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# Late Jurassic syn-extensional sedimentary deposition and Cenozoic basin inversion as recorded in The Girón Formation, northern Andes of Colombia

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ABSTRACT. The Yariguíes Anticlinorium, a regional structure located at the western flank of the Eastern Cordillera of Colombia, includes the thickest record of continental sedimentary rocks accumulated near to the Jurassic-Cretaceous boundary. The sedimentary rocks are lithoarenites and feldspathic arenites, grouped in the Girón Formation, and deposited in a Late Jurassic extensional basin interpreted in this work as a rift basin. We analysed the sedimentologic and compositional characteristics of two sections that accumulated in a complex rift system. We identified important thickness variations, from 3,350 m in the type section to at least 525 m in a reference section in the Zapatoca area, as well as petrographic and lithofacies changes. This led us to confirm that the Girón Formation encompasses all the continental facies, whose source rock correspond mainly to the exhumed blocks of the Santander Massif during the Late Jurassic. The synrift successions were segmented by transverse structures and regional longitudinal faults of the rift-shoulder, as the Suárez Fault. The tectonic frame of the study area shows the relevance of the W-E compressional regimes, explaining the local kinematics as a heritage of the former configuration and tectonic inversion of the basins. However, clockwise rotation of the stress field was detected from the stress tensor analysis. The latest orientation of the stress tensors and shear joints are related to the effect of the transpressional Bucaramanga and Lebrija faults along the study area.

Keywords: Yariguies Anticlinorium, Los Cobardes Anticline, Eastern Cordillera, Synrift, Transverse zones, Stress tensors.

RESUMEN. Sedimentación sin-extensional durante el Jurásico tardío e inversión Cenozoica de la cuenca según registro de la Formación Girón, Andes del norte en Colombia. El Anticlinorio de los Yariguíes es una estructura regional localizada en el flanco occidental de la cordillera Oriental de Colombia e incluye el registro más potente de rocas sedimentarias continentales acumuladas cerca del límite Jurásico-Cretácico. Las rocas sedimentarias corresponden a litoarenitas y arenitas feldespáticas, pertenecientes a la Formación Girón, que fueron acumuladas en una cuenca extensional del Jurásico tardío, interpretada en este trabajo como una cuenca de rift. Se analizan las características sedimentológicas y composicionales de dos secciones depositadas en un sistema de rift complejo. Se identificaron variaciones importantes de espesor, desde 3,350 m en la sección tipo hasta 525 m en una sección de referencia en Zapatoca; también se identificaron cambios en las características petrográficas y en las litofacies de las unidades. Esto llevó a confirmar que la Formación Girón agrupa todas las facies continentales cuya fuente estaba localizada principalmente en los bloques exhumados del Macizo de Santander durante el Jurásico tardío. Las sucesiones syn-rift estaban segmentadas por estructuras transversales y por fallas longitudinales regionales del hombro del rift como la Falla Suárez. El marco tectónico del área de estudio muestra un predominio de regímenes compresivos con dirección O-E; esto permite asociar la cinemática local con la configuración original de la cuenca y con su posterior inversión tectónica. Sin embargo, una rotación horaria del campo de esfuerzos puede ser detectada del análisis de tensores de esfuerzo. La orientación final de los tensores de esfuerzo y de las fracturas de cizalla se relaciona con el efecto transpresivo de las fallas Bucaramanga y Lebrija en el área de estudio.

Palabras clave: Anticlinorio de Los Yariguíes, Anticlinal de los Cobardes, Cordillera Oriental, Syn-rift, Zonas transversales, Tensores de esfuerzo.

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#### 1. Introduction

The Jurassic stratigraphy has been a long-debated subject in the Colombian geological literature. Lateral and vertical correlations between sedimentary and volcanic units of this age are some of the most challenging topics, although several authors have attempted to establish valid correlations, no satisfying consensus has been reached. One clear example of these issues is the unique nature of the type section of one of the most well-known Upper Jurassic sedimentary units: the Girón Formation. This type section is different in fundamental stratigraphic aspects (e.g., thickness, architecture and facies successions) from all the other similar aged successions, precluding valid regional correlations. However, these differences can also be seen as tools for reconstructing a plausible scenario in which all the data can be conciliated. This has been achieved for some Jurassic basins located in Colombia and Mexico. In the Guaiira Peninsula of Colombia, the Jurassic sedimentary rocks of the Cosinas Group have been interpreted as the result of the infilling of one of multiple sub-basins created by Pangea's break-up (Nova et al., 2019). Units with similar characteristics to those of the Girón Formation are reported in Mexico for the Middle Jurassic (e.g., Todos Santos Formation, Huizachal Formation). They are interpreted also as the infilling of extensional basins (Michalzik, 1991; Godínez-Urban et al., 2011) located adjacent to the limit between Laurentia and Gondwana during Pangea's rupture, in the Middle-Late Jurassic (Martini and Ortega-Gutiérrez, 2016; Nova et al., 2019). Despite this, only the magmatic evolution of the basins is considered in most North-Andean Jurassic tectonic models (Spikings et al., 2015; Zuluaga et al., 2015; Bustamante et al., 2016; Rodríguez et al., 2018; Zuluaga and López, 2019); therefore, they lack a description of the sedimentary environments and their variations. Other studies try to conciliate all the geological data into different plausible tectonic models but lack a detailed scenario of each of the involved units (e.g., Martini and Ortega-Gutiérrez, 2016; Bayona et al., 2020).

We collected stratigraphic, sedimentologic and petrologic data, from two sections located along the same extensional structure, which was one of the multiple sub-basins developed during the Jurassic in the northern part of South America (*i.e.*, Yariguíes Basin *sensu* Velandia, 2017), located in the current

Yariguíes Range. This allows us to describe the basin characteristics and the possible along strike variations in structure and in the source area of the sedimentary rocks.

The geological mapping and measurement of joints and slickensides enable us to carry out an analysis of the structural geology to correlate stress tensors with the tectonic evolution since the initial inversion of the former basin. We also consider necessary to present the deformational frame along the Yariguíes Anticlinorium, as the regional structure that involves other subordinate folds as the Los Cobardes Anticline.

# 2. Geological Framework

#### 2.1. Tectonics and regional geology

The Colombian Andes are tectonically controlled by the interaction between the oceanic Nazca and Caribbean Plates with the continental South American Plate (Cediel et al., 2003; Cortés et al., 2005), and additionally by the influence of the Chocó-Panamá Block on the western continental margin since the Miocene (Duque-Caro, 1990; Taboada et al., 2000; Montes et al., 2015). Different episodes of subduction and terrane accretion in this border have generated the three mountain chains that compose the Northern Andean Orogen, i.e., Western Cordillera, Central Cordillera and Eastern Cordillera (Toussaint, 1995; Cooper et al., 1995; Cediel et al., 2003; Cortés et al., 2005). The geometry and composition of the orogen have been controlled, at least since the end of the Cretaceous, by the obliquity between convergent plates and their relative velocity, the allocthony/authorthony of accreted terranes, the reactivation of pre-existent anisotropies and by the buttress effect from the South American Plate and the Amazonian Craton interaction (Boinet et al., 1985; Mora et al., 2013, 2015; Jiménez et al., 2014; Velandia, 2017).

The Eastern Cordillera is a divergent orogen whose flanks are tectonically transported to its surrounding basins (Magdalena Valley Basin to the west and Llanos Basin to the East, Fig. 1). The Eastern Cordillera consists of thick Mesozoic-Cenozoic sedimentary and volcano-sedimentary successions, deposited over Paleozoic sedimentary/metamorphic and/or Cambrian-Ordovician and Proterozoic metamorphic

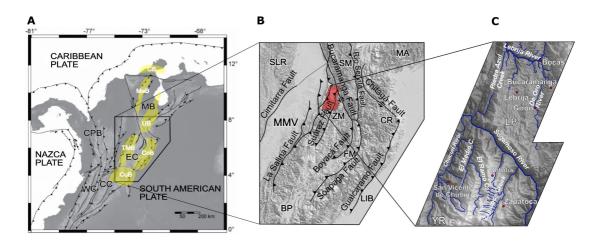


FIG. 1. A. Tectonic picture of Colombia, the main sedimentary basins are displayed in yellow. Modified from Mora et al. (2009);
B. Regional fault systems and morphostructural units of central Colombia. Fault names after Gómez-Tapias et al. (2015).
CPB: Chocó-Panamá Block; MB: Maracaibo Block; EC: Eastern Cordillera; CC: Central Cordillera; WC: Western Cordillera; CB: Cosinas Basin; MaB: Machiques Basin; UB: Uribante Basin; TMB: Tablazo-Magdalena Basin; CoB: Cocuy Basin; CuB: Cundinamarca Basin; SLR: San Lucas Range; SM: Santander Massif; MA: Merida Andes; MMV: Middle Magdalena Valley; FM: Floresta Massif; LlB: Llanos Basin; BP: Bogota Plateau; LP: Lebrija Platform; YR: Yariguíes Range; CR: El Cocuy Range; ZM: Zona de Mesas.

basement rocks that crop out in some localities associated with regional faults (Gómez-Tapias et al., 2015). Some igneous plutonic bodies of different ages (Paleozoic to Miocene) cut the metamorphic and sedimentary rocks (Mantilla et al., 2011; Leal-Mejía et al., 2019). The general trend of the Eastern Cordillera changes from SW-NE to SE-NW in an inflection area around the El Cocuy Range (Mora et al., 2015, Fig. 1). This inflection is attributed to the inherited structure from previous extensional tectonic phases (Jurassic-Cretaceous rift) and to the buttress effect exerted by the rigid South American Plate against the softer Eastern Cordillera orogen (Rossello et al., 2004; Tesón et al., 2013; Jiménez et al., 2014; Mora et al., 2015).

The origin of the Eastern Cordillera was conditioned by Mesozoic or older structures derived from an extensional tectonic regime, the Suárez, Bucaramanga, Boyacá, Río Servitá among other faults are some of these structures (Fig. 1). These faults, although highly debated, seem to have been originated or reactivated from a combined action of rifting and back-arc extension, since Pangea's spreading was starting and the Farallon Plate was subducting beneath the western margin of the South and North American plates (Pindell and Dewey, 1982; Toussaint, 1995; Sarmiento-Rojas et al., 2006; Bayona et al., 2006; Martini and

Ortega-Gutiérrez, 2016; Bayona et al., 2020). This extensional tectonism created several half-graben systems that were filled with thick volcanoclastic and clastic sequences of mostly continental affinity, some examples of theses basins are the Yariguíes Basin and Arcabuco-Norean Basin for the Jurassic, and Tablazo-Magdalena Basin, Cocuy Graben, and the Guatiquía and Pisba grabens for the Cretaceous (Fabre, 1983; Mojica and Kammer, 1995; Cooper et al., 1995; Sarmiento-Rojas et al., 2006; Clavijo et al., 2008; Mora et al., 2009; Tesón et al., 2013; Caballero et al., 2013; Velandia, 2017; Bayona et al., 2020). The Yariguíes Basin (Velandia, 2017) was one of the multiple depressions generated during the lithospheric stretching and extension, limited by former normal faults (the Suárez, Bucaramanga, San Vicente, and La Salina faults) which controlled the distribution of the sedimentary deposits. These faults were part of a rift-shoulder and juxtaposed uplifted basement highs with subsided sub-basins. Some of these rift-shoulder structures were connected with other major faults as the Boyacá, Río Servitá or Soapaga faults, which also controlled the distribution of the accommodation space therefore developing the basins (Kammer and Sánchez, 2006; Velandia, 2017). In posterior thermal subsidence conditions during the Cretaceous, marine sequences were

deposited across the maximum extension of the basin (Fabre, 1983; Cooper *et al.*, 1995; Sarmiento-Rojas *et al.*, 2006).

The onset of compressional deformation in the Eastern Cordillera was related to Maastrichtian-Paleocene inversion of former normal faults (the Suárez, Boyacá, and Río Servitá faults), associated with the basin closure and to the Eastern Cordillera orogen generation. An eastern advance of the deformation, with the highest orogenic pulses in the Oligocene, Miocene and Pliocene-Pleistocene is detected with thermochronology (Ross et al., 2009; Caballero et al., 2010, 2013; Horton et al., 2010; Parra et al., 2012; Bayona et al., 2013; Mora et al., 2013, 2015). This deformation pattern is associated with an episodic accretion of terranes driven by subduction in the western continental border (e.g., Quebrada grande Arc, Arquía Complex, the basement of the Western Cordillera and the Chocó-Panama Block; Duque-Caro, 1990; Villagómez and Spikings, 2013).

The current structural configuration of the Eastern Cordillera was attained by the combination of different processes related to tectonic positive inversion (Colletta et al., 1990; Cooper et al., 1995; Rossello et al., 2004; Mora et al., 2013; Tesón et al., 2013; Kammer et al., 2020), interpreted as transpression result of oblique subduction-accretion (Kammer, 1999; Montes, 2001; Rossello et al., 2004; Acosta et al., 2004, 2007; Montes et al., 2005; Velandia, 2005; Bayona et al., 2013; Montes et al., 2019) or thick-and thin-skinned tectonics (Julivert, 1970; Dengo and Covey, 1993; Roeder and Chamberlain, 1995).

## 2.2. Geology of the study area

The Yariguíes Anticlinorium is a divergent folded and faulted structure constituted by Jurassic-Cretaceous sedimentary rocks, trending NNE-SSW and limited to the north by the sinistral Bucaramanga Fault, to the east by the reverse Suárez Fault and to the west by a complex reverse fault system (San Vicente, La Parroquia, Cútiga, El Medio and Río Chucurí faults; Figs. 2 and 3). All these structures separate the Yariguíes Anticlinorium from the Santander Massif, Zona de Mesas and Middle Magdalena Valley respectively (Julivert, 1958; Royero and Clavijo, 2001) (Fig. 1). The southern termination of the anticlinorium

consists of a south-plunging symmetric fold named Los Cobardes Anticline, bounded by reverse faults (Pulido, 1979; Pulido et al., 1986). Besides Los Cobardes Anticline as the main and central structure, the anticlinorium is formed by several minor folds. Towards its western flank the folds are related to the reverse fault system with vergence to the west (Jiménez et al., 2016; Cetina et al., 2019); from this side to the axis of Los Cobardes Anticline other folds are shaped between the El Ramo and El Medio faults. To the eastern flank, the Zapatoca Syncline appears as a conspicuous fold in the hanging wall of the Suárez Fault, along which structural styles are related to thick-skinned tectonics, changing from higher or lower dip angles according to transversal compartmentalization (Flórez and Núñez, 2015). Recent tectonic activity was also reported for the Suárez Fault, mainly from geomorphological observations (Julivert, 1958; Díaz and Suárez, 1998; París et al., 2000; Diederix et al., 2008).

The core of the Yariguíes Anticlinorium is composed of a continental fluvial-alluvial sedimentary succession named Girón Group (sensu Cediel, 1968; Etayo-Serna, 1989) of Late Jurassic-Early Cretaceous age (Pons, 1982). The base of the Girón Group is the Girón Formation (Upper Jurassic) while the Los Santos Formation (Berriasian) constitutes the top (Cediel, 1968; Ward et al., 1973; Etayo-Serna and Rodríguez, 1985). The name Lebrija River Formation has been proposed by Etayo-Serna (1989) and Clavijo and Camacho (1993) in exchange for the name Girón Formation to avoid the homonymy between the two stratigraphic hierarchies involved (i.e., Girón Group and Girón Formation), and also considering the geographical location of the best preserved and most complete succession on the Lebrija River.

Towards the northeastern and central part of the study area, the Girón Formation is resting upon an angular unconformity over the volcano-sedimentary Jordán Formation of the Lower Jurassic (Zr U-Pb ages of 199.37±0.34 Ma and 198.49±0.33 Ma; Alarcón and Rodríguez, 2019). In the northern area, the Girón Formation makes an angular unconformity with both the Jordán Formation and the Upper Triassic-Lower Jurassic Bocas Formation (Ward *et al.*, 1973; Royero and Clavijo, 2001) (Figs. 2 and 3), the angular unconformity with the Bocas Formation is faulted (Ward *et al.*, 1973). The overlying Cretaceous

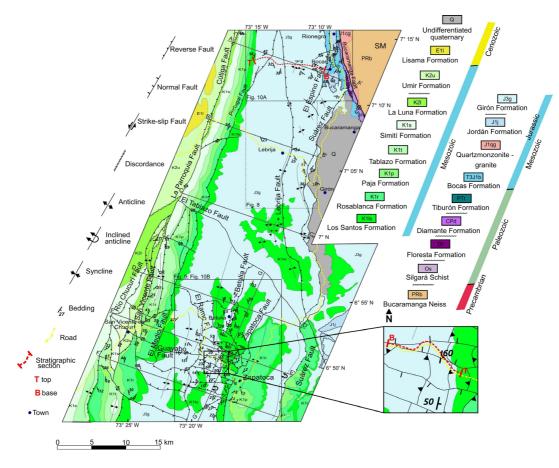


FIG. 2. Geologic map of study area. Cross sections are presented in figure 3. The legend shows the lithostatigraphic units located in geologic time.

marine succession of Valanginian to Maastrichtian age (Sarmiento *et al.*, 2015) crops out in the flanks of the Yariguíes Anticlinorium, and in the core of some inner synclines (Figs. 2 and 3) (Ward *et al.*, 1973; Guzmán, 1985; Cetina *et al.*, 2019).

The Girón Formation shows variations in its thickness and lithofacies in different sections along the Eastern Cordillera, including the Santander Massif. In the north western flank of the massif, the Girón Formation is 135.5 m thick, and contrasting with other sections, lacks conglomerates (Ward et al., 1973). In the southern central part of the Santander Massif, close to the Río Servitá Fault (Fig. 1), thicknesses of 700 m had been reported (Ward et al., 1973). In the Zona de Mesas the Girón Formation has a maximum thickness of 50 m and pinches out in an eastward direction until it disappears under the Los Santos Formation (Pinto

et al., 2008; Ayala-Calvo et al., 2005), whereas, south of the study area, an upward fining succession of 704 m was reported by Pulido (1979). Farther south, in the Floresta Massif (Fig. 1), the Girón Formation varies in thickness from a few meters to ca. 500 m, and develop upward coarsening successions in the proximity of interpreted ancestral normal faults (e.g., Soapaga Fault; Kammer and Sánchez, 2006; Méndez-Espinosa, 2017). In all these outcrops the Girón Formation rests over different rock types, from Precambrian-Paleozoic metamorphic rocks, Triassic-Jurassic marine marginal siliclastic (Bocas Formation) to volcanoclastic and/or sedimentary rocks (Jordán Formation). After a future detailed stratigraphic study, the above exposed variations in thickness, lithofacies types and vertical profiles may support the usage of the Girón Group nomenclature to encompass the different sections.

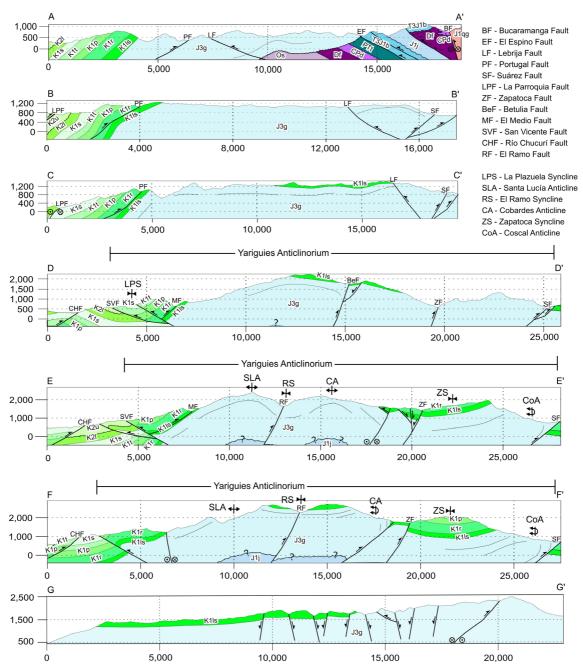


FIG. 3. A-A' to G-G' cross sections of the study area as indicated in figure 2. A thickness of 2,500 m is assumed for Girón Formation in sections D-D', E-E', F-F'. Legend as in the geologic map in figure 2. This figure illustrates the along strike variations in the structuration of the Yariguíes Anticlinorium.

# 3. Methodology

We carried out a multidisciplinary approach based on geological mapping, stratigraphic, sedimentologic, petrologic and structural data compilation and analysis. For the cartographic phase, we conducted firstly an analysis of Landsat imagery (LC80080552015004LGN00, 2015) and aerial photography (Flights C-2642-218\_225, C-2643-153\_155; C-2588-10\_19, 27\_33, 85\_93,

from the Agustín Codazzi Geographic Institute) for the lineament and outcrop identification. Secondly, several field trips were made to verify and refine the map published by Ward *et al.* (1977); additional geological information in Julivert (1958), Cediel (1968), Ward *et al.* (1973), Chacón (1981), Clavijo (1985), Laverde and Clavijo (1985), Renzoni (1985) and Guzmán (1985) was analysed. The resulting map also took into account some data published in the maps of Royero and Vargas (1999), Diederix *et al.* (2008), Jiménez *et al.* (2016) and Cetina *et al.* (2019).

The stratigraphic analysis was focused on the Girón Formation, with its type locality in the gorge of the Lebrija River. We measured this section using a Jacob staff and considered the stratigraphic descriptions of Cediel (1968) to compare this succession with a stratigraphic section measured and described in the surroundings of Zapatoca (Fig. 2); we used sedimentological criteria by Campbell (1987) and Reineck and Singh (1973) and the facies associations and architectural analysis of Miall (2006).

Eleven sandstone samples were taken for petrographic analysis, five from the Zapatoca section and five from the Lebrija River section. One sample was obtained near Lebrija for comparison. A 400 point counting was made in each sample using the Gazzi-Dickinson methodology (Ingersoll *et al.*, 1984), with the criteria given in table 1.

The inversion of stress tensors was derived from fault planes with slickensides measured in 14 sites, located along the Lebrija River, and around Lebrija and Zapatoca localities. Only one of these sites corresponds to outcrops of Cretaceous rocks (Los Santos Formation), while the other data are associated with the Girón Formation. At each site, fault slip data were collected under a standard procedure that mainly consisted of measurements of dip and dip direction of the fault plane and orientation of the slickenline (pitch and its azimuth). The sense of the movement was determined according to the kinematic indicators from Petit (1987) and Doblas (1998), especially Riedel and PT-type structures.

The Win-Tensor software (Delvaux and Sperner, 2003) was used for the inversion of stress tensors. It deals with the four parameters defined by Angelier (1994): the three principal stress axes ( $\sigma$ 1,  $\sigma$ 2 and  $\sigma$ 3) and the stress ratio R ( $\sigma$ 2- $\sigma$ 3/ $\sigma$ 1- $\sigma$ 3). Additionally, R' is also quantified (Delvaux *et al.*, 1997) for consideration of the vertical stress axis:

 $\sigma$ 1 (extensional, R'=R),  $\sigma$ 2 (strike-slip, R'=2-R) and  $\sigma$ 3 (compressional, R'=2+R).

During processing, Win-Tensor allows the supervision of mechanical, kinematic and quality parameters. In this way, it was possible to separate low confidence data to better constrain the stress tensor. Every subset of data was first filtered until reaching improved counting values:  $\alpha$  lower than 30° and the optimisation of function F5. For Delvaux and Sperner (2003) the quality factor for each tensor (QRt) depends mainly on the data amount (n), their level of confidence, and the percentage of used planes based on the total data per site, among others (Sperner and Zweigel, 2010), but in cases of few collected data, it is important to have different orientations of the planes.

Joints were analysed by grouping them according to the location of nearest measurement sites into the structural framework and by plotting data using Stereonet 9.2.3 software to obtain rose and pole diagrams.

#### 4. Results

# 4.1. Geological mapping

The geology of the northern part of the Yariguies Anticlinorium is presented in figure 2 (YR in Fig. 1) as bordered by the Suárez Fault to the east, and the thrust fault system led by the San Vicente Fault to the west (Fig. 3). It is important to note the effect of the Suárez Fault and other longitudinal faults within the Yariguíes Anticlinorium configuring the structural style of the area (Figs. 2 and 3). These faults control the development of almost all the folds. From the geological mapping, the Yariguíes Anticlinorium is recognized as the regional structure that involves other minor folds as the La Plazuela, El Ramo and Zapatoca synclines, and the Santa Lucía, Los Cobardes and Coscal anticlines (Fig. 3). The asymmetry of these latter two folds in cross section F-F' (Fig. 3) marks a clear eastward vergence in the southern segment that is not evident in the northern segment of the study area (e.g., cross section C-C' in Fig. 3). Other minor related folds are present in the western flank of the anticlinorium, related to the San Vicente Fault and/or other west-verging and east-verging faults.

As exceptions, the El Medio and Portugal faults do not develop related folds, in contrast they are

TABLE 1. POINT COUNTING PARAMETERS AND RECALCULATED MODAL POINT-COUNT RESULTS FOR SAMPLES IN LEBRIJA RIVER AND ZAPATOCA SECTIONS.

Symbol		Defin	ition						Recalcu	lated par	ameters			
Qm		Mono	ocrystallir	e quartz					QtFL%0	Qt=100Qt	/(Qt+F+L)	)		
Qpq		Polyc	ristalline	quartz					QtFL%l	F=100F/(C	Qt+F+L)			
Qc		Chert	;						QtFL%l	L=100L/(0	Qt+F+L)			
K		Potas	sium feld	spar					QmFLt <sup>9</sup>	%Qm=100	Qm/(Qm	+F+Lt)		
P		Plagi	oclase fel	dspar					QmFLt <sup>o</sup>	%F=100F/	(Qm+F+I	Lt)		
Lvf		Felsit	ic volcan	ic lithic gr	ains				QmFLt <sup>o</sup>	%Lt=100L	t/(Qm+F-	+Lt)		
Lvl		Lathy	vork volc	anic lithic	grains					s%Lm=10	,			
Lvm		Micro	olitic volc	anic lithic	grains				LmLvL	s%Lv=100	0Lv/(Lm+	Lv+Ls)		
Lvt		Turra	ceus and	vitric volc	anic lithic	grains			LmLvL	s%Ls=100	$\frac{1}{2}$	Lv+Ls)		
Lm		Meta	morphic g	grains					QmPK%	%Qm=100	Qm/(Qm+	+P+K)		
Ls		Sedin	nentary g	rains					QmPK%	6P=100P/	(Qm+P+K	<b>(</b> )		
Qt		Total	quartzose	grains (=	Qm+Qpq	+Qc)				-				
F		Total	feldspar (	=K+P)						-				
Lv		Total	volcanic	grains (=L	_vf+Lvl+I	Lvm+Lvt	)			-				
L		Total	unstable	lithic grain	ns (=Lm+	Lv+Ls)				-				
Qp		Total	polycryst	alline qua	rtz (=Qpq	+Qc)				-				
Lt	Total polycrystalline quartz (=Qpq+Qc)													
Sample							QmKP%							
Sample	Qt	F	L	Qm	F	Lt	Lm	Lv	Ls	Qm	K	P	P/F	Lv/L
Lebrija River	r section													
RL1	70	16	14	63	16	21	15.3	68	17	80	14	6	0.30	0.68
RL2	49	8	43	41	8	51	33	53	14	83	13	4	0.21	0.53
RL3	63	28	9	58	28	14	12	81	7	68	21	11	0.35	0.81
RL4	67	20	13	61	20	19	48	13	39	75	14	11	0.44	0.13
RL5	65	27	8	62	27	11	25	18	57	70	20	10	0.32	0.18
Zapatoca sect	tion													
Z1	83	0	17	71	0	29	47	0	53	100	0	0	0.00	0.00
Z2	47	29	24	43	29	28	7	3	90	60	26	14	0.34	0.03
Z3	50	36	14	47	36	17	17	3	80	57	25	18	0.43	0.03
Z4	77	5	18	76	5	19	6	0	94	94	0	6	1.00	0.00
	1	2	18	77	2	21	6	16	78	98	0	2	0.89	0.16
Z5	80	2	10	, ,	-	21					•	_	0.05	
Z5 Lebrija samp			10	,,,									0.05	
	''													

considered as slip planes linked to flexural faults along syncline limbs (cross sections B-B' to D-D', Fig. 3). Along the Lebrija and El Espino faults, in the central and northern part of the area (Lebrija Platform, Fig. 1) the relief is less pronounced than in the south, and the internal folding and faulting is less developed (Figs. 2 and 4A). In addition, the topographic effect of longitudinal faults differs, being more evident along the Bucaramanga Fault

with evidences of neotectonic activity (Jiménez et al., 2015; García-Delgado et al., 2019, 2020; Velandia et al., 2020) than along the Lebrija, El Espino and La Plata faults, whose recent activity is still uncertain (Fig. 3, sections A-A', B-B' and C-C', and Fig. 4A). In the north, La Plata Fault is related to the outcropping oldest geological units (Bocas, Floresta and Diamante formations).

Several transverse faults border the termination of longitudinal faults and folds, as the El Tablazo Fault, which marks the abrupt northern end of the San Vicente, Betulia and Zapatoca faults (Figs. 2 and 3 section G-G' and 4E and F). El Tablazo Fault is responsible for the actual orientation of the Sogamoso River which cuts the Yariguíes Range in a NW-SE direction (Fig. 1). Other minor transverse faults (*e.g.*, La Zarza Fault, Quebraditas Fault, Fig. 2) separate beds with different attitude or juxtapose different geological units along the trend of the major folds, and in some cases, these transverse faults seem to control the change in sedimentological attributes of the Girón Formation, as described below.

# 4.2. Stratigraphy of the Girón Formation

#### 4.2.1. Lebrija Type section

The following description is based on the work of Cediel (1968). The succession of the Girón Formation in the Lebrija River type section has been divided in seven segments (A-G) according to their lithology and facies (Cediel, 1968) (Fig. 5). The base of the succession (Segment A) makes an angular unconformity with the underlying Bocas Formation. Segments A and C are similar and consist of very thick (>100 cm) lenticular beds of medium-coarse to conglomeratic sandstones with cross stratification and scarce interbeds of conglomerates and mudstones. In the conglomerates the largest clast diameter is 4 cm.

Segments B, D and F are similar and are characterized by the presence of reddish to purple mudstones (red-beds, representing 30%-60% of the total), interbedded with thick (30 cm-100 cm) lenticular beds of medium-coarse grained sandstones with trough-cross stratification. There are scarce conglomeratic beds; less than in the sandy segments (*i.e.*, segments A, B). The contacts between sandstones and mudstones are erosive. Segment B has sporadic coal lenses.

Segment E is different from the rest of the succession and is composed of fine grained sandstones and grey mudstones in beds no thicker than 70 cm, the sandstone beds have cross-stratification. There are more coal lenses than in the segment B, also there are assymetric ripples, dissecution cracks and root fossils that could indicate the presence of paleosoils (Cediel, 1968). The conglomeratic beds are less frequent than in the other segments.

Segment G represents the top of the succession and is composed of fine-medium grained sandstones, with abscence of interbedded mudstones. The bed thickness decreases up-section from very thick beds (>1 m) at the base to medium-thick beds (10-40 cm) at the top, this segment also shows a fining upward succession. The presence of conglomeratic beds is similar to that in segments A and C, but in this segment they increase up-section. The main structures present are cross-stratification, tool marks at the base of the sandstones, and asymmetric ripples and desiccation cracks at the top of the succession. Above this segment, there is continuity in the facies development between the Girón and Los Santos formations (Fig. 4B, C and D) (Cediel, 1968; Clavijo, 1985).

The measurement of the thickness in the type section of the Girón Formation gave as result a total thickness of 3,350 m, similar to the thickness measured by Langenheim (1959) (i.e., 3,500 m) (Fig. 5). The stratigraphic scheme of Cediel (1968) allowed us to make a correct upward advance during the measurement of the succession, avoiding the repetition or missing of stratigraphic intervals. The methodology used to measure the section allows a direct observation and correction of the minor displacements along faults in the succession, thus giving an accurate calculation of the stratigraphic thickness. Although two regional reverse and reversesinistral strike-slip faults cross the succession at the western side of the section (Portugal and Lebrija faults; Figs. 2, 3 and 5), their outcrop expression is along narrow damage zones, including some joint families, and meso-scale dip-slip components, which were easily controlled to follow bedding continuity.

#### 4.2.2. Zapatoca Section

The 525 m thick succession of sedimentary rocks described in Zapatoca (Fig. 6) is incomplete because the base of the Girón Formation does not crop out. We infer a thickness of *ca.* 2 km considering a mean between a reported thickness of 1.2 km in the southern tip of the anticlinorium (Pulido *et al.*, 1986; although the base does not crop out there either) and 3.35 km reported here for the northern part of the structure (see cross sections E-E', F-F' in Fig. 3). The lower 350 m are predominantly sandy and consist of lenticular-bedded pebbly sandstones, interbedded with medium-to fine-grained sandstones



FIG. 4. Field photos of study area. **A.** the closest area from the Bucaramanga Fault and its splay faults. **B.** and **C.** show the transitional contact between the top of the Girón Formation and bottom of the Los Santos Formation. Notice the inverted succession in **D.**, **E.** and **F.** show some of the transverse faults that affect the eastern flank of the Cobardes Anticline. Labels as in the geologic map (Fig. 3).

(Fig. 6F). Fining-upward successions start with erosive bases, where a pebbly sandstone bed rests over a mudstone package; to the top, sandstone bodies of systematic upward decreasing grain size grade to purple mudstones, which are again cut by

conglomeratic sandstones (Fig. 6C and D). Below the base of this 350 m succession, the rocks contain coarser clasts, reaching cobble sizes. Concave-upward cross stratification, trough-cross bedding and normal gradation are the most common structures in the

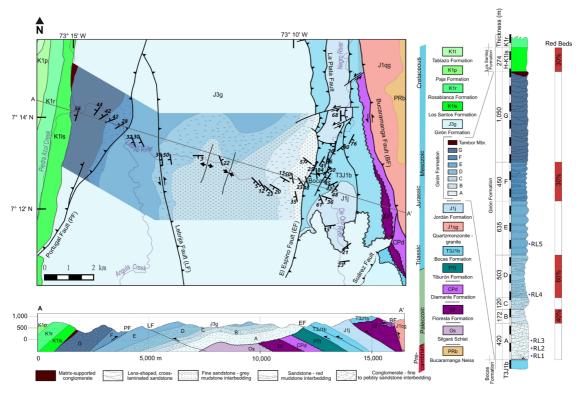


FIG. 5. Geological map of the Lebrija River zone. To the right, stratigraphic section of the Girón Formation, subdivisions according to Cediel (1968), thickness measured in this work. Notice that the red beds are not ubiquitous through the whole succession. Dots labelled RL (1-5) represent petrographic samples. The Bucaramanga and Lebrija faults are marked as transpressional structures with left lateral slip. **PF:** Portugal Fault; **LF:** Lebrija Fault; **EF:** El Espino Fault.

sandstones (Fig. 6E), whereas the mudstones have parallel lamination.

The upper 175 m are muddy dominated, with local lenticular sandstones (Fig. 6A and B). Towards the top, the sandstone beds are finer grained and thinner, and become scarce. Concave-upward stratification is still common in the sandstones. Some isolated sandstone beds include climbing ripples. Green horizons and spots are common in the upper part of the succession, interbedded and affecting the mudstones. The whole succession shows a big fining-upward cycle with subordinated fining-upward successions (Fig. 6).

# 4.3. Petrology

The results of petrographic analysis are listed in table 1. Five samples were taken from segments A, D and E in the type section of the Girón Formation (Fig. 5), one sample was collected near Lebrija

locality that may likely corresponds to segment G, and four samples were collected, distributed along the whole succession of Zapatoca section (Fig. 6), which corresponds to the upper segment of the Girón Formation. The analysed samples of the Zapatoca section plot in the sublitharenite and arkose lithic fields, and the Lebrija River samples are arkose lithic and litharenites, whereas the Lebrija sample plots in the feldspathic litharenite field of the QFR diagram (Folk, 1968) (Fig. 7A). This classification remarks the importance of feldspar-lithic-rich sources. In the provenance QtFL triangle (Dickinson, 1985), one provenance field (recycled orogen) is obtained for the whole set (Fig. 7B). In the QmFLt discrimination diagram (Dickinson, 1985), three fields (continental transitional, mixed and recycled quartzose) are common for both Zapatoca and Lebrija River samples (Fig. 7C). One Zapatoca sample plots in the dissected arc field and the Lebrija and one Lebrija River sample plot in the recycled transitional field

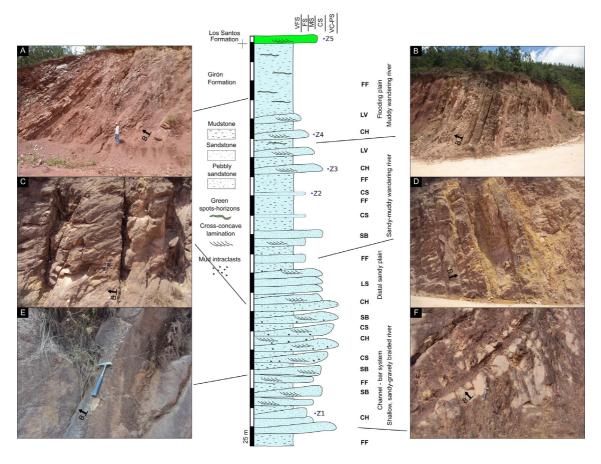


FIG. 6. Stratigraphic section measured and described in Zapatoca. A to F field photos of the sedimentary rocks, the black arrow shows the stratigraphic way-up direction of the strata. Architectural names from Miall (2006). Arquitectural elements formed within channels: CH: Channels; LS: Laminated sand sheets; SB: Sandy bedforms. Arquitectural elements of the overbank environment: LV: Levee deposits; CS: Crevasse splay deposits; FF: Floodplain fines. Dots labeled Z (1-5) represent petrographic samples.

(Fig. 7C). Althought with dispersion, the LmLvLs diagram (Marsaglia and Ingersoll, 1992) separates some Lebrija River and Zapatoca samples, putting the Lebrija River samples closer to the Lv corner and relating them to a volcanic source, whereas Zapatoca samples plot closer the Ls corner (Fig. 7D). In the QmKP diagram (Dickinson, 1985) almost all the samples are grouped in the field related to the highest compositional maturity with sources in continental blocks (Fig. 7E).

# 4.4. Structural geology

# 4.4.1. Stress tensor analysis and interpretation

One stress tensor was obtained per each one of the 14 sites considered in this study (Figs. 8 and 9); only 73 of the total 103 measured fault planes were taken into account for the inversion method (71% of the data). The results are summarised in table 2 and shown in the geological maps of the Lebrija River, Lebrija and Zapatoca sectors (Figs. 8 and 9).

The obtained stress tensors for the Lebrija River (Fig. 8) show a dominant compressional stress regime, as evidenced by the reverse faults and local folds. Transverse faults with a NW strike and reverse kinematics are especially related to the stress tensor (sites 1, 3-5, and 7 in Fig. 8), as well as other W-E trending faults with dextral movement as shear planes of the same stress orientation (site 2 in Fig. 8). The systematic NW-SE orientation of the horizontal compressive axes (or horizontal maximum stress: Shmax) seems to be related to the current stress tensor imposed by the sinistral kinematics of the Bucaramanga Fault.

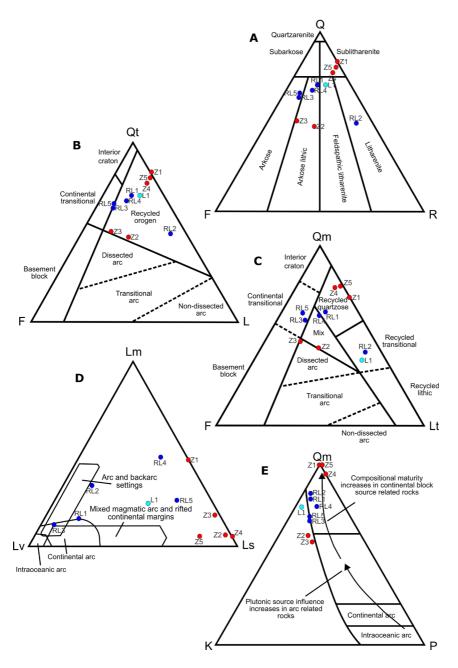


FIG. 7. Classification and provenance diagrams for sedimentary rocks used in this work. Modified from A. Folk, 1968; B., C., E. Dickinson, 1985; D. Marsaglia and Ingersoll, 1992.

Stress tensors located near Lebrija (site 8 in Fig. 8) show horizontal compressional axes oriented NNE-SSW, under an extensional or strike-slip regime. The NWW-SEE stress tensor near the Suárez Fault was obtained from oblique minor faults with the same trend of the tensor and with a strike-slip regime

(site 6 in Fig. 8). These minor transverse faults may correspond to the local accommodation of the Suárez Fault. This NWW-SEE tensor is also related to the regional stress tensor of the sinistral strike-slip Bucaramanga Fault (Velandia and Bermúdez, 2018; Velandia *et al.*, 2020).

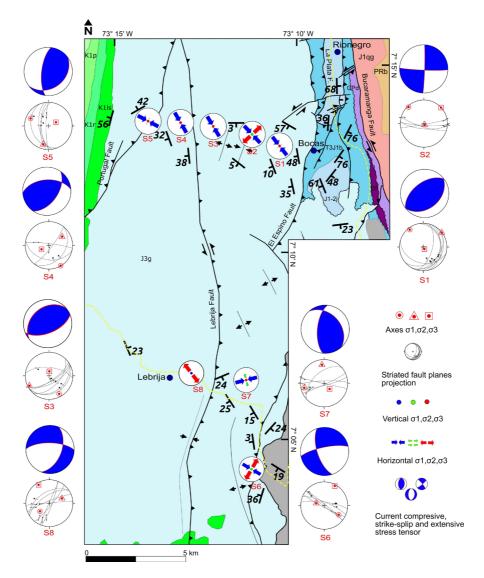


FIG. 8. Tensor and beachball distribution in the Lebrija River area. Angelier (1994) graphics are also plotted for a better fault visualisation. Square, triangle and circle represent  $\sigma 1$ ,  $\sigma 2$  and  $\sigma 3$ , respectively. Legend and conventions as in the geologic map.

In the Zapatoca sector, several orientations of the stress tensors were obtained, implying that even local differences of the fault planes orientations can be related to changes in the stress field affecting the area (Fig. 9, Table 2). The interpreted latest stress field is related to the kinematics of the Bucaramanga Fault, since the drag of the western block induced a NW-SE tensor, as in sites 9 and 12 (Fig. 9) under extensional and strike-slip regimes, respectively. Most of the folds and longitudinal reverse faults confirm a NWW-SEE stress tensor, as well as the transverse normal faults trending almost parallel to

this tensor (Fig. 9). Nevertheless, other normal faults trending near S-N are also observed. Such orientation can be associated to interpreted previous NE-SW stress tensors obtained for the other four sites (sites 10, 11, 13 and 14 in Fig. 9), whose stress regimes in strike-slip and extension explain transtensional and/or normal faults. The transverse normal faults are related to strike-slip faults as revealed by the planes projected to the lower hemisphere and stress tensors in beach balls, and even have been reactivated with such components under the NW-SE stress tensor (sites 12 and 9 in Fig. 9, Table 2).

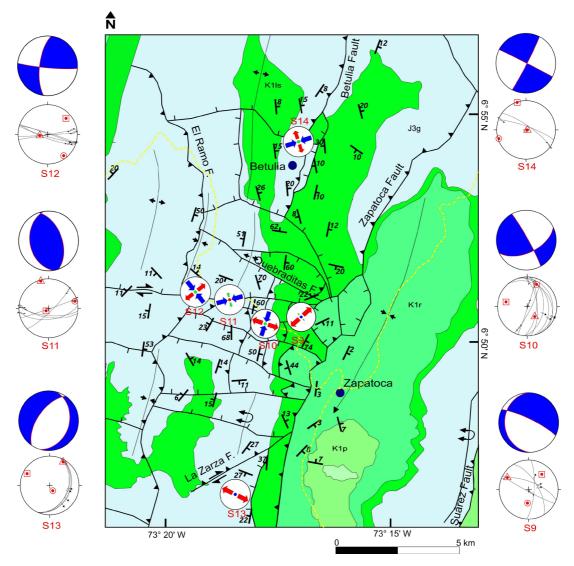


FIG. 9. Tensor and beachball distribution in the Zapatoca area. Angelier (1994) graphics are also plotted for a better fault visualisation. Square, triangle and circle represent σ1, σ2 and σ3, respectively. Legend and conventions as in the geologic map.

Differences in the horizontal compressional axes (or Shmax) of this previous stress tensor indicate some clockwise rotation from NE-SW to NEE-SWW, perhaps in accordance with the local kinematics of the structures.

#### 4.4.2. Joints

Considering the structural framework of the area and the location of sites with measured joints, it was possible to group data around the Lebrija River and Zapatoca areas. For the first sector, we analysed the data distributed into four areas

bounded by faults (Fig. 10A). Joints between the Bucaramanga and El Espino faults show a main NNW trend parallel to the Bucaramanga Fault, the main strike-slip structure of this part of the Eastern Cordillera. The second order joints of this group consist of conjugate fractures to the Bucaramanga Fault, and together configure a simple shear pattern that confirms the sinistral kinematics of the fault. Joint data located between the El Espino and Lebrija faults show the same pattern, but with a prevalence of the NW trend (conjugate to Bucaramanga Fault). Meanwhile, data

TABLE 2. SOLUTIONS STRESS TENSORS FROM PLANES WITH SLICKENSIDES.

 Coordinates	inates	Geological		=	S <sub>2</sub>	Stress axes		Count.		-		-		Š	
 Longitude (°W)	Latitude (°N)	unit	g	subset	61	62	63	Dev.	8	<u>ē</u>	×	¥	Shmax	QRt	Stress regime
73°10°34"	7°12'34"	Girón	7	11	08/322	01/053	81/152		6.5	2.4	0.45	2.45	142	ш	Pure compressional
73°11'00"	7°12'37"	Girón	4	4	05/317	85/146	01/047		8.1	2.8	0.5	1.5	137	Э	Pure strike-slip
 73°12'17"	7°13'13"	Girón	7	10	13/151	08/243	900/5/	1	3.9	2.6	0.52	2.52	149	О	Pure compressional
73°13'04"	7°13'18"	Girón	4	9	01/150	29/059	61/242	1	24.3	21	0.5	2.5	150	Э	Pure compressional
 73°13'39"	7°13'35"	Girón	S	9	20/293	20/195	61/064		10.9	4.6	0.41	2.41	118	Э	Pure compressional
 73°11'09"	7°04'53"	Girón	S	6	28/122	61/286	07/028		9.5	4.3	0.59	1.41	120	Э	Pure strike-slip
73°11'26"	7°06'13"	Girón	S	9	15/257	23/353	62/136	ı	3.7	0.7	60.0	2.09	92	Э	Strike-slip compressional
 73°12'33"	7°06'33"	Girón	7	13	46/229	42/069	10/330	1	9.4	3.4	0.26	0.26	53	О	Oblique extensive
73°12'48"	6°47'17"	Los Santos	4	S	52/185	18/299	33/041		S	3.3	89.0	89.0	138	Э	Pure extensional
73°14'33"	6°48'00"	Girón	∞	14	20/023	55/143	28/282		8.3	3.2	0.52	1.48	18	О	Pure strike-slip
 73°18'26"	95.05.9	Girón	5	9	08/075	05/345	81/225		5.5	1.4	0.13	2.13	75	Э	Compressional strike-slip
73°19'00"	6°51'05"	Girón	9	9	11/143	68/260	19/049		7.3	2.6	0.33	1.67	142	Э	Pure strike-slip
73°18'23"	6°46'22"	Girón	4	4	73/149	08/030	15/298		15	7.4	0.5	0.5	26	Ħ	Pure extensional
73°16'35"	6°55'04"	Girón	7	ж	03/252	260/98	01/342	9.3			0.25	1.47	72	Щ	Compressional strike-slip

Main parameters as, n: number of striated planes used for the inversion of stress tensor; n subset: of n lane subset; σ1, σ2, σ3: orientation of the stress axes; α: mean deviation slip value; F5: optimization function; R: stress ratio (σ2-σ3/σ1-σ3); R': stress regime index; Shmax: Horizontal maximum stress; QRt: Quality factor.

located between the Lebrija and Portugal faults maintain the previous trends of shear but show a W-E orientation as the main set. These transverse joints are also observed westward of the Portugal Fault, but in a tensile pattern with a NNE trend, which is almost parallel to this longitudinal fault.

For the Zapatoca area, we have clustered the data into three areas: (i) between the Zapatoca and Suárez faults, (ii) Betulia and (iii) NW Zapatoca, between the El Ramo and Zapatoca faults (Fig. 10B). The first group shows the N trending longitudinal joints, but with high angles, which are consistent

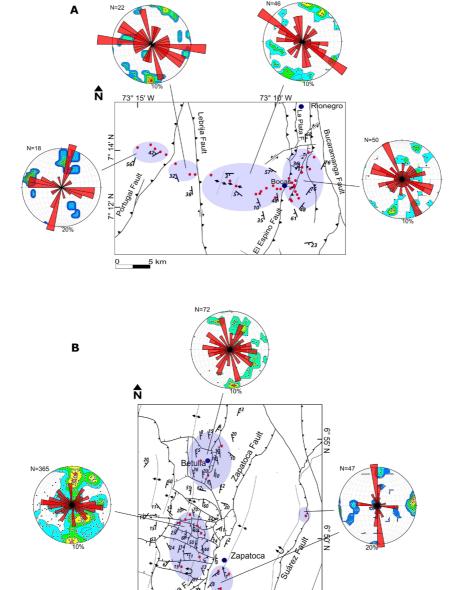


FIG. 10. Distribution of joints measured in the two studied areas. A. Lebrija River and B. Zapatoca. Red dots represent measurement stations. Graphics present both cumulative directional data and pole density.

5 km

with tensile fractures parallel to the axial plane of the Coscal Anticline, interpreted as a drag fold of the Suárez Fault. This assumption rises since most of the measured joints of the group correspond to the closest site to the fault, whereas the data of the second set (Betulia) show a random distribution, but for the same reason can be representative of the whole fracture frame of the area. In contrast, the third group which includes the highest data population exhibits in a clear way the W-E trend that matches well with the abundant normal faults of the sector, disposed transverse to the reverse longitudinal faults.

#### 5. Discussion

# 5.1. Sedimentology and stratigraphy of the Girón Formation

The Girón Formation in the Lebrija River type section shows cyclicity in the facies evolution. The first six segments (A-F) show various cycles of deposition in a braided river system (segments A and C) and its floodplain (segments B, D and F); generating different depositional forms as sandy-gravelly bars, channel fill profiles, and levees and crevasse splays in the floodplain. Segment E represents a less energetic environment in which soils developed, probably a swamp as revealed by the presence of fossil roots (Cediel, 1968).

It is worth noting that the contact between the Girón Formation and the overlying Los Santos Formation is controversial. It has been pointed out as discordant by Ward et al. (1973), but detailed studies by Cediel (1968), Clavijo (1985) and Laverde and Clavijo (1985) have recognised this contact as a transitional one. Although the transition extends to almost 20 m, the lithological composition of both units is contrasting which allows the detection of a change from a unit with rocks composed primarily of feldspar and rock fragments (Girón Formation) to another whose quartz content is higher to almost unique (Los Santos Formation). Using this contact as an indicator of the top, a section of the Girón Formation was measured and described along the Zapatoca-Betulia-San Vicente de Chucurí road, in the Alto Tú y Yo (Figs. 2 and 6).

The thickness of 525 m described in the Zapatoca section right under the contact with Los Santos Formation, can be compared with the upper 1,050 m

of the Girón Formation in the Lebrija River section (segment G by Cediel (1968) in Fig. 5) (Fig. 11). This part of the Lebrija River section exhibits a sandy homogeneous succession with scarce mudstone interbedding; its facies architecture has been attributed to the action of braided rivers close to a mountain front (Cediel, 1968). Right on the top of this succession. a thick matrix-supported conglomerate, named previously as the Tambor Formation (Morales et al., 1958 in Ward et al., 1973) and better defined as the Tambor Member by Etayo-Serna (1989), is interpreted as a debris flow deposit related to an alluvial fan (Clavijo, 1985). None of these characteristics were observed in the Zapatoca section. There, based on the facies associations (Fig. 6) characterized by the presence of fining upward facies sequences with architectural elements such as levees, crevasse splays and channel fill cycles, the succession was interpreted as generated by gravelly-sandy braided rivers in the lower part, which evolve to more sinuous and stable wandering streams up-section. The upward fining sequence in Zapatoca is the result of a progressive retreat of the clastic sources and widening of the valley, as shown by Gawthorpe and Leeder (2000) for extensional basins; in this sort of basins, well defined by bordering faults, high amounts of subsidence contributes to the establishment of axial drainage systems near the fault traces (Blair, 1988; Prosser, 1993) (Fig. 12). In contrast, The Girón Formation in the Lebrija River section reveals different stacking patterns, from retrogradational in the segments from A to E, to progradational and/or aggradational in the segments F to G (Figs. 5 and 11).

The observed variations in the facies sequences in the two sections can be interpreted in two ways: (i) a normal fluvial spatial evolution caused by a southward decrease of the gradient or (ii) a spatial variation in environmental characteristics due to geographical barriers. The short distance between the two sections (~50 km) inhibits the first alternative as the more plausible. As a consequence, the presence of geographical barriers such as mountain ranges and/or depressions, which changed the characteristics of the sedimentary conditions along the strike of the basin is proposed as the principal factor controlling the depositional of sediments (e.g., Athmer and Luthi, 2011) (Fig. 12). In this sense, we propose a close proximity of the Lebrija River segment of the basin to the ancestral Bucaramanga Fault, and consider this structure as a dextral strike-slip fault

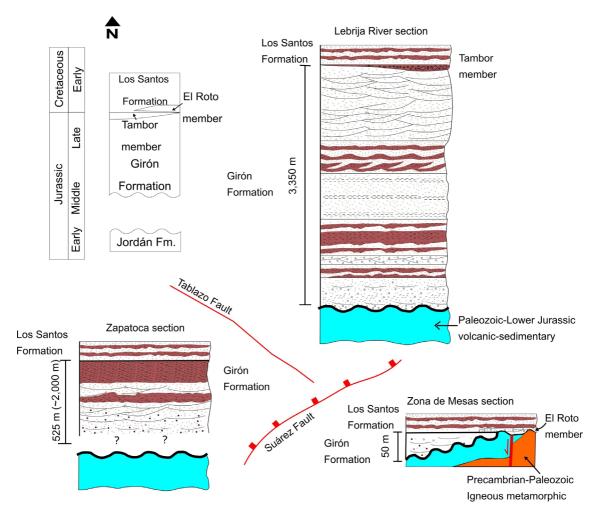


FIG. 11. Correlation between differents sections of the Girón Formation in the reconstructed Yariguíes Basin. Notice the variations in thickness, facies and in the lower contact at each side of the Suárez and Tablazo faults.

(transtensional) as proposed by Kammer and Sánchez (2006), Velandia (2017), and Kammer *et al.* (2020). The presence of releasing and restraining bends along the fault will promote the development of both the accommodation space and the source for a constant flow of clastic material (Fig. 12).

Barriers along the course of extensional basins have been observed both on analogue modelling (McClay *et al.*, 2002) and on natural examples (Gawthorpe and Leeder, 2000; Athmer and Luthi, 2011), and are related to accommodation zones, relay ramps and/or transfer fault zones. The presence of along-strike variations in the sedimentary basin conditions could contribute to the heterogeneous character of the Girón Formation; that varies in thick-

ness, composition and facies sequences, depending on the amount of subsidence and the rock type of the source area for each sub-basin, and also on the climate as a clue factor (Cediel, 1968; Ramos *et al.*, 1986; Gawthorpe and Leeder, 2000). Transverse faulting and folding relative to the main regional longitudinal structures is the current expression of those ancient barriers. Transverse structures presented here (*e.g.*, Quebraditas Fault, El Guayabo Fault, La Zarza Fault, Tablazo Fault, among other unnamed faults), and in previous research (*e.g.*, Infantas High, Gómez *et al.*, 2005; Río Negro Syncline, Kammer and Sánchez, 2006; Río Sogamoso Lineament, Ujueta, 2014) constitute some of the testimony of the ancient barriers.

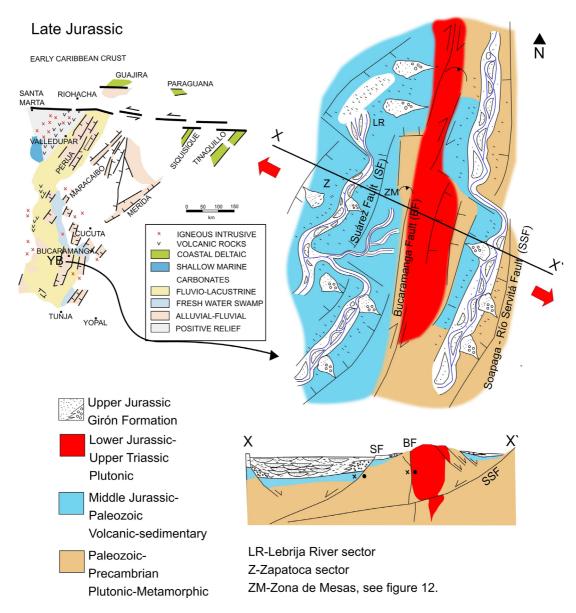


FIG. 12. Sketch of depositional conditions for Girón Formation during Late Jurassic. Inset (Tectonic map of the Late Jurassic) from Cediel (2019). Legend as in the geologic map in figure 2. **YB:** Yariguíes Basin.

The local nature of every Jurassic succession that crops out in the area, and along the Eastern Cordillera and the Santander Massif, is evident after having recognised the compartmentalised nature of the basin, generating facies and thickness changes along and across its strike (Julivert, 1958; Cediel, 1968; Pulido, 1979; Ward *et al.*, 1973; Pinto *et al.*, 2008) (Figs. 11 and 12). In this sense, the proposal of a type section is not definite because this section

does not describe the characteristics of the whole basin, but only the local features of the succession where analysed (Fig. 11).

The Girón Formation is constituted by stratigraphically dissimilar units cropping out along and across the Eastern Cordillera; lateral facies and thickness changes between them would preclude any direct correlation, although characteristics as provenance, age, fossil content and paleosol horizons

can be correlated. The described clastic succession near Zapatoca first known as "Girón layers" (Hettner, 1892 *in* Julivert, 1968) is considered as a part of the Girón Formation. The different sedimentary facies present in the Zapatoca section are similar to those observed in some parts of the type section at Lebrija River, but not necessarily are synchronic deposits.

# 5.2. Petrology, provenance and basin tectonics

The sedimentary rocks of the Girón Formation display compositions varying from lithic dominant to quartz-feldspar rich, with different provenance (Fig. 7). These variations can be the result of the unroofing of basement blocks, composed by a volcanic-sedimentary carapace covering a metamorphic succession with some igneous intrusions (Garzanti, 2016). The erosion of these unroofing basement blocks could be responsible of the facies changes observed in the Giron Formación rocks.

The lithologic LmLvLs diagram shows a distinction between the Lebrija River and Zapatoca samples of the Girón Formation. There is a closer relationship between Lebrija River and a volcanic source, whereas the source area for Zapatoca sandstones included mainly a sedimentary source. Some basalts of the Jordán Formation are currently cropping out near the Lebrija River (Cediel, 1968; Ward *et al.*, 1973; Ayala-Calvo *et al.*, 2005; Alarcón and Rodríguez, 2019), and were probably exposed to erosion when the Girón Formation was deposited.

Although a vertical evolution was not detected in our samples, the previous scenario is the most plausible due to the presence of several recycled components coming from different sources. Cediel (1968) and Chacón (1981) in the Yariguíes Range and Méndez-Espinosa (2017) in the Floresta Massif (Fig. 1) report petrographic data of sedimentary rocks from the Girón Formation; showing similar compositional groups, mainly characterized by considerable amounts of plagioclase and potassium feldspar, metamorphic, volcanic and sedimentary lithic components. Farther to the north, Jurassic sedimentary rocks in Guajira Peninsula and Perijá Range plot in the same portions of the tectonic discrimination diagrams as rocks of the Girón Formation (Nova et al., 2019); therefore, suggesting similar sources, at least lithologically, and a similar basin configuration in which segmented blocks and basins were exposed to local erosion and deposition regimes (Fig. 12).

Detrital U-Pb zircon data presented by Horton et al. (2010, 2015) from samples of the Girón Formation in the study area and in the Magdalena Valley show peaks in the Mesoproterozoic-Neoproterozoic (Greenvillian), Cambrian-Ordovician, Permian, and in the Early-Middle Jurassic. This data shows a maximum depositional age of 166 Ma (Horton et al., 2015); nevertheless, this age probably reflects the reworking of Early-Middle Jurassic volcanic and plutonic rocks of the Santander Massif and the San Lucas proto-Range (Van der Lelij et al., 2016a; Alarcón and Rodríguez, 2019; Correa-Martínez et al., 2019; Leal-Mejía et al., 2019). The older peaks correspond to ages of rocks found in both the Santander Massif and the San Lucas Range (Ward et al., 1973; Van der Lelij et al., 2016a; Leal-Mejía et al., 2019) (Fig. 1). In this scenario, these blocks could have been exhumed for the time of deposition of the Girón Formation, or previously, providing the major part of the sediment (Cediel, 1968).

Sources in southern latitudes (Floresta Massif) could have provided grains, as have been proposed for Jurassic basins at those latitudes (Kammer and Sánchez, 2006; Méndez-Espinosa, 2017). Part of the older grains could have travelled from farther eastern sources in the Amazonian Craton (Guyana Shield in Horton *et al.*, 2010). Nevertheless, a detailed study regarding paleocurrent directions would be necessary to test these hypotheses in the study area, together with a paleomagnetic survey defining the vertical axis rotations and correcting paleocurrent with those rotations.

# 5.3. Structural geology

The regional structural geology of the Yariguíes Range shows the complexity of an anticlinorium as part of the fold and thrust belt, which is crossed not only by longitudinal faults, but transverse minor structures. This makes the area interesting for getting new structural data to refine crustal models, since considering the range as a single fold (Los Cobardes Anticline) for regional cross sections (e.g., Tesón et al., 2013) does not allow to describe the changes in dip angles of the faults, neither the other minor related folds that could define in detail the structural style of the region (Machuca et al., 2021). The Yariguíes Anticlinorium as presented here offers a chance to redefine the inner and lateral

structuration of the Cretaceous?-Cenozoic tectonic inversion of the Jurassic basin.

For discussion of the tectonic implications of the stress tensor results it is necessary to consider that with the exception of one locality, all the collected data in Zapatoca and Lebrija River areas were measured in rocks of the Girón Formation. Limitations of the results can be related to low amount of measured data in some sites, and some stress tensors are probably more associated with local kinematics.

The Shmax oriented NE-SW, can be related to the onset of compressional deformation in the Eastern Cordillera driven by the accretion of the Western Cordillera to the western continental border 75-70 Ma ago (Bayona et al., 2013; Villagómez and Spikings, 2013; Mora et al., 2015). Although it is considered the oldest stress tensor among the obtained ones in the area (Cortés et al., 2005; Cetina et al., 2019), some works propose the existence of previous deformational phases in the Eastern Cordillera during the Early and Late Cretaceous, and relate these compressive events to an east directed flat slab subduction (e.g., Guerrero, 2019). The few tensors in the zone show this event in local extensional (S8 in Fig. 8 and S13 in Fig. 9) and transtensional (S10 in Fig. 9) regimes. The orientation of these stress tensors, as well as the transverse faults in the area, can be related to the reactivation of the transverse barriers of the former Jurassic-Cretaceous basin; since the associated transverse structures settle control as zones of anisotropy. Jiménez et al. (2016) explain lateral variation is the structural styles for a sector of the Middle Magdalena Valley Basin in this same sense.

The stress field seems to have rotated to a W-E orientation, which may have reactivated the former normal longitudinal faults (e.g., Suárez, Zapatoca, and Betulia faults) as reverse and transpressional (S5, S7 in Fig. 8, S11 and S14 in Fig. 9). This orientation of the stress tensors can be correlated to the post Early Eocene deformational events driven by the accretion of terranes to the western continental border and by the flattening of the subducted plate (e.g., Gómez et al., 2005; Parra et al., 2012; Bayona et al., 2013; Mora et al., 2015; Guerrero, 2019). Finally, the NW-SE tensor is related to the drag that imposes the transpressional and sinistral kinematics of the Bucaramanga and Lebrija faults (S1, S2, S3, S4 and S6 in Fig. 8), as regionally is explained by Velandia et al., (2020), which locally generates compression across the faults oriented perpendicular to this latest

tensor. The NW-SE tensor is described in the western flank of the Yariguíes Anticlinorium (Cetina *et al.*, 2019) and toward the south of the Bucaramanga Fault (Velandia and Bermúdez, 2018), and can be associated with the Oligocene-Pliocene deformational and exhumational events that had been reported with thermochronology (van der Lelij *et al.*, 2016b; Amaya *et al.*, 2017; Velandia, 2017).

Along the Lebrija River, we observe the mechanical correlation of the stress tensors located between the Lebrija and Bucaramanga faults with the joints, which confirm simple shear of both type of kinematic indicators (slickensides and joints) (Figs. 8, 9 and 10). It is evident that west of the Lebrija Fault, there is a marked influence of the W-E compression that explains the longitudinal reverse faults (related to tectonic inversion) and the transverse fractures as joints of high angles and normal faults. For the Zapatoca area, it is also possible to conclude the same correlation, although some data show local structural conditions.

# 5.4. Geological evolution

The data presented and discussed here allow us to hypothesise about the geological evolution of the region, from the Late Jurassic, the time when the sequence was deposited (Ward *et al.*, 1973; Clavijo, 1985; Laverde and Clavijo, 1985), until the Miocene-Pliocene, the time when the last and major orogenic pulses occurred (Bayona *et al.*, 2013; Mora *et al.*, 2015).

During the Late Jurassic, the deposition of the Girón Formation occurred in extensional or transtensional basins with half-graben geometry (Yariguíes Basin as we hypothesize here). This geometry is assumed by a comparison with the adjacent Middle Magdalena Valley Basin (i.e., Tablazo-Magdalena Basin during the Cretaceous; Fabre, 1983) as revealed by the thickness variations and by seismic profiles (Rolón, 2004; Guerrero, 2019). The eastern and northeastern bounding faults separated the basin from the Santander Massif, one of the sediment sources. Inside the basin, normal faults had formed parallel and transverse to the basin, creating inner horst blocks that could generate local sediment sources and configured the sedimentary agents (e.g., changing river direction and creating local depocenters) (Fig. 12). The Suárez, Zapatoca, El Ramo (N-S faults) and Tablazo, El Guayabo, among other faults (WNW to ESE transverse) correspond to

this type of structures. Paleomagnetic data support basin compartmentalization, as different amounts of rotation have been reported for Jurassic rocks in blocks separated by faults (Ayala-Calvo et al., 2005). Farther north of the study area a regional graben structure may have developed, surrounded by the Santander Massif to the east and the San Lucas proto-Range to the west (Clavijo et al., 2008); this geometry is supported by reported U-Pb ages in zircons of the Girón Formation close the the San Lucas Range (Horton et al., 2015), which reveal provenance ages of 190-170 Ma age, also found in Jurassic plutonic rocks of the San Lucas Range (188.9-155.6 Ma; Leal-Mejía et al., 2019; Bayona et al., 2020).

We recognise the Yariguíes Basin (Fig. 12) as part of one of the multiple regional extensional and/or transtensional basins located in the western equatorial part of Pangea (Machiques, Uribante or Cosinas basins, *e.g.*, Sarmiento-Rojas *et al.*, 2006; Nova *et al.*, 2019), and originated by rift-related extension (Maze, 1984; Martini and Ortega-Gutiérrez, 2016; Nova *et al.*, 2019; Bayona *et al.*, 2020). The ancient location and orientation of these basins is uncertain due to probable block translation and rotation (Maze, 1984; Bayona *et al.*, 2006).

After Cretaceous predominantly marine accumulation, some of the normal faults bounding and/or inside the basin, started an inversion process of the former basin during the Paleocene (Julivert, 1958, 1970; Mora et al., 2009; Parra et al., 2012; Bayona et al., 2013; Restrepo-Moreno et al., 2019) or since latest Cretaceous (Parra et al., 2012; Caballero et al., 2013; Bayona, 2018), with major pulses at the Eocene, Oligocene-Miocene and finally in the Pliocene-Pleistocene (Mora et al., 2015). These orogenic pulses were the consequence of stress fields generated at the western continental border, as different terrains were being accreted and probably the subducting plate was shallowing (Kennan and Pindell, 2009; Guerrero, 2019), which produced an asynchronic and systematic block uplifting from W to E in the nascent Eastern Cordillera. Similar frames have been proposed for other orogenic chains (e.g., Eastern Sierra Madre, Mexico).

The origin and/or reactivation of the deformational structures, is related in the case of the EC, to the clockwise evolving stress tensors (Cortés *et al.*, 2005; Cetina *et al.*, 2019). Finally, the Bucaramanga Fault, a structure that can be as old as Triassic-Jurassic

(Mojica et al., 2001; Kammer and Sánchez, 2006; Clavijo et al., 2008; Kammer et al., 2020), but proven as young as Pliocene (Diederix et al., 2008, 2009; Jiménez et al., 2015; Amaya et al., 2017; Velandia, 2017; García-Delgado et al., 2019, 2020; Velandia et al., 2020) marked the deformational conditions of the region.

#### 6. Conclusions

The Yariguíes Anticlinorium is a regional structure between the Eastern Cordillera and the Middle Magdalena Valley Basin in Colombia, and it is flanked by the Suárez Fault to the east and a complex reverse fault system to the west led by the San Vicente Fault, and involves a series of minor anticlines and synclines.

The Girón Formation encompass all the fluvialalluvial units deposited during the Late Jurassic in basins shaped as half-grabens, segmented and separated by accommodation zones, relay ramps and/ or transfer faults, whose presence was the cause of the lateral variations in thickness, provenance and sedimentary facies between the synchronic units deposited in these basins.

The source rock for the sediment accumulated in the Yariguíes Basin were continental exhumed blocks, composed by a sedimentary-volcanic sequence covering metamorphic units intruded by plutonic rocks, these rock types crop out in different sectors surrounding the basin. These blocks (the Santander and Floresta massifs and the San Lucas Range) and probably others as the Amazonian Craton provided grains with U-Pb ages as Mesoproterozoic-Neoproterozoic, Paleozoic, Triassic and Jurassic.

Along the Yariguíes Anticlinorium, the longitudinal reverse faults, transverse normal or transtensional faults, and most of the minor folds are related to near W-E compressional stress regimes. Nevertheless, during the tectonic inversion of the former basins, a clockwise rotation of the stress field can be detected, from NE-SW to NW-SE, the latest one more associated to current transpressional regimes of the Bucaramanga and Lebrija faults.

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#### References

- Acosta, J.; Lonergan, L.; Coward, M. 2004. Oblique transpression in the western thrust front of the Colombian Eastern Cordillera. Journal of South American Earth Sciences 17 (3): 181-194.
- Acosta, J.; Velandia, F.; Osorio, J.; Lonergan, L.; Mora, H. 2007. Strike-slip deformation within the Colombian Andes. Geological Society of London, Special Publications 272 (1): 303-319.
- Amaya, S.; Zuluaga, C.; Bernet, M. 2017. New fission-track age constraints on the exhumation of the central Santander Massif: Implications for the tectonic evolution of the Northern Andes, Colombia. Lithos 282-283: 388-402.
- Angelier, J. 1994. Fault slip analysis and palaeostress reconstruction. *In Continental Deformation (Hancock, P.L.*; editor). Pergamon Press: 53-100. Oxford.
- Alarcón, C.M.; Rodríguez, J.G. 2019. Estratigrafía, facies y paleoambiente de sedimentación de la Formación Jordán: un registro fluvio-lacustre con incidencia de actividad volcánica. Bachelor Geology Thesis (Unpublished), Universidad Industrial de Santander: 130 p. Colombia.
- Athmer, W.; Luthi, S.M. 2011. The effect of relay ramps on sediment routes and deposition: A review. Sedimentary Geology 242 (1-4): 1-17.
- Ayala-Calvo, R.C.; Veloza Fajardo, G.E.; Bayona, G.; Gómez Casallas, M.; Rapalini, A.E.; Costanzo-Álvarez, V.; Aldana, M.; Cortés, M. 2005. Paleomagnetismo y mineralogía magnética en las unidades del Mesozoico de Bucaramanga y Macizo de Floresta. Geología Colombiana 30: 49-66.
- Bayona, G. 2018. The onset of the mountain uplift in the northern Andes: A perspective based on Coniacian to Paleocene tectono-sedimentary studies. Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales 42 (165): 364-378.

- Bayona, G.; Rapalini, A.; Costanzo-Álvarez, V. 2006. Paleomagnetism in Mesozoic rocks of the northern Andes and its implications in Mesozoic tectonics of northwestern South America. Earth Planets Space 58 (10):1255-1272.
- Bayona, G.; Cardona, A.; Jaramillo, C.; Mora, A.;
  Montes, C.; Caballero, V.; Mahecha, H.; Lamus, F.;
  Montenegro, O.; Jiménez, G.; Mesa, A.; Valencia, V.
  2013. Onset of fault reactivation in the Eastern
  Cordillera of Colombia and proximal Llanos
  basin; response to Caribbean-South American
  collision in early Palaeogene time. *In* Thick-Skin-Dominated Orogens: From Initial Inversion to Full
  Accretion (Nemčok, M.; Mora, A.; Cosgrove, J.;
  editors). Geological Society of London, Special
  Publications 377: 285-314. London.
- Bayona, G.; Bustamante, C.; Nova, G.; Salazar-Franco, A.M. 2020. Jurassic evolution of the northwestern corner of Gondwana: Present knowledge and future challenges in studying Colombian Jurassic rocks. *In* The Geology of Colombia, Volume 2 Mesozoic (Gómez, J.; Pinilla-Pachón, A.O.; editors). Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 36: 37 p. Bogotá. doi: 10.32685/pub.esp.36.2019.05.
- Blair, T. 1988. Development of tectonic cyclothems in rift, pull-apart and foreland basins: sedimentary response to episodic tectonism. Geology 16: 517-520.
- Boinet, T.; Bourgois, J.; Mendoza, H.; Vargas, R. 1985. Le Poinçon de Pamplona (Colombie): Un jalon de la frontière meridionale de la plaque Caraïbe. Bulletin de la Société Géologique de France 8: 403-413.
- Bustamante, C.; Archanjo, C.J.; Cardona, A.; Vervoort, J.D. 2016. Late Jurassic to Early Cretaceous plutonism in the Colombian Andes: A record of long-term arc maturity. Geological Society of America, Bulletin 128 (11-12): 1762-1779.
- Caballero, V.; Parra, M.; Mora, A. 2010. Levantamiento de la Cordillera Oriental de Colombia durante el Eoceno tardío-Oligoceno temprano: proveniencia sedimentaria en el Sinclinal de Nuevo Mundo, Cuenca Valle Medio del Magdalena. Universidad Industrial de Santander, Boletín de Geología 32 (1): 45-77. Colombia.
- Caballero, V.; Mora, A.; Quintero, I.; Blanco, W.; Parra, M.;
  Rojas, L.; López, C.; Sánchez, N.; Horton, B.;
  Stockli, D.; Duddy, I. 2013. Tectonic controls on sedimentation in an intermontane hinterland basin adjacent to inversion structures: the Nuevo Mundo Syncline, Middle Magdalena Valley, Colombia.
  In Thick-Skin-Dominated Orogens: From Initial

- Inversion to Full Accretion (Nemčok, M.; Mora, A.; Cosgrove, J.; editors). Geological Society of London, Special Publications 377: 315-342. London.
- Campbell, C. 1987. Lamina, Laminaset, bed and bedset. Sedimentology 8: 7-26.
- Cediel, F. 1968. El Grupo Girón, una molasa Mesozoica de la Cordillera Oriental. Servicio Geológico Nacional, Boletín Geológico 16 (1-3): 5-96. Bogotá.
- Cediel, F. 2019. Phanerozoic Orogens of Northwestern South America: Cordilleran-Type Orogens. Taphrogenic Tectonics. The Maracaibo Orogenic Float. The Chocó-Panamá Indenter: The pacific-Caribbean-Andean Junction. *In* Geology and Tectonics of Northwestern South America. Springer: 3-95.
- Cediel, F.; Shaw, R.; Cáceres, C. 2003. Tectonic assembly of the Northern Andean Block. *In* The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics (Bartolini, C.; Buffler, R.T.; Blickwede, J.; editors). American Association of Petroleum Geologists (AAPG), Memoir 79: 815-848. USA.
- Cetina, L.M.; Velandia, F.; Patiño-Sanabria, H.A. 2019. Análisis de deformación al occidente del Anticlinorio de Los Yariguíes-Cordillera Oriental de Colombia. Universidad Industrial de Santander, Boletín de Geología 41 (3): 31-56. Colombia.
- Chacón, M. 1981. Estratigrafía y Análisis Paleoambiental de la Formación Girón en los alrededores de Chima y Contratación (Santander). Bachelor Geology Thesis (Unpublished), Universidad Nacional de Colombia: 51 p.
- Clavijo, J. 1985. La secuencia de la Formación Los Santos en la Quebrada Piedra Azul: registro de una hoya fluvial evanescente. *In* Proyecto Cretácico, Contribuciones (Etayo-Serna, F.; Laverde-Montaño F.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 16 (4): 1-18. Bogotá.
- Clavijo, J.; Camacho, J. 1993. Contribución al conocimiento de la geología de los Santanderes. *In* Simposio de Geología Regional, No. 4, Servicio Geológico Colombiano (INGEOMINAS): 99 p. Bogotá.
- Clavijo, J.; Mantilla, L.; Pinto, J.; Bernal, L.; Pérez, A. 2008. Evolución geológica de la Serranía de San Lucas, norte del Valle Medio del Magdalena y noroeste de la Cordillera Oriental. Universidad Industrial de Santander, Boletín de Geología 30 (1): 45-62. Colombia.
- Colletta, B.; Hebrard, F.; Letouzey, J.; Werner, P.; Rudkiewicz, J. 1990. Tectonic style and crustal structure of the Eastern Cordillera (Colombia) from a balanced cross-section. *In* Petroleum and tectonics in

- mobile belts (Letouzey, J.; editor). Editions Technip: 81-100. Paris.
- Cooper, M.; Addison, F.; Álvarez, R.; Coral, M.; Graham, R.; Hayward, A.; Pulham, A. 1995. Basin development and tectonic history of the Llanos Basin, Eastern Cordillera, and middle Magdalena Valley, Colombia. American Association of Petroleum Geologists (AAPG), Bulletin 79 (10): 1421-1442.
- Correa-Martínez, A.M.; García, G.R.; Mejía, M.I.A.; García, G.Z. 2019. Petrografía, geoquímica y geocronología U-Pb de las rocas volcánicas y piroclásticas de la Formación Noreán al NW del Macizo de Santander, Colombia. Universidad Industrial de Santander, Boletín de Geología 41 (1): 29-54. Colombia.
- Cortés, M.; Angelier, J.; Colletta, B. 2005. Paleostress evolution of the northern Andes (Eastern Cordillera of Colombia): Implications on plate kinematics of the South Caribbean region. Tectonics 24 (1) 1-27. doi: 10.1029/2003TC001551.
- Delvaux, D.; Sperner, B. 2003. Stress tensor inversion from fault kinematic indicators and focal mechanism data: the tensor program. *In* New Insights into Structural Interpretation and Modelling (Nieuwland, D.; editor). Geological Society of London, Special Publications 212: 75-100. London.
- Delvaux, D.; Moeys, R.; Stapel, G.; Petit, C.; Levi, K.; Miroshnichenko, K.; Ruzhich, V.; Sankov, V. 1997. Paleostress reconstructions and geodynamics of the Baikal region, Central Asia, Part 2. Cenozoic rifting. Tectonophysics 282: 1-38.
- Dengo, C.; Covey, M. 1993. Structure of the Eastern Cordillera of Colombia: Implications for Trap Styles and Regional Tectonics. American Association of Petroleum Geologists (AAPG), Bulletin 77: 1315-1337.
- Díaz, G.; Suárez, M. 1998. Evidencias Neotectónicas del Sistema de Fallas del Suárez en su Confluencia con el Sistema de Fallas de Bucaramanga. Bachelor Geology Thesis (Unpublished), Universidad Industrial de Santander: 150 p. Colombia
- Dickinson, W.R. 1985. Interpreting provenance relations from detrital modes of sandstones. *In* Provenance of arenites (Zuffa, G.G; editor). Springer: 333-361. Netherlands. doi: 10.1007/978-94-017-2809-6 15.
- Diederix, H.; Torres, E.; Hernández, C.; Botero, P. 2008.

  Modelo de evolución morfotectónica cuaternaria basado en evidencias estructurales, neotectónicas y paleosimológicas de los principales sistemas de falla en la región de Bucaramanga (Inédito). Servicio Geológico Colombiano (INGEOMINAS): 145 p. Bogotá.

- Diederix, H.; Torres, E.; Hernández, C.; Botero, P. 2009. Resultados preliminares del primer estudio paleosismológico a lo largo de la Falla de Bucaramanga, Colombia. Ingeniería Investigación y Desarrollo 9 (2): 18-23.
- Doblas, M. 1998. Slickenside kinematic indicators. Tectonophysics 295 (1-2): 187-197.
- Duque-Caro, H. 1990. The Choco Block in the northwestern corner of South America: Structural, tectonostratigraphic, and paleogeographic implications. Journal of South American Earth Sciences 3: 71-84.
- Etayo-Serna, F. 1989. Análisis facial del inicio del avance marino del Cretácico en la región SW del Macizo de Santander. *In* Congreso Colombiano de Geología, No. 5, Guía de Excursión Técnica: 41 p. Bucaramanga.
- Etayo-Serna, F.; Rodríguez, G. 1985. Edad de la Formación Los Santos. *In* Proyecto Cretácico, Contribuciones (Etayo-Serna, F.; Laverde-Montaño F.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 16 (26): 1-13. Bogotá.
- Fabre, A. 1983. La subsidencia de la Cuenca del Cocuy (Cordillera Oriental de Colombia) durante el Cretáceo y el Terciario. Segunda parte: esquema de evolución tectónica. Revista Norandina 8: 21-27.
- Flórez, S.; Núñez, A. 2015. Análisis cinemático y estilo estructural de la Falla del Suárez entre El Hato y La Fuente, Santander. Bachelor Geology Thesis (Unpublished), Universidad Industrial de Santander: 145 p. Colombia.
- Folk, R.L. 1968. Petrology of sedimentary rocks. Hemphill Publishing Company 170: 85 p. Austin.
- García-Delgado, H.; Villamizar, N.; Bernet, M. 2019. Recent tectonic activity along the Bucaramanga fault system (Chicamocha river canyon, Estern Cordillera of Colombia): a geomorphological approach. Annals of Geomorphology 62: 199-215. doi: 10.1127/zfg/2019/0630.
- García-Delgado, H.; Machuca, S.; Velandia, F.; Audemard, F. 2020. Along-strike variations in recent tectonic activity in the Santander Massif: New insights on landscape evolution in the Northern Andes. Journal of South American Earth Sciences 98: 22 p. doi: 10.1016/j.jsames.2019.102472.
- Garzanti, E. 2016. From static to dynamic provenance analysis-Sedimentary petrology upgraded. Sedimentary Geology 336: 3-13.
- Gawthorpe, R.; Leeder, M. 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research 12 (3-4): 195-218.

- Godínez-Urban, A.; Lawton, T.F.; Molina Garza, R.S.; Iriondo, A.; Weber, B.; López-Martínez, M. 2011. Jurassic volcanic and sedimentary rocks of the La Silla and Todos Santos Formations, Chiapas: Record of Nazas arc magmatism and rift-basin formation prior to opening of the Gulf of Mexico. Geosphere 7 (1): 121-144.
- Gómez, E.; Jordan, T.E.; Allmendinger, R.; Hegarty, K.; Kelley, S. 2005. Syntectonic Cenozoic sedimentation in the northern middle Magdalena Valley Basin of Colombia and implications for exhumation of the Northern Andes. Geological Society of America, Bulletin 117 (5-6): 547-569. doi: 10.1130/B25454.1.
- Gómez-Tapias, J.; Montes, N.; Nivia, A.; Diederix, H. 2015.
  Mapa Geológico de Colombia. Escala 1:1.000.000.
  Servicio Geológico Colombiano (INGEOMINAS).
  Bogotá.
- Guerrero, J. 2019. Pre-Andean tectonic events from Albian to Eocene in the Middle Magdalena Valley and situation of the western flank of the proto-Eastern Cordillera (Colombia). Ph.D. Thesis (Unpublished), Université Grenoble Alpes-Universidad Nacional de Colombia: 480 p.
- Guzmán, G. 1985. Los Grifeidos Infracretácicos Aetostreon couloni y Ceratostreon boussingaulti, de la Formacion Rosablanca, como indicadores de oscilaciones marinas. *In* Proyecto Cretácico, Contribuciones (Etayo-Serna, F.; Laverde-Montaño, F.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 16 (12): 1-16. Bogotá.
- Horton, B.; Saylor, J.; Nie, J.; Mora, A.; Parra, M.; Reyes-Harker, A.; Stockli, D. 2010. Linking sedimentation in the northern Andes to basement configuration, Mesozoic extension, and Cenozoic shortening: Evidence from detrital zircon U-Pb ages, Eastern Cordillera, Colombia. Geological Society of America, Bulletin 122 (9-10): 1423-1442.
- Horton, B.K.; Anderson, V.J.; Caballero, V.; Saylor, J.E.; Nie, J.; Parra, M.; Mora, A. 2015. Application of detrital zircon U-Pb geochronology to surface and subsurface correlations of provenance, paleodrainage, and tectonics of the Middle Magdalena Valley Basin of Colombia. Geosphere 11 (6): 1790-1811.
- Ingersoll, R.; Bullard, T.; Ford, R.; Grimm, J.; Pickle, J.; Sares, S. 1984. The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method. Journal of Sedimentary Research 54 (1): 103-116.
- Jiménez, G.; Speranza, F.; Faccenna, C.; Bayona, G.; Mora, A. 2014. Paleomagnetism and magnetic fabric of the Eastern Cordillera of Colombia: Evidence for

- oblique convergence and non-rotational reactivation of a Mesozoic intracontinental rift. Tectonics 33: 2233-2260.
- Jiménez, G.; Speranza, F.; Faccena, C.; Bayona, G.; Mora, A. 2015. Magnetic stratigraphy of the Bucaramanga alluvial fan: Evidence for a 3 mm/yr slip rate for the Bucaramanga-Santa Marta Fault, Colombia. Journal of South American Earth Sciences 57: 12-22.
- Jiménez, G.; López, O.; Jaimes, L.; Mier, R. 2016. Variaciones en el estilo estructural relacionado con anisotropías de basamento en el Valle Medio del Magdalena. Revista de la Academia Colombiana de Ciencias Exactas Físicas y Naturales 40 (155): 312-319.
- Julivert, M. 1958. La morfoestructura de la zona de mesas al SW de Bucaramanga. Boletín de Geología 1: 9-43.
- Julivert, M. 1968. Colombie. Lexique stratigraphique International. Precambrian, Paleozoique et Mesozoique. Centre National de la Recherche Scientifique 5 (4a): 651 p. Paris.
- Julivert, M. 1970. Cover and basement tectonics in the Cordillera Oriental of Colombia, and a comparison with other folded chains. Geological Society of America, Bulletin 81: 3623-3646.
- Kammer, A. 1999. Observaciones acerca de un origen transpresivo de la Cordillera Oriental. Geología Colombiana 24: 29-53.
- Kammer, A.; Sánchez, J. 2006. Early Jurassic rift structures associated with the Soapaga and Boyaca faults of the Eastern Cordillera, Colombia: Sedimentological inferences and regional implications. Journal of South American Earth Sciences 21 (4): 412-422.
- Kammer, A.; Piraquive, A.; Gómez, C.; Mora, A.; Velásquez, A. 2020. Structural Styles of the Eastern Cordillera of Colombia. *In* The Geology of Colombia 3 Paleogene-Neogene (Gómez, J.; Pinilla-Pachón, A.O.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 36: 41 p. Bogotá.
- Kennan, L.; Pindell, J. 2009. Dextral shear, terrane accretion and basin formation in the Northern Andes: best explained by interaction with a Pacific-derived Caribbean Plate? Geological Society of London, Special Publications 328: 487-531.
- Langenheim, R. 1959. Preliminary report on the stratigraphy of the Girón Formation in Santander and Boyacá. Universidad Industrial de Santander, Boletín de Geología 3: 35-50. Colombia.
- Laverde, F.; Clavijo, J. 1985. Análisis facial de la Formación Los Santos, según el corte de «Tu y Yo» (Zapatoca). *In* Proyecto Cretácico, Contribuciones (Etayo-Serna,

- F.; Laverde-Montaño, F.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 16 (6): 1-9. Bogotá.
- Leal-Mejía, H.; Shaw, R.P.; Melgarejo, J.C. 2019. Spatial-temporal migration of granitoid magmatism and the Phanerozoic tectono-magmatic evolution of the Colombian Andes. *In* Geology and tectonics of northwestern South America: The Pacific-Caribbean-Andean junction. Frontiers in Earth Sciences (Cediel, F.; Shaw, R.P.; editors). Springer: 253-410. Germany. doi: 10.1007/978-3-319-76132-9 5.
- Machuca, S.; García-Delgado, H.; Velandia, F. 2021. Studying active fault-related folding on tectonically inverted orogens: A case study at the Yariguíes Range in the Colombian Northern Andes. Geomorphology 375: 107515. doi: 10.1016/j.geomorph.2020.107515.
- Mantilla, L.; Mendoza, H.; Bissig, T.; Craig, H. 2011.
  Nuevas evidencias sobre el magmatismo Miocénico en el distrito minero de Vetas-California (Macizo de Santander, Cordillera Oriental, Colombia). Universidad Industrial de Santander, Boletín de Geología 33 (1): 43-58. Colombia.
- Marsaglia, K.M.; Ing ersoll, R.V. 1992. Compositional trends in arc-related, deep-marine sand and sandstone: a reassessment of magmatic-arc provenance. Geological Society of America, Bulletin 104 (12): 1637-1649.
- Martini, M.; Ortega-Gutiérrez, F. 2016. Tectonostratigraphic evolution of eastern Mexico during the break-up of Pangea: a review. Earth Science Reviews 183: 38-55.
- Maze, W. 1984. Jurassic La Quinta Formation in the Sierra Perijá, northwestern Venezuela: geology and tectonic environment of red beds and volcanic rocks. *In* The Caribbean-South American Plate Boundary and Regional Tectonics (Bonini, W.; Hargraves, R.; Shagam, R.; editors). Geological Society of America, Memoir 162: 263-282.
- McClay, K.; Dooley, T.; Whitehouse, P.; Mills, M. 2002.
  4-D evolution of rift systems: Insights from scaled physical models. American Association of Petroleum, Geologist Bulletin 86 (6): 935-959.
- Méndez-Espinosa, S.C. 2017. Análisis de procedencia de rocas siliciclásticas de las formaciones Girón y Tibasosa en el macizo de Floresta. Magíster en Ciencias (Inédito), Universidad Nacional de Colombia: 219 p. Bogotá.
- Miall, A. 2006. The Geology of Fluvial Deposits. Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer: 582 p. Heidelberg.

- Michalzik, D. 1991. Facies sequence of Triassic-Jurassic red beds in the Sierra Madre Oriental (NE Mexico) and its relation to the early opening of the Gulf of Mexico. Sedimentary Geology 71 (3-4): 243-259.
- Mojica, J.; Kammer, A. 1995. Eventos jurásicos en Colombia. Geología Colombiana 19: 165-172.
- Mojica, J.; González, H.; Núñez, A.; Kammer, A.; Schwabe, E.; Toro, G.; Kairuz Ch.; Ferreira, P.; Cediel, F.; Torres, J. 2001. Comunicaciones científicas breves y notas geocientíficas. Universidad Industrial de Santander, Boletín de Geología 23 (38): 83-93. Colombia
- Montes, C. 2001. Three dimensional structure and kinematics of the Piedras-Girardot foldbelt in the northern Andes of Colombia. Ph.D. Thesis (Unpublished), The University of Tennessee: 201 p.
- Montes, C.; Hatcher, R.; Restrepo-Pace, P. 2005. Tectonic reconstruction of the northern Andean blocks: Oblique convergence and rotations derived from the kinematics of the Piedras-Girardot area, Colombia. Tectonophysics 399 (1): 221-250.
- Montes, C.; Cardona, A.; Jaramillo, C.; Pardo, A.; Silva, J.; Valencia, V.; Ayala, C.; Pérez-Angel, L.; Rodríguez-Parra, L.; Ramírez, V.; Niño, H. 2015. Middle Miocene closure of the Central American Seaway. Science 348: 226-229.
- Montes, C.; Rodríguez-Corcho, A.F.; Bayona, G.; Hoyos, N.; Zapata, S.; Cardona, A. 2019. Continental margin response to multiple arc-continent collisions: The northern Andes-Caribbean margin. Earth-Science Reviews 198: 1-19.
- Mora, A.; Gaona, T.; Kley, J.; Montoya, D.; Parra, M.; Quiroz, L.I.; Strecker, M.R. 2009. The role of inherited extensional fault segmentation and linkage in contractional orogenesis: A reconstruction of Lower Cretaceous inverted rift basins in the Eastern Cordillera of Colombia. Basin Research 21 (1): 111-137.
- Mora, A.; Reyes-Harker, A.; Rodríguez, G.; Tesón, E.; Ramírez-Arias, J.C.; Parra, M.; Caballero, V.; Mora, J.P.; Quintero, I.; Valencia, V.; Ibáñez, M.; Horton, B.; Stockli, D. 2013. Inversion tectonics under increasing rates of shortening and sedimentation: Cenozoic example from the Eastern Cordillera. *In* Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion (Nemčok, M.; Mora, A.; Cosgrove, J.; editors). Geological Society of London, Special Publications 377: 411-442. London.
- Mora, A.; Parra, M.; Forero, G.; Blanco, V.; Moreno, N.; Caballero, V.; Stockli, D.; Duddy, I.; Ghorbal, B. 2015. What drives orogenic asymmetry in the Northern Andes?: A case study from the apex of the Northern

- Andean Orocline. *In* Petroleum geology and potential of the Colombian Caribbean Margin (Bartolini, C.; Mann, P.; editors). American Association of Petroleum Geologists (AAPG), Memoir 108: 547-586.
- Nova, G.; Bayona, G.; Silva-Tamayo, J.; Cardona, A.; Rapalini, A.; Montaño, P.; Eisenhauer, A.; Dussan, K.; Valencia, V.; Ramírez, V.; Montes, C. 2019. Jurassic break-up of the Peri-Gondwanan margin in northern Colombia: Basin formation and implications for terrane transfer. Journal of South American Earth Sciences 89: 92-117.
- París, G.; Machette, M.N.; Dart, R.L.; Haller, K.M. 2000.
  Map and Database of Quaternary Faults and Folds in Colombia and its Offshore Regions: United States Geological Survey Open File Report 00-0284. A Project of the International Lithosphere Program Task Group II-2, Major Active Faults of the World: 61 p. Denver.
- Parra, M.; Mora, A.; López, C.; Rojas, L.; Horton, B. 2012. Detecting earliest shortening and deformation advance in thrust-belt hinterlands: Example from the Colombian Andes. Geology 40 (2): 175-178. doi: 10.1130/G32519.1.
- Petit, J. 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. Journal of Structural Geology 9: 597-608.
- Pindell, J.; Dewey, J. 1982. Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. Tectonics 1 (2): 179-211.
- Pinto, J.; Morales, C.; Clavijo, J.; Velandia, F.; Gómez-Isidro, S.; Hincapié, G.; Toledo, D.; Forero, H.; Mora-Ortiz, J.; Duarte, R.; Rojas, N.; Vargas, M.; de Bermoudes, O. 2008. Investigación geológica e hidrogeológica en la Mesa de Los Santos, Sector Nordeste de Curití y borde occidental del Macizo de Santander, Departamento de Santander. Informe Interno (Inédito), Servicio Geológico Colombiano (INGEOMINAS): 363 p. Bogotá.
- Pons, D. 1982. Etudes paleobotanique et palynologique de la Formation Giron (jurassique moyen-cretace inferieur) dans la region de Lebrija, Departamento de Santander, Colombie. *In* Congrès National des sociétés Savantes, No. 107, Brest. Sci. Journal of the American Society of Cytopathology (JASC) 1: 53-78.
- Prosser, S. 1993. Rift-related linked depositional systems and their seismic expression. *In* Tectonics and seismic sequence stratigraphy (Williams, G.D.; Dobb, A.; editors). Geological Society, Special Publication (71): 35-66.

- Pulido, O. 1979. Geología de las planchas 135 (San Gil)
   y 151 (Charalá) cuadrángulo I-12 escala 1:100.000.
   Memoria explicativa, Servicio Geológico Colombiano
   (INGEOMINAS): 69 p. Bogotá.
- Pulido, O.; Ulloa, C.; Rodríguez, E. 1986. Relaciones estratigráficas entre el Jurásico y el Cretácico de la Cordillera de Los Cobardes. Geología Colombiana 15: 55-64.
- Ramos, A.; Sopeña, A.; Pérez-Arlucea, M. 1986. Evolution of Buntsandstein fluvial sedimentation in the northwest Iberian Ranges (Central Spain). Journal of Sedimentary Research 56 (6): 862-875.
- Reineck, H.; Singh, I. 1973. Depositional sedimentary environments with reference to terrigenous clastics. Springer-Verlag: 453 p. Berlin.
- Renzoni, G. 1985. Paleoambientes de la Formacion Tambor en la Quebrada Pujamanes. *In* Proyecto Cretácico, Contribuciones (Etayo-Serna, F.; Laverde-Montaño F.; editors). Servicio Geológico Colombiano (INGEOMINAS), Publicación Geológica Especial 16 (3): 1-18. Bogotá.
- Restrepo-Moreno, S.A.; Foster, D.A.; Bernet, M.; Min, K.; Noriega, S. 2019. Morphotectonic and Orogenic Development of the Northern Andes of Colombia: A Low-Temperature Thermochronology Perspective. *In* Geology and Tectonics of Northwestern South America, Springer International Publishing: 749-832.
- Rodríguez, G.; Arango, M.I.; Zapata, G.; Bermúdez, J.G. 2018. Petrotectonic characteristics, geochemistry, and U-Pb geochronology of Jurassic plutons in the Upper Magdalena Valley-Colombia: Implications on the evolution of magmatic arcs in the NW Andes. Journal of South American Earth Sciences 81: 10-30.
- Roeder, D.; Chamberlain, R. 1995. Eastern Cordillera of Colombia: Jurassic-Neogene crustal evolution. *In* Petroleum Basins of South America (Tankard, A.; Suárez, R.; Welsink, H.; editors). American Association of Petroleum Geologists (AAPG) 62: 633-645.
- Rolón, L.F. 2004. Structural geometry of the Jura-Cretaceous rift of the Middle Magdalena Valley basin, Colombia. M. Sc. Thesis (Unpublished), West Virginia University: 69 p.
- Ross, I.; Parra, P.; Mora, C.; Pimentel, C. 2009. Afta apatite fission track analysis constraints on the Mesozoic to Quaternary thermal and tectonic evolution of the Middle Magdalena Basin and Santander Massif, Eastern Cordillera, Bucaramanga area, Colombia. *In* Simposio Bolivariano: Exploración Petrolera en Cuencas Subandinas, No. 10, Memoir: 1-14. Cartagena de Indias.

- Rossello, E.; Navistic, L.; Araque, L.; Bettini, F.; Bordarampe, C.; Castro, E.; Colo, C.; Corsico, S.; Covellone, G.; Haring, C.; Pina, L.; Pinilla, C.; Ruiz, J.; Salvay, R. 2004. La sintaxis tectónica neógena de las cordilleras Oriental y Santander: Aportes de modelos analógicos y controles regionales sobre sistemas petroleros. *In* Convención técnica de la Asociación Colombiana de Geólogos y Geofísicos del Petróleo (ACGGP), No. 3: 1-14. Colombia.
- Royero, G.; Clavijo, J. 2001. Mapa geológico generalizado del Departamento de Santander, escala 1:400.000. Memoria explicativa, Servicio Geológico Colombiano (INGEOMINAS): 92 p. Bogotá.
- Royero, J.; Vargas, R. 1999. Geología del Departamento de Santander. Mapa Geológico, escala 1: 300.000. Servicio Geológico Colombiano (INGEOMINAS). Bogotá.
- Sarmiento, G.; Puentes, J.; Sierra, C. 2015. Evolución geológica y estratigrafía del Sector Norte del Valle Medio del Magdalena. Geología Norandina 12: 51-82.
- Sarmiento-Rojas, L.; Van Wess, J.; Cloetingh, S. 2006. Mesozoic transtensional basin history of the eastern Cordillera, Colombian Andes: Inferences from tectonic models. Journal of South American Earth Sciences 21: 383-411.
- Sperner, B.; Zweigel, P. 2010. A plea for more caution in fault-slip analysis. Tectonophysics 482: 29-41.
- Spikings, R.; Cochrane, R.; Villagomez, D.; Van der Lelij, R.; Vallejo, C.; Winkler, W.; Beate, B. 2015. The geological history of northwestern South America: from Pangaea to the early collision of the Caribbean Large Igneous Province (290-75 Ma). Gondwana Research 27 (1): 95-139.
- Taboada, A.; Rivera, L.; Fuenzalida, A.; Cisternas, A.;
  Philip, H.; Bijwaard, H.; Olaya, J.; Rivera, C. 2000.
  Geodynamics of the northern Andes: Subductions and Intracontinental deformation (Colombia). Tectonics 19 (5): 787-813.
- Tesón, E.; Mora, A.; Silva, A.; Namson, J.; Teixell, A.; Castellanos, J.; Casallas, W.; Julivert, M.; Taylor, M.; Ibáñez, M.; Valencia, V. 2013. Relationship of Mesozoic graben development, stress, shortening magnitude, and structural style in the Eastern Cordillera of the Colombian Andes. *In* Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion (Nemčok, M.; Mora, A.; Cosgrove, J.; editors). Geological Society of London, Special Publications 377: 257-283. London.
- Toussaint, J. 1995. Evolución geológica de Colombia
   2. Triásico Jurásico. Contribución al IGCP 322
   "Correlation of Jurassic events in South America"
   International Geological Correlation Programme

- Unesco-International Union of Geological Sciences (IUGS), Universidad Nacional de Colombia: 94 p.
- Ujueta, G. 2014. Tectónica de bloques, delimitados por lineamientos NNE-SSO y NO-SE, en Colombia. Geología Colombiana 39: 37-54.
- Van der Lelij, R.; Spikings, R.; Ulianov, A.; Chiaradia, M.; Mora, A. 2016a. Palaeozoic to Early Jurassic history of the northwestern corner of Gondwana, and implications for the evolution of the Iapetus, Rheic and Pacific Oceans. Gondwana Research 31: 271-294.
- Van der Lelij, R.; Spikings, R.; Mora, A. 2016b. Thermochronology and tectonics of the Mérida Andes and the Santander Massif, NW South America. Lithos 248: 220-239.
- Velandia, F. 2005 Interpretación de transcurrencia de las fallas Soapaga y Boyacá a partir de Imágenes LANDSAT TM. Universidad Industrial de Santander, Boletín de Geología 27 (1): 81-94. Colombia.
- Velandia, F. 2017. Cinemática de las fallas mayores del Macizo de Santander-énfasis en el modelo estructural y temporalidad al sur de la Falla de Bucaramanga. Ph.D. Thesis (Unpublished), Universidad Nacional de Colombia: 222 p.
- Velandia, F.; Bermúdez, M. 2018. The transpressive southern termination of the Bucaramanga fault (Colombia): Insights from geological mapping, stress tensors, and fractal analysis. Journal of Structural Geology 115: 190-207.
- Velandia, F.; García-Delgado, H.; Zuluaga, C.A.; López, J.A.; Bermúdez, M.A.; Audemard, F.A. 2020. Present-

- day structural frame of the Santander Massif and Pamplona Wedge: The interaction of the Northern Andes. Journal of Structural Geology 137: 21 p. doi: 10.1016/j.jsg.2020.104087.
- Villagómez, D.; Spikings, R. 2013. Thermochronology and tectonics of the Central and Western Cordilleras of Colombia: Early Cretaceous-Tertiary evolution of the northern Andes. Lithos 160: 228-249.
- Ward, D.; Goldsmith, R.; Cruz, J.; Restrepo, H. 1973.
  Geología de los Cuadrángulos H-12 Bucaramanga y
  H-13 Pamplona, departamento de Santander. Servicio
  Geológico Colombiano (INGEOMINAS), Boletín
  Geológico 21 (1-3): 1-132. Bogotá.
- Ward, D.; Goldsmith, R.; Jimeno, A.; Cruz, J.; Restrepo,
  H.; Gómez, E. 1977. Mapa Geológico del Cuadrángulo
  H-12 Bucaramanga. Escala 1:100.000. Servicio
  Geológico Colombiano (INGEOMINAS). Bogotá.
- Zuluaga, C.; Pinilla, A.; Mann, P. 2015. Jurassic silicic volcanism and associated continental-arc basin in Northwestern Colombia (southern boundary of the Caribbean plate). *In Petroleum Geology and Potential of the Colombian Caribbean Margin (Bartolini, C.; Mann, P.; editors)*. American Association of Petroleum Geologists (AAPG), Memoir 108: 137-160.
- Zuluaga, C.; López, J.A. 2019. Ordovician Orogeny and Jurassic Low-Lying Orogen in the Santander Massif, Northern Andes (Colombia). *In* Geology and Tectonics of Northwestern South America. Springer: 195-250. doi: 10.1007/978-3-319-76132-9 4.

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