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Key Points:
- We linked Upper Cretaceous to Eocene tectonostratigraphic evolution of the San Jacinto fold belt of NW Colombia with plate kinematics
- Eocene major change in plate kinematics caused to the onset of flat subduction and cessation of arc magmatism in northwest Colombia
- The existence of a tear or STEP fault in the Caribbean Plate, located toward the western end of the Oca-San Sebastián-El Pilar Fault System is proposed

Supporting Information:
- Supporting Information S1

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Linking Late Cretaceous to Eocene Tectonostratigraphy of the San Jacinto Fold Belt of NW Colombia With Caribbean Plateau Collision and Flat Subduction

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Abstract Collision with and subduction of an oceanic plateau is a rare and transient process that usually leaves an indirect imprint only. Through a tectonostratigraphic analysis of pre-Oligocene sequences in the San Jacinto fold belt of northern Colombia, we show the Late Cretaceous to Eocene tectonic evolution of northwestern South America upon collision and ongoing subduction with the Caribbean Plate. We linked the deposition of four fore-arc basin sequences to specific collision/subduction stages and related their bounding unconformities to major tectonic episodes. The Upper Cretaceous Cansona sequence was deposited in a marine fore-arc setting in which the Caribbean Plate was being subducted beneath northwestern South America, producing contemporaneous magmatism in the present-day Lower Magdalena Valley basin. Coeval strike-slip faulting by the Romeral wrench fault system accommodated right-lateral displacement due to oblique convergence. In latest Cretaceous times, the Caribbean Plateau collided with South America marking a change to more terrestrially influenced marine environments characteristic of the upper Paleocene to lower Eocene San Cayetano sequence, also deposited in a fore-arc setting with an active volcanic arc. A lower to middle Eocene angular unconformity at the top of the San Cayetano sequence, the termination of the activity of the Romeral Fault System, and the cessation of arc magmatism are interpreted to indicate the onset of low-angle subduction of the thick and buoyant Caribbean Plateau beneath South America, which occurred between 56 and 43 Ma. Flat subduction of the plateau has continued to the present and would be the main cause of amagmatic post-Eocene deposition.

1. Introduction

The northwestern margin of South America has experienced a complex Cretaceous to Recent tectonic history that involves subduction of the Caribbean Plate and later collision of the Caribbean oceanic plateau, causing accretion of oceanic terranes in some areas or the subduction of the plateau in others (Bayona et al., 2012; Cediel et al., 2003; Mora et al., 2017; Restrepo et al., 2009; Spikings et al., 2015; Villagómez, Spikings, Magna, et al., 2011). While oceanic terrane accretion and later subduction of the Farallón and Nazca Plates has been better studied in central western Colombia (Chiarabba et al., 2015; Pennington, 1981; Syracuse et al., 2016; Taboada et al., 2000; Van der Hilst & Mann, 1994; Vargas & Mann, 2013; Zarifi et al., 2007), collision, accretion, and subduction of the Caribbean Plateau remain poorly understood in northwestern Colombia. This is caused by the lack of good quality geological and geophysical information and by the low seismicity of the area, which has made very difficult to image the lithospheric configuration of the NW Colombia convergent margin.

In this study we present a tectonostratigraphic analysis of the San Jacinto fold belt of northwestern Colombia and propose correlations of the interpreted tectonostratigraphic sequences and their bounding unconformities with specific tectonic and geodynamic settings, as deduced from the interpretation of reflection seismic, earthquake, and seismicity data. The San Jacinto fold belt (Figures 1 and 2) is a west verging fold and thrust belt in which an Upper Cretaceous to lower Eocene marine basin has been preserved (Duque-Caro, 1979, 1984, 1991; Flinch, 2003; Guzman, 2007), and it has remained poorly studied due to the structural complexity, poor outcrops, few drill holes, and widely spaced and low-quality reflection seismic data. However, it is an

