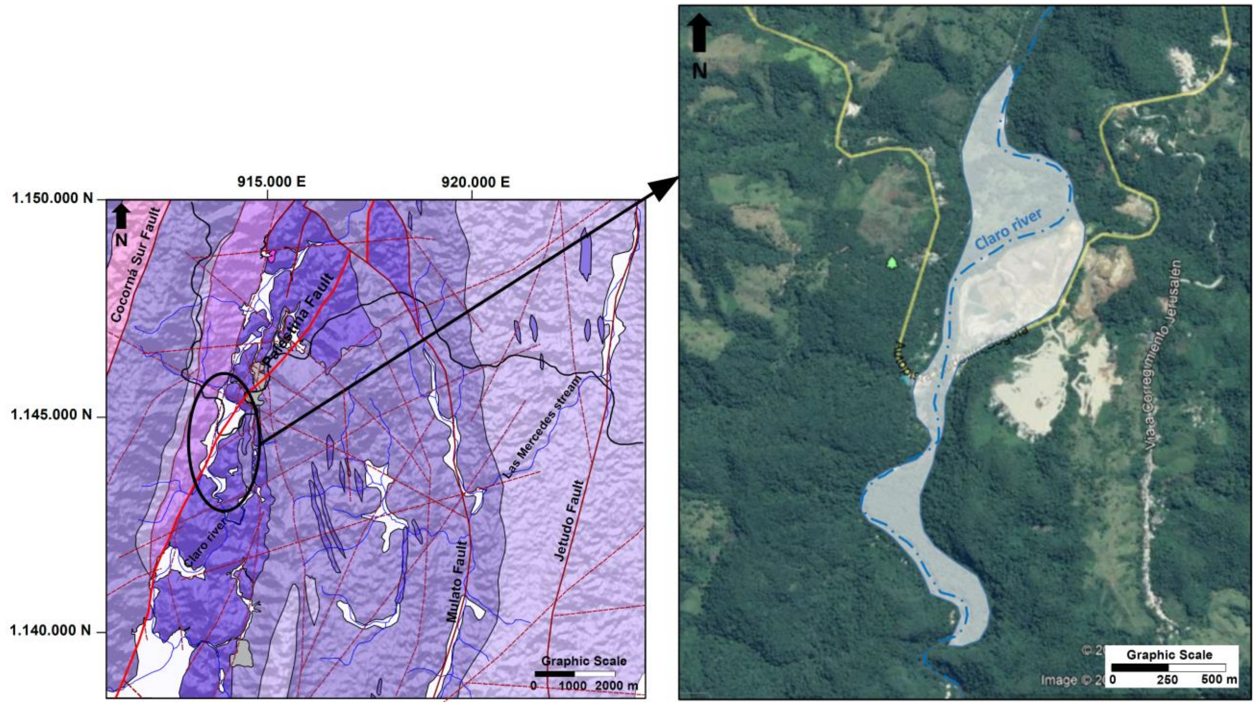

Figure 14. "*Lazy Z*" shaped *pull-apart* basin at the Rio Claro sector. Geological legend as in Figure 4. Modified from Feininger et al. (1970); Feininger et al. (1975).

was induced by two factors: a) the arrival of the aseismic Carnegie Ridge to the South American trench (Gutscher et al., 1999), causing the northeastward "*escape*" of the Northern Andean Block by adding a NE-SW strike-slip component to the previous compression (Egbue and Kellogg, 2010; Egbue et al. 2014); and b) the break of the Choco-Panamá Block and the subsequent Chocó accretion to the Norther Andes.

5. FAULT-SLIP DATA ANALYSIS

Collected data along the whole study area was graphed as rose diagrams (Fig. 15). The dominant structural tendency is governed by structures trending from N20°W to N40°E with dipping angles ranging from 50° to vertical (Fig. 15A). With a minor group of structures located orthogonal to the main tendency, trending ~N60°W, dipping between ~60° - 70° (Fig. 15A). The main Palestina fault trace was measured both at Rio Claro and Puerto Berrío sectors, with similar results. Around Rio Claro, the main trace trends N(20-40°)E dipping ~70-80° (Fig. 15B), and around Puerto Berrío the structure trends between N(0- 40°)E dipping ~60-70° (Fig. 15C).

Fault kinematic tendency could be inferred based on the fault plane dip and slickenside plunge (Duque-Trujillo et al., 2014). Figure 16 illustrates the kinematic tendency for all measured structures. PFS associated structures display noticeable differences along both measured sectors.

Associated structures (excluding the main trace) show both right-lateral and left-lateral kinematics at both sectors when measured in the field; nevertheless, they plot between the oblique and normal fields when they are dipping to the east along the Rio Claro sector, and mostly

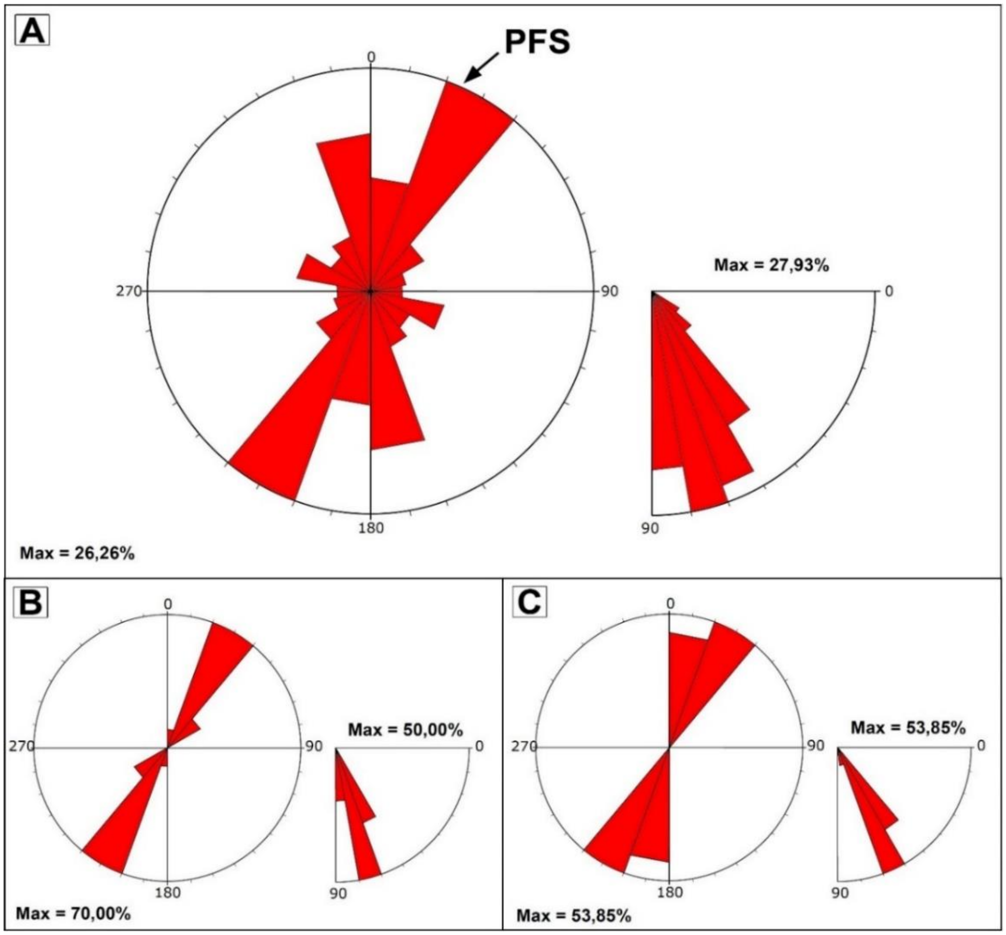

Figure 15. Rose diagrams for the measured faults in the study area. A) Rose diagram for all measured faults along the study area; B) Rose diagram for the main Palestina fault trace along Rio Claro sector; C) Rose diagram for the main Palestina fault trace along Puerto Berrío sector. Attitude angle: 20°, dip angle interval: 10°, maximum values (%) represent the percentage of the data grouped in the maximum value.

in the normal field at Puerto Berrío sector (Fig. 16A). However, based on the kinematic indicators observed in the field, an inverse movement was deducted for these structures. When dipping to the west these structures plot along the reverse and oblique fields (Fig. 16B).

Regarding the main trace, a right-lateral kinematics was measured on segments dipping both to the east and to the west. At the Rio Claro sector, planes fall on the normal field when dipping to the west and on the oblique field when dipping to the east (Fig. 16C). Nevertheless, fault planes classified as normal on the graphic have inverse kinematic indicators observed in the field. On Puerto Berrío sector the Palestina main trace was only measured on one site with a purely right-lateral strike-slip kinematics, dipping to the west (Fig. 16C).

The second group of faults, orthogonal to the PFS, display both right-lateral and left-lateral kinematics along both sectors, with most planes verging to the west (Fig. 16D and E). Fault planes measured on the Rio Claro sector fall between the strike-slip and oblique fields, meanwhile faults from the Puerto Berrío sector mostly graph on the normal field (Fig. 16E), although the kinematic indicators measured in the field indicate inverse displacement.

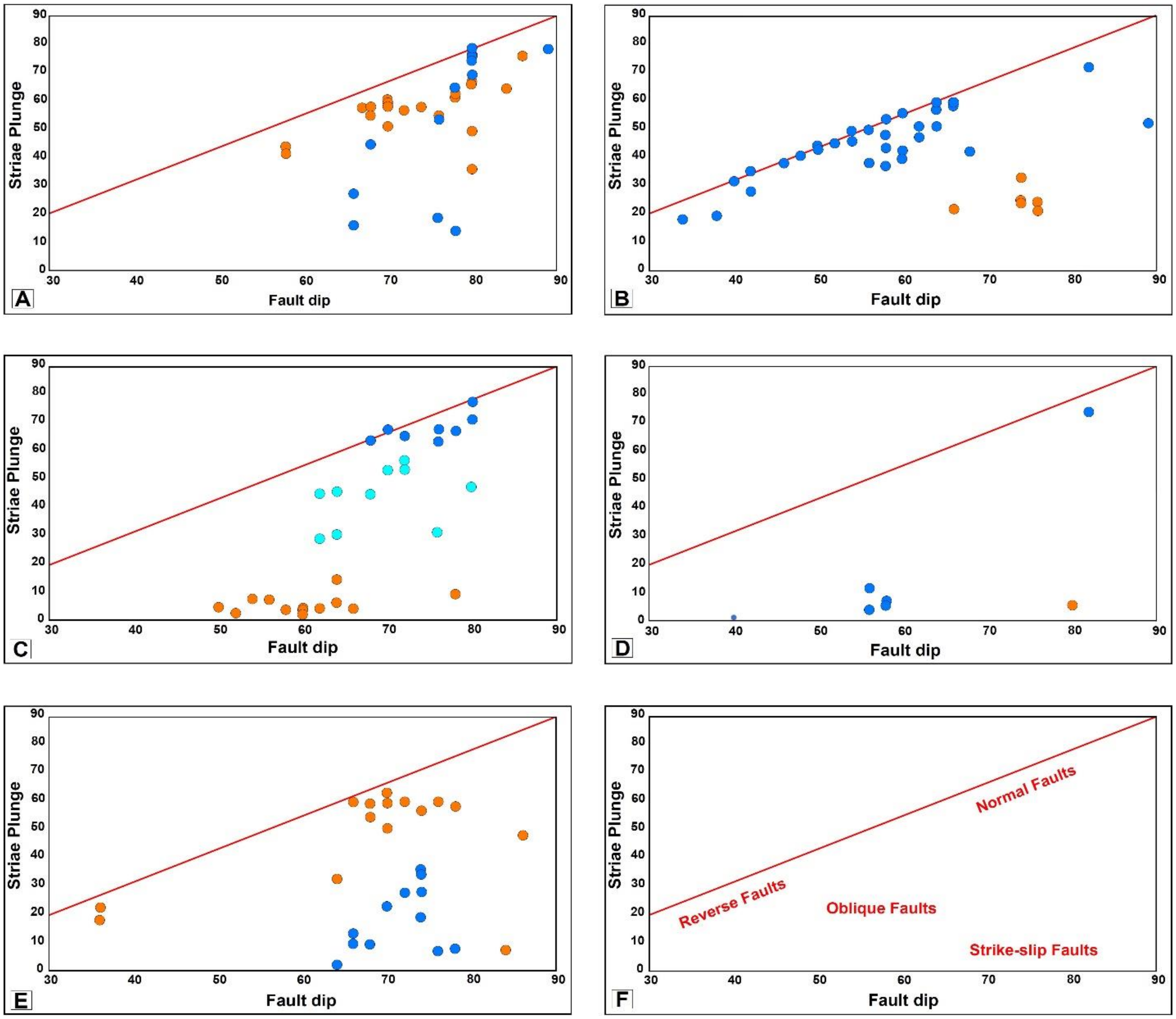

Figure 16. Fault classification diagram based on the fault dip *vs.* striae plunge values. Blue dots correspond to Rio Claro sector data, orange dots correspond to Puerto Berrío sector data. **A:** Faults associated to the PFS, verging to the east, not including the Palestina main trace; **B:** Faults associated to the PFS, verging to the west, not including the Palestina main trace; **C:** Palestina main trace, the light-blue correspond to the data verging to the east in Rio Claro; **D:** Faults associated to the orthogonal system, verging to the east; **E:** Faults associated to the orthogonal system, verging to the west; **F:** Classification of fault kinematics according to Duque-Trujillo et al. (2014).

6. STRESS TENSOR ANALYSIS

Right-dihedra method (Angelier, 1979; 1984), applied in order to constrain paleo-stress analysis, were obtained from sites where fault-slip data and kinematic indicators were measured (Fig. 17) Stress tensors show a WSW-ENE general orientation for the maximum horizontal stress with mostly strike-slip to oblique behavior along the Rio Claro sector (Fig. 17A). Two dihedrals exhibit more of a normal behavior (MS012 and MS017) and one has a thrust behavior (MS013), near the Mulato and Jetudo faults. At Puerto Berrío sector (Fig. 17B) most of the stress tensors in faults with a NE strike, exhibit a SW-NE general orientation for the maximum horizontal stress,

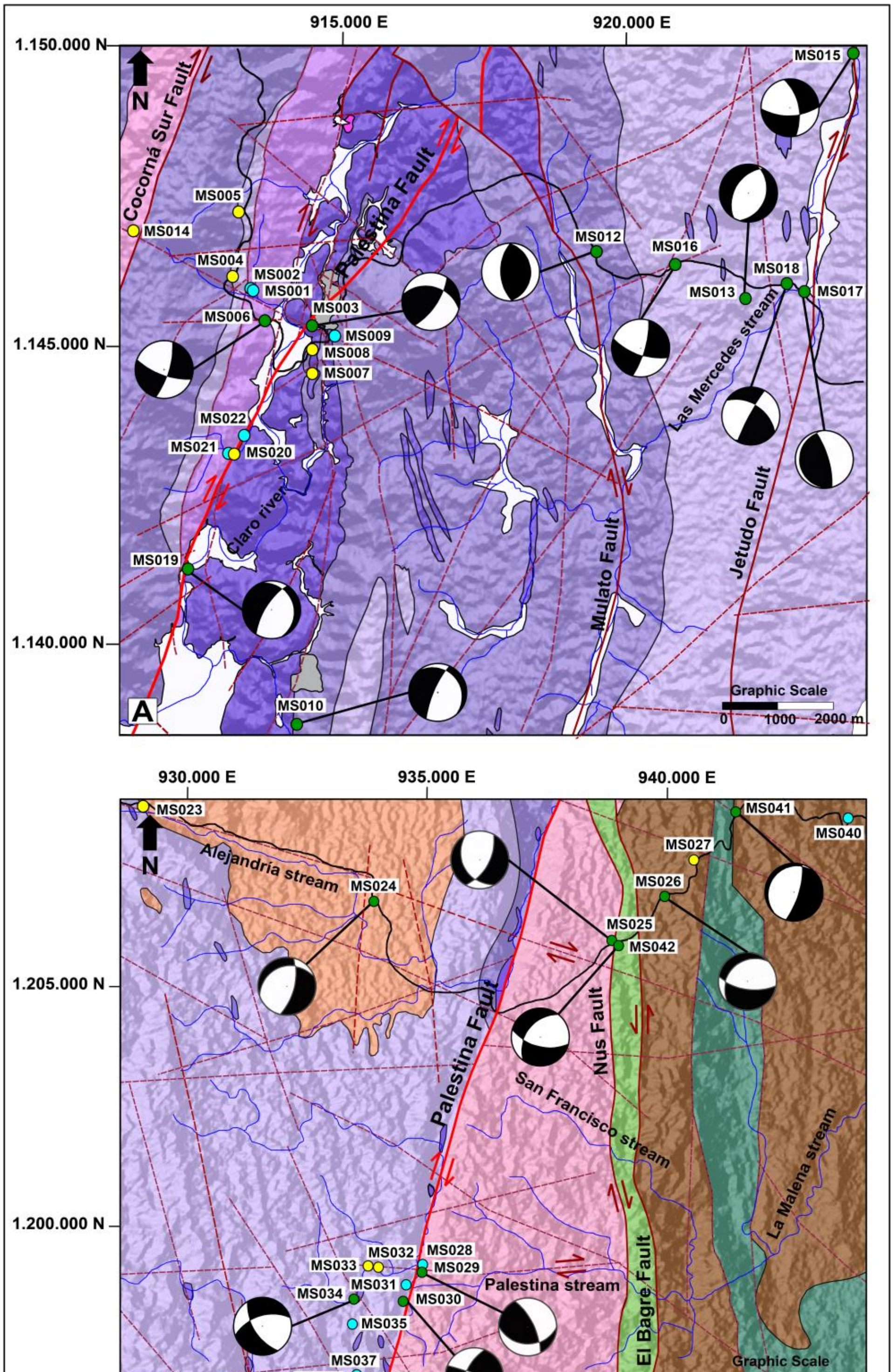

Figure 17. Geological maps from Rio Claro **(A)** and Puerto Berrío **(B)** sectors showing field stations and right-dihedra diagrams. Dark green spots are stations were fault-plane and sense of shear was measured; yellow is where fault-plane without sense of shear; light-blue is where no fault-plane was measured. On right-dihedra: black quadrants indicate compression and white quadrants indicate tension. Geological legend as in Figure 4. Modified from Feininger et al. (1970); Feininger et al. (1975); Fonseca et al. (2011).

nevertheless a NW-SE stress direction was found for one NE-SW striking fault (MS024) and three E-W faults (MS026, MS029 and MS042). Two dihedrals exhibit a thrust behavior (MS025 and MS041), one of them probably referring to the Nus Fault.

Fault-slip data and paleo-stress tensors are illustrated separately for each sample site on Rio Claro (Fig. 18) and Puerto Berrío (Fig. 19). Dihedral density plots were constructed for each locality in order to establish the degree of confidence of the obtained results. This type of plots reflects graphically the degree of compatibility that each dataset has for P and T areas (Delvaux and Sperner 2003). A good data correlation indicates that the adjustment between the density quadrants is accurate, allowing to define the orientation of the obtained stress tensor with greater reliability. The degree of fitting for each dataset was evaluated with a right-dihedral density plot and cross checked with the retrieved fault-slip data. Both at the Rio Claro and Puerto Berrío sectors, the stress tensors have high density indicating a good concordance of the data, only at Puerto Berrío sector, the paleo-stress tensor resulting in the MS041 and MS042 field stations show a medium density distribution, but still with acceptable statistic for the data.

A general right-dihedra gathering all fault planes and slickenside data obtained from each sector was constructed (Fig. 20). For Rio Claro sector (Fig. 20A), the resulting right-dihedra indicates a maximum stress field ($\sigma1$) near the horizontal at 075-255°, with an acceptable statistic for so many data. This paleo-stress tensor is similar to the result obtained for all measured fault planes along the Puerto Berrío sector (Fig. 20B), where the general right-dihedra indicates an almost horizontal maximum stress field ($\sigma1$) located at 097-277°.

7. DISCUSSION

7.1. KINEMATICS OF THE PFS AND THE MAIN TRACE

The PFS is figured out as a classic strike-slip system exhibiting mainly a *horse-tail splay*, large branch faults, connecting faults, synthetic and antithetic secondary faults, isolated lenses and *pull-apart* basins (Kim et al., 2004).

The study area, located between the CML and the southern part of the NML, is governed by two orthogonal sets of structures, in which the dominant N to NE striking faults correspond to the regional PFS. From south to north the strike of the main Palestina trace has different trends: on the south (SML) the fault trends NE, then along the central part (CML) the fault trends NNE, and finally, on its northern segment (NML) the fault trends N-S. These different trends are also recognizable in the west of the CC in the RFS, when passing close to the Antioquia Batholith (Fig. 11). The difference in rheology between the fragile Antioquia Batholith contrasting the ductile behavior of the gneisses and schists of the Cajamarca Complex, causes the PFS to bend with the ductile units instead of passing through the fragile ones, hence explaining the change in the strike of the main Palestina Fault.

A transversal normal and usually left-lateral *R´Riedel* fault system has been documented in the SML (Cortés, 1990; Mejía, 2012) (Fig. 7A) and also inside the Antioquia Batholith, where these

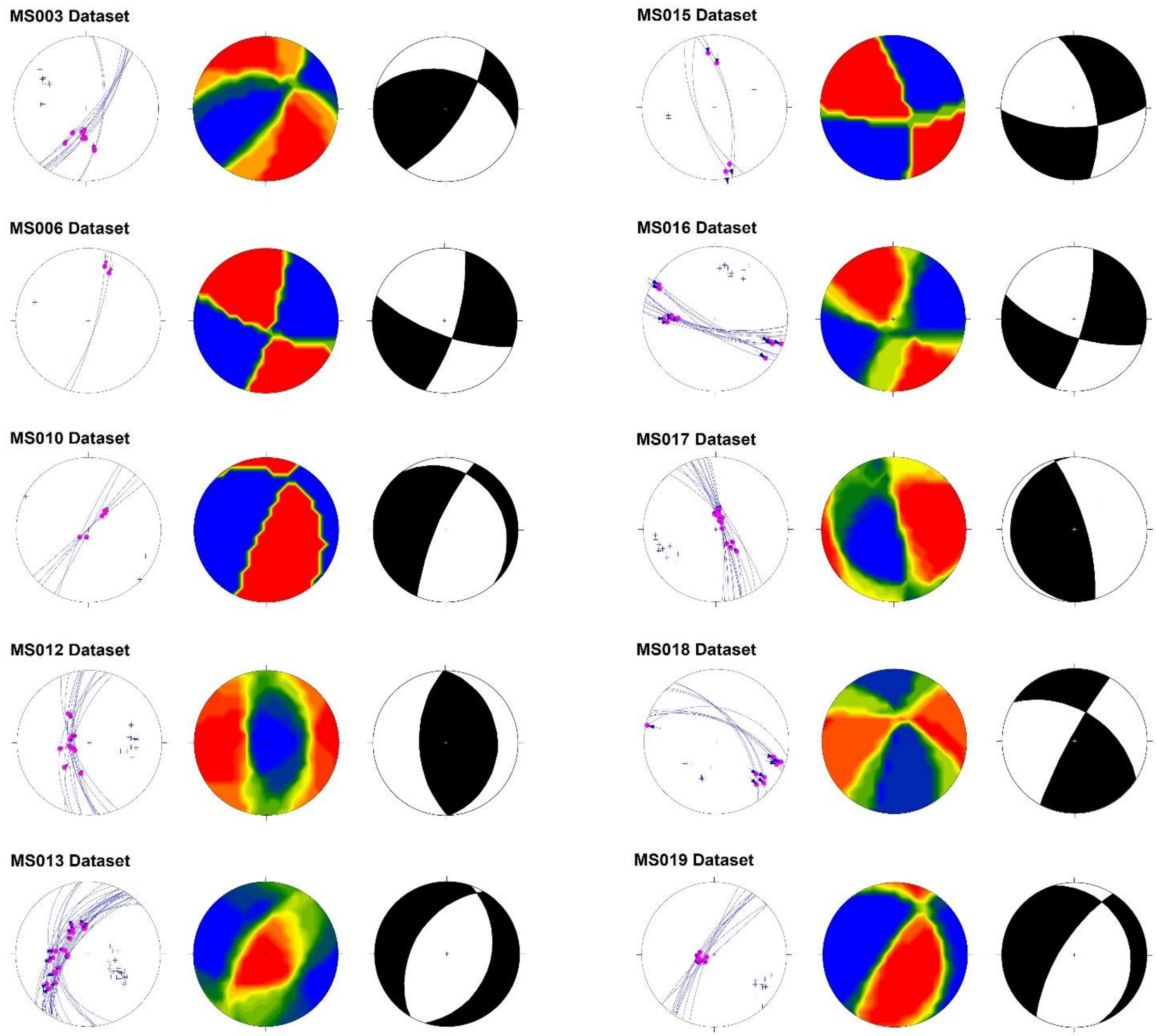

Figure 18. Fault planes and fault-slip data, dihedral density plot and right-dihedra stereogram figure, for each field station measured along Rio Claro sector. On dihedral density plot red indicate high density and blue indicate low density. On right-dihedra: black quadrants indicate compression and white quadrants indicate tension.

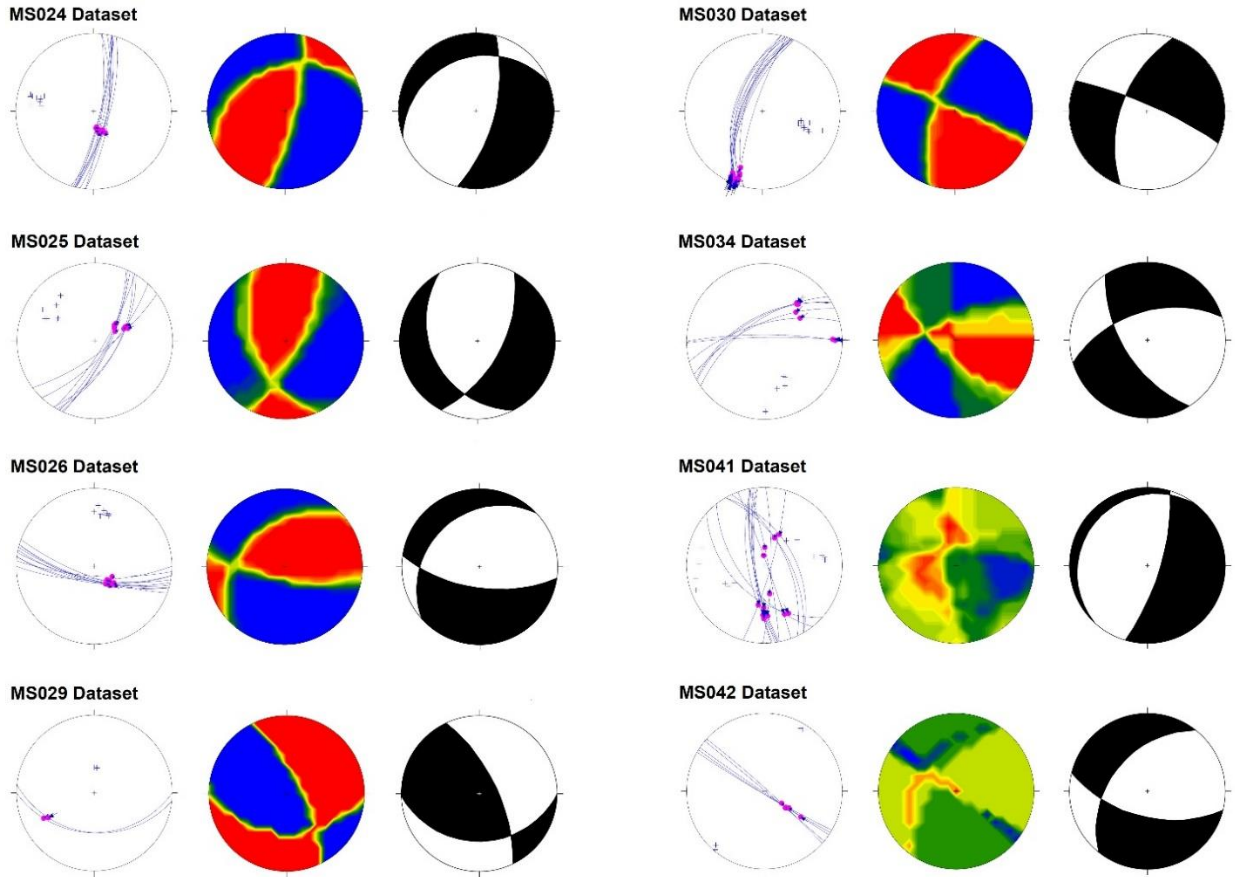

Figure 19. Fault planes and fault-slip data, dihedral density plot and right-dihedra stereogram figure, for each field station in the Puerto Berrío sector. On dihedral density plot red indicate high density and blue indicate low density. On right-dihedra: black quadrants indicate compression and white quadrants indicate tension.

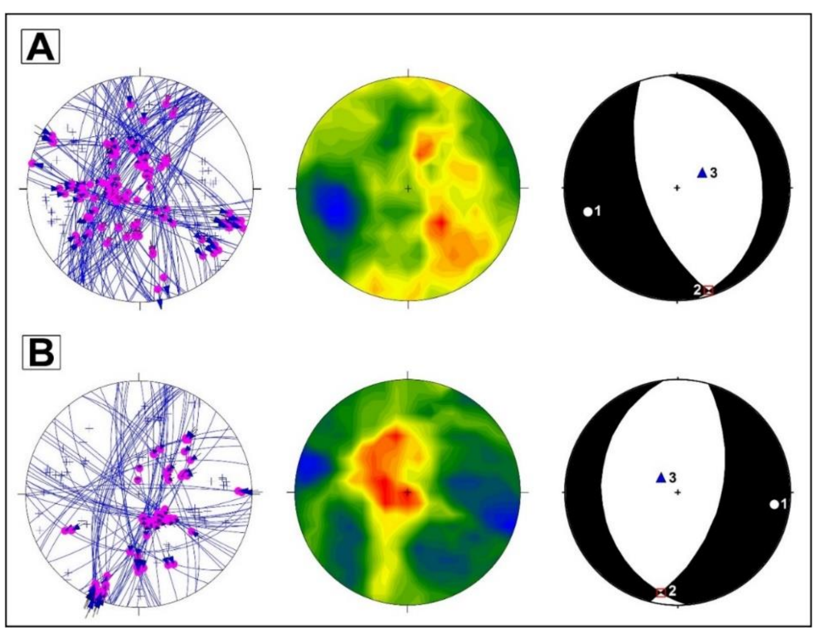

Figure 20. Fault planes and fault-slip data, dihedral density plot and right-dihedra stereogram figures resulting when gathering all data from Rio Claro sector **(A)** and Puerto Berrío sector **(B)**. Black quadrants indicate compression and white quadrants indicate tension. σ1: circle, σ2: square and σ3: triangle.

faults indicate a dextral-sense of shear for the whole "*mega-augen*" system (Rodríguez et al., 2005) hence, a dextral-sense for the PFS as it represents the east boundary of it (Fig. 11).

Along the study area, faults orthogonal to the main fault trace were identified in the DEM (Fig. 8). Those faults have the same orientation of those orthogonal faults identified along the SML, nevertheless, these display both right-lateral and left-lateral kinematics. Although these planes are characteristic of normal faults, and so, plot on the normal field on Figure 16E, kinematic indicators on those fault planes suggest inverse displacement along them. This orthogonal group of faults cut and displace the PFS, implying that those must be younger than the main trace.

Along its trace, the PFS has a high dipping angle, as all classical strike-slip faults found on the upper crust. The high dipping angle besides normal sinuosity found along fault planes, make easy for the Palestina main trace to change vergence from west to east, shifting its vertical component from normal to reverse. The N to NE structures associated to the PFS have noticeable differences along both sectors, showing both right-lateral and left-lateral kinematics with both inverse, oblique or normal behaviors depending on the dipping vergence. This is the case of some Palestina fault planes which have attitudinal characteristics of normal planes, and so are plotted on Figure 16A (east dipping when located along Puerto Berrío sector) and Figure 16C (west dipping when located along Río Claro sector). However, their kinematic indicators deducted on the field indicate an inverse movement for them.

Morphological features found in the study area, including horizontal and vertical displaced scarps and drainage, aligned fault saddles, pressure ridges, *pull-apart* basins and triangular facets, besides the calculated Sinuosity Index and Triangular Facet Slope, are clear evidences of recent right-lateral kinematic for the main Palestina Fault trace. García-Delgado and Velandia (2019) conducted a recent study at the SLR, where they found similar morphological features that led them to conclude as we did. The left-lateral slip locally reported for the main trace of the Palestina Fault (Page, 1986; Paris et al., 2000; Naranjo et al., 2018) could be explained by block rotation caused by the complex interactions between NE-SW and NW-SE structures, causing an apparent reverse displacement sense between blocks (Mandl, 1987).

7.2. STRESS TENSOR

The resultant stress-tensor from kinematic analysis performed along the study area indicates a coherent compressive regime with a maximum stress direction located ENE-WSW to E-W (Fig. 21), which concurs with other data obtained in different sectors of the CC and EC of Colombia (Cortés et al., 2005; Toro and Osorio, 2005; Mejía, 2012; Mariño and Duque-Trujillo, 2017; Velandia and Bermúdez 2018; Mora-Páez et al., 2019; García-Delgado and Velandia, 2019).

Although along the study area, no slip measurements were made in rocks younger than Cretaceous, we interpret that the stress tensor here obtained corresponds to the actual regional stress field, supported in our evidences of an actual right-lateral kinematics for the main trace. This analysis is in concordance with the new evidences recently published by Mora-Páez et al. (2019), regarding the establishment of a ENE-WSW stress regime since 1-2 Ma.

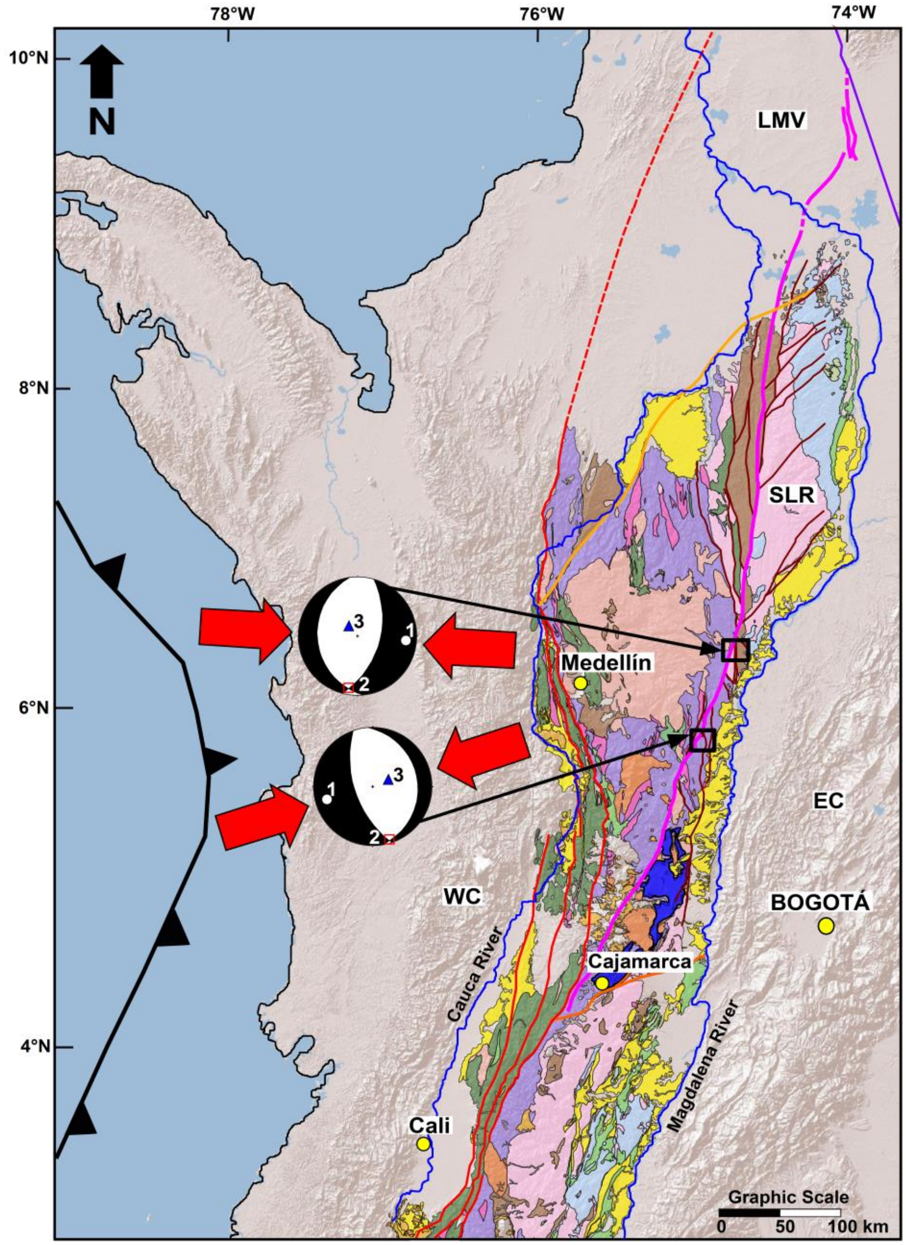

Figure 21. Resulting stress regime for the study area, with a maximum stress direction located ENE-WSW to E-W. Geological legend as in Figure 3. Modified from Gómez et al. (2015) and Bustamante et al., 2017a.

8. CONCLUSIONS

The PFS corresponds to series of NE-SW strike correlative structures that have had large dextral transcurrent displacements and exhibit actual tectonic activity with right-lateral kinematics, which could represent a potential hazard. This structures are related to the occurrence of major gold deposits and the dismembering and displacement of marble units, making it important for future exploration projects and the mining industry.

The analysis of stress tensor shows an actual ENE-WSW to E-W direction for the maximum horizontal stress which induces dextral displacements along N-NE striking faults in the CC. This evidence, along with morphotectonic features and structural analysis conducted at the study area, indicate that the main Palestina fault trace correspond to an active structure with a right-lateral kinematics.

No evidences of left-lateral kinematics, north of the 4-5°N latitude, were found in this study. It would seem that the kinematic discrepancies locally reported for the Palestina Fault are not the result of a NW-SE stress field as it has been established by some authors; but the consequence of a complex interaction of different factors such as the local influence of transversal faults and possible block rotation due to branching and connection of parallel faults associated to the PFS.

In that sense, this study would be the first registered evidence along the PFS that a NW-SE stress field does not govern the tectonic regime north of the 4-5°N latitude in this sector of the CC of Colombia.

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