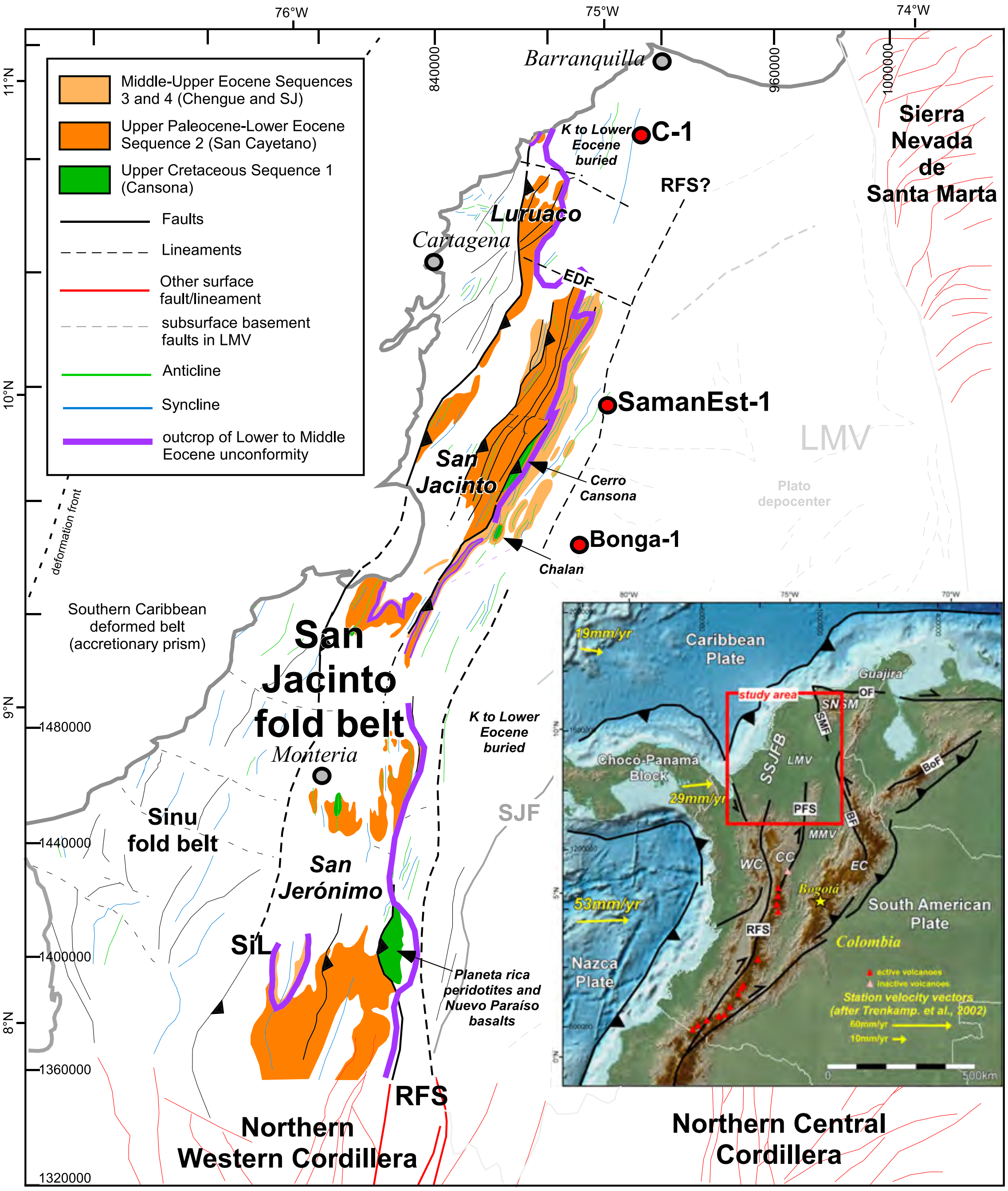

Figure 1. Geological map of the San Jacinto fold belt, highlighting outcrops of Cretaceous to Eocene units and showing major structural and morphologic features. RFS: Romeral Fault System; SJF: San Jerónimo Fault; SiL: Sinu Lineament; and EDF: El Dique Fault. Based on Gomez et al. (2007). Inset: Tectonic map of northwestern South America with topography and bathymetry, showing the location of the Lower Magdalena Valley basin (LMV), the Sinú-San Jacinto fold belt (SSJFB), and the active volcanoes. Present-day tectonic plate motions are shown in yellow (after Trenkamp et al., 2002). WC: Western Cordillera; CC: Central Cordillera; EC: Eastern Cordillera; RFS: Romeral Fault System; PFS: Palestina Fault System; BF: Bucaramanga Fault; SMF: Santa Marta Fault; OF: Oca Fault; and BoF: Bocono Fault.

area of NW Colombia in which Cretaceous to Eocene sedimentary sequences are well preserved, hence its importance for pre-Oligocene tectonostratigraphic and plate tectonic studies. Furthermore, in the past decade the National Hydrocarbons Agency of Colombia (ANH-Agencia Nacional de Hidrocarburos) made important efforts to acquire new information in the San Jacinto fold belt by drilling stratigraphic boreholes and acquiring new geophysical data, including air gravity (Bouguer anomaly), magnetics, and reflection seismic

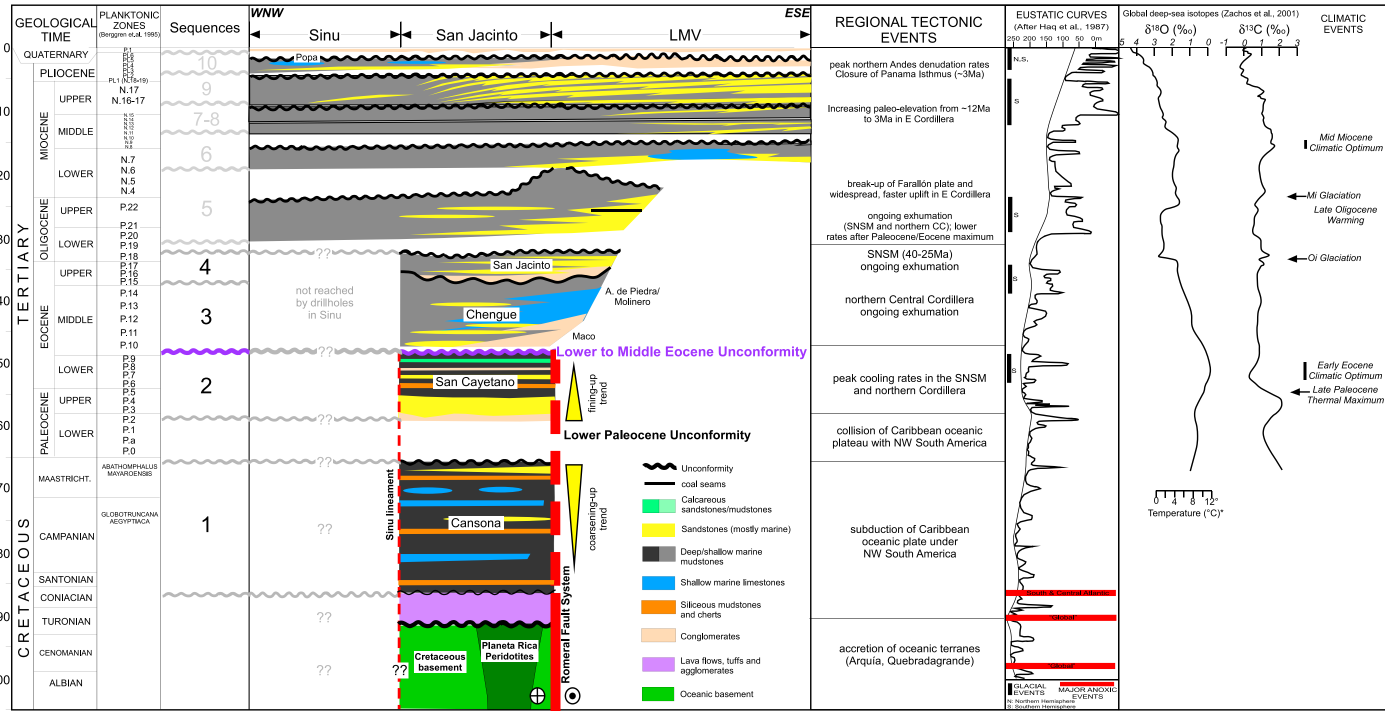

Figure 2. WNW-ESE trending chronostratigraphic chart of the Sinú, San Jacinto, and Lower Magdalena areas, based on different sources (Hocol, 1993; ICP (Instituto Colombiano del Petróleo), 2000; Guzman, 2007) and adjusted with our recent analyses of well and outcrop samples. Biostratigraphy is based on numerous papers and industry reports by Duque-Caro (1979, 1984, 1991, 2000, 2001, 2010), tectonic events are after Villagómez, Spikings, Mora, et al. (2011), Parra et al. (2012), Saylor et al. (2012), Mora, Reyes-Harker, et al. (2013), Caballero, Mora, et al. (2013), Caballero, Parra, et al. (2013), Mora et al. (2015), and De la Parra et al. (2015), while the eustatic curves are from Haq et al. (1987) and the climatic events from Zachos et al. (2001).

data. This has been complemented by new well and seismic data acquired by oil and gas companies doing hydrocarbon exploration in the area.

Taking advantage of the recently acquired data in the area, we have revised and updated Upper Cretaceous to Eocene tectonostratigraphic framework of the San Jacinto fold belt, which has been integrated to surrounding basins in order to identify the main regional sequences and unconformities in northwest Colombia. The tectonostratigraphic analysis included new seismic interpretations and maps, outcrop and well log correlations, biostratigraphy, organic geochemistry, and sedimentary provenance analyses through detrital zircon U-Pb geochronology and Hf isotope geochemistry. In order to look for correlations between our defined sequences, unconformities, and major regional tectonic events such as collision/subduction of the Caribbean oceanic plateau, we used reflection seismic, earthquake, and seismicity data, including our own interpretations and maps and previous published work on lithospheric imaging of northwestern South America. Based on previous studies and on the results of our new data and analyses, we also propose a present-day geometric model of the lithospheric configuration of NW Colombia.

2. Geological Setting

The San Jacinto fold belt (SJFB) is located in northwestern South America, close to the northern end of the western South American convergent margin (Figure 1). However, convergence in the study area does not involve the Nazca Plate, but instead, it involves the Caribbean Plate, which is separated from the Cocos and Nazca Plates by the Panama-Chocó block (inset in Figure 1). It has been proposed that this area is characterized by the slow and flat slab subduction of the Caribbean oceanic plate beneath South America, forming the Bucaramanga and Caribbean flat slabs imaged and described by several researchers (Bernal-Olaya, Mann, & Vargas, 2015; Chiarabba et al., 2015; Pennington, 1981; Syracuse et al., 2016; Taboada et al., 2000; Van der Hilst & Mann, 1994). Slow and flat slab subduction would be the cause of the low seismicity and of the lack of a magmatic arc in northwestern Colombia (inset in Figure 1).

The SJFB is a SW-NE trending terrane that makes part of the subduction complex of northwestern Colombia (Mantilla, 2007; Mantilla et al., 2009) and is located between an Oligocene to Recent fore-arc basin to the east (Lower Magdalena Valley basin (LMV), Figure 1) and the Miocene to Recent accretionary prism to the west (Sinú-Southern Caribbean deformed belt) (Bernal-Olaya, Mann, & Escalona, 2015; Duque-Caro, 1979, 1984; Mantilla et al., 2009). According to Mantilla et al. (2009), the SJFB represents the fossilized part of the accretionary prism of the northwest Colombia subduction complex, which today acts as dynamic backstop. It is formed by three discontinuous ranges or anticlinoria, called by Duque-Caro (1979) from south to north, San Jerónimo, San Jacinto, and Luruaco (Figure 1). Pre-Oligocene sedimentary units exposed in this fold belt have been considered the northward extension of the Western Cordillera of Colombia (Barrero et al., 1969; Cediel et al., 2003; Duque-Caro, 1979, 1984) and have been related to an oceanic-type basement. The Romeral Fault System (RFS), which is also considered to continue from the south to form the eastern boundary of the SJFB, appears to be separating the oceanic to transitional basement under the belt from the felsic continental basement of the South American crust, which floors the LMV in the east (Duque-Caro, 1979, 1984; Flinch, 2003; Mora et al., 2017). The RFS makes part of a ~2,000 km long tectonic suture that extends from Ecuador (Peltetec Fault), and there is general consensus about the large-scale right-lateral strike-slip movement that occurred along this fault zone during the Cretaceous, causing the juxtaposition of allochthonous oceanic terranes against Central Cordillera basement blocks (Cediel et al., 2003; Spikings et al., 2015; Villagómez, Spikings, Magna, et al., 2011). The northern extension of the RFS has also been an important tectonostratigraphic feature as shown by the different stratigraphic successions preserved on both sides of the fault system (Figure 2). In the SJFB, west of the RFS, there are Upper Cretaceous to Eocene sedimentary units that are not preserved in the LMV to the east (Duque-Caro, 1979, 1984), which will be the focus of the tectonostratigraphic analysis performed in this study.

2.1. The Basement of the San Jacinto Fold Belt (SJFB)

Basement information in the SJFB comes from localized outcrops located in the southernmost SJFB, close to the northern Western Cordillera (WC), and from a couple of reports from old drill holes, which have a high degree of uncertainty, suggesting the predominance of mafic and ultramafic rocks (Figure 2). These Upper Cretaceous mafic and ultramafic rocks have been related to allochtonous, accreted oceanic terranes (Cediel et al., 2003; Villagómez, Spikings, Magna, et al., 2011). From gravity modeling, the basement under the SJFB is considered to be thinned continental to transitional, with localized mafic allochthonous blocks (Bernal-Olaya, Mann, & Vargas, 2015; Cerón et al., 2007; Mantilla et al., 2009). However, recent Hf isotope geochemistry of a pluton in the western Lower Magdalena Valley (Bonga pluton, Mora et al., 2017) suggests that it intruded a young crust of possible oceanic affinity, such as the Quebradagrande and related terranes that have been studied farther south, within the RFS between the Central and Western Cordilleras.

2.2. Upper Cretaceous to Lower Oligocene Stratigraphic Units

Several researchers used the name "Cansona" to refer to the Upper Cretaceous strata that outcrops in the "Cerro Cansona" area of the San Jacinto Anticlinoria (Figure 2; Duque-Caro, 1972; Duque-Caro et al., 1996; Guzman et al., 2004). The Cretaceous strata in the SJFB consists of a volcano-sedimentary succession with a predominantly volcanic lower part and an upper part consisting of organic-rich and calcareous mudstones, limestones, and cherts with few quartzarenites (Aleman, 1983; Clavijo & Barrera, 1999; Guzman, 2007), deposited in marine environments.

Upper Paleocene to lower Eocene rocks have been described in outcrops and drill holes all along the SJFB (Guzman, 2007; Figure 2). They comprise a fining upward succession of polymictic conglomerates and litharenites toward the base and gray siltstones and mudstones with minor chert and limestone interbeds (Guzman, 2007; Guzman et al., 2004). Though several names have been proposed for this succession, the most common name is "San Cayetano" (Figure 2, Chenevart, 1963; Guzman, 2007; Guzman et al., 2004). Interpretations of its depositional environment range from deep marine turbiditic fans (Aleman, 1983; Duque-Caro, 1972; Guzman, 2007), turbiditic to distal deltaic (Geosearch Ltda, 2006), and fan deltas (ATG-ANH, 2009). The lower contact with the Upper Cretaceous Cansona sequence has been described as unconformable (Duque-Caro, 1979; Guzman, 2007; Guzman et al., 2004).

An angular middle Eocene unconformity separates the upper Paleocene to lower Eocene San Cayetano deposits from polymictic conglomerates, lithic sandstones, red algae limestones, and mudstones of middle

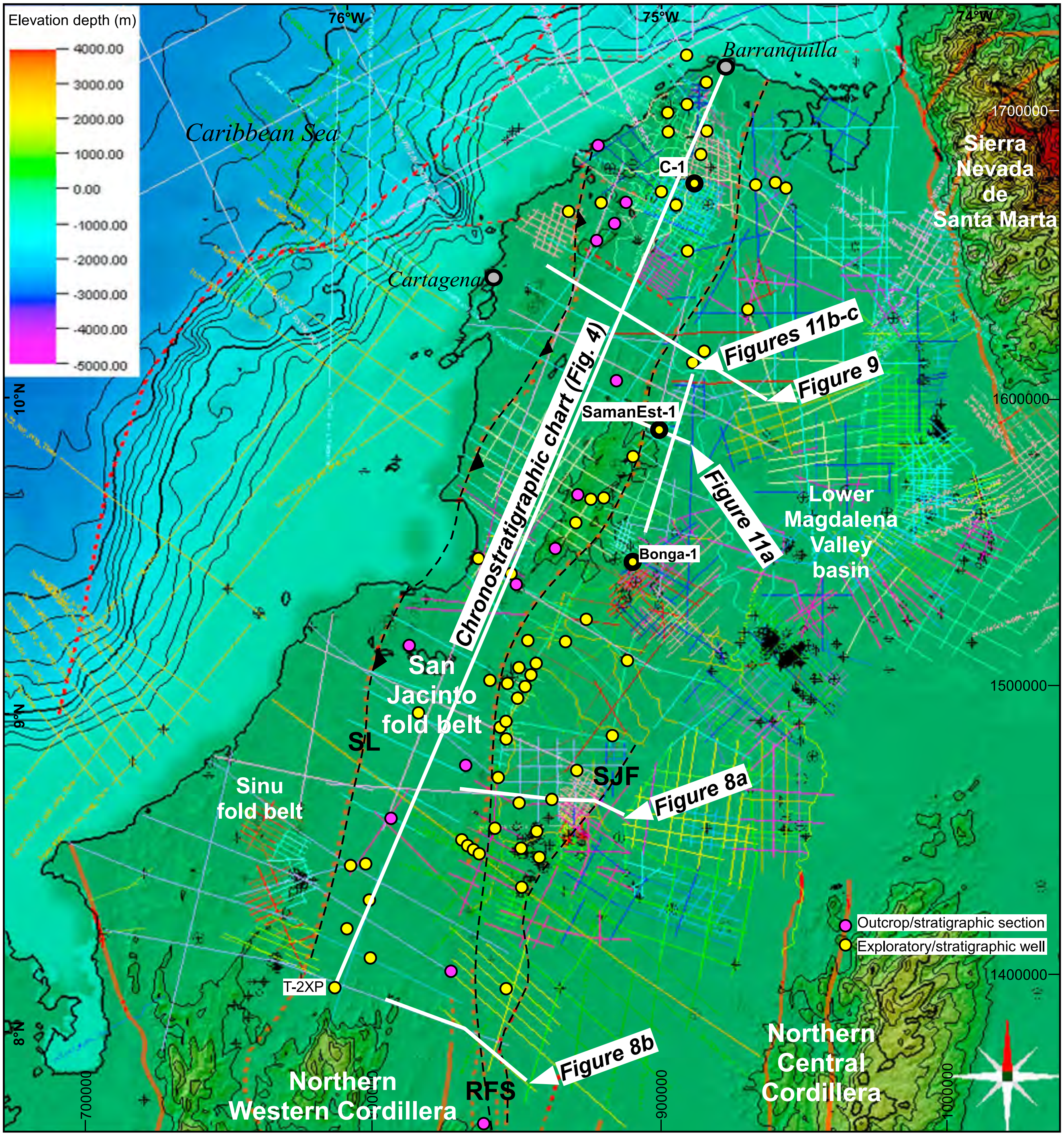

Figure 3. Reflection seismic and well database used for this study, provided by Hocol S.A. Colors represent different seismic surveys; the wells used in this study are shown in yellow and outcrops in pink. Location of Figure 4 and of seismic sections in Figures 8–11 are shown in white. Exact location of lines in Figure 10 is not shown due to confidentiality.

to upper Eocene age, which have received different names depending on the lithology and locality (Guzman, 2007; Guzman et al., 2004). For simplicity, the sedimentary succession of middle to upper Eocene age will be called here Chengue (Figure 2, Guzman, 2007; Guzman et al., 2004). The conglomeratic facies were deposited in fan deltas and related submarine slope deposits (Guzman, 2007), while the limestone facies were deposited in shallow marine carbonate platforms (Guzman et al., 2004).

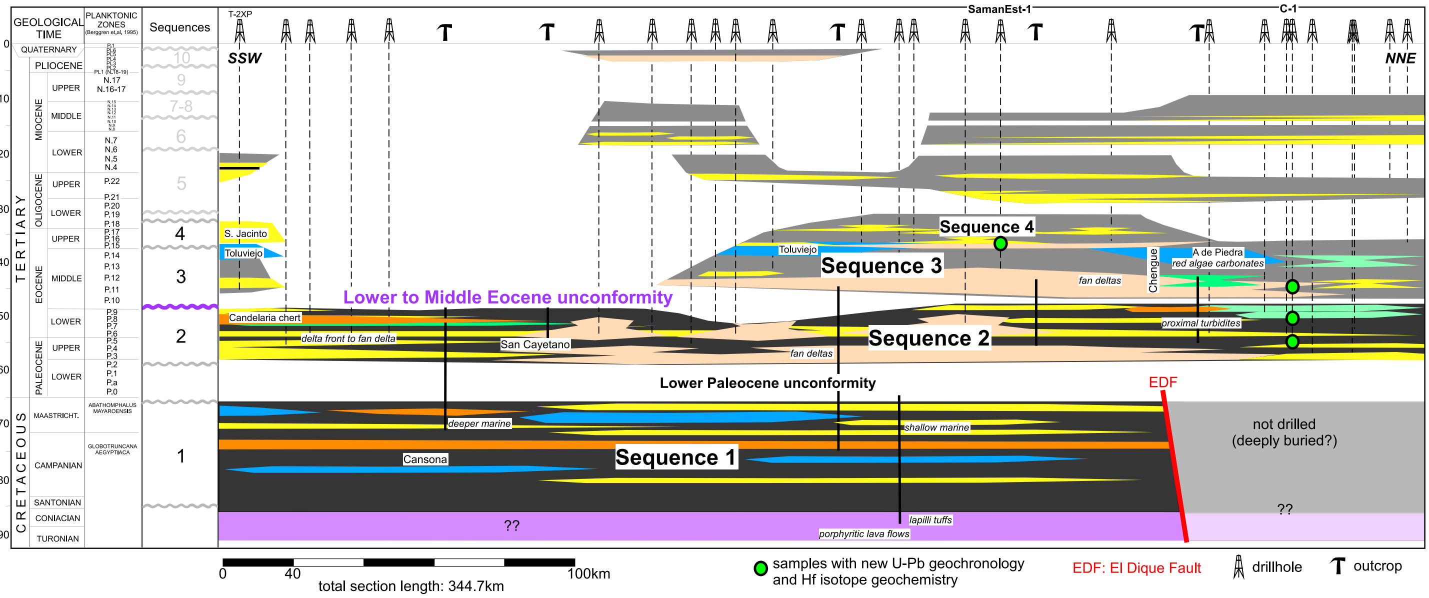

Figure 4. SSW-NNE trending chronostratigraphic chart along the strike of the San Jacinto fold belt, built with available well and outcrop data, showing the studied tectonostratigraphic sequences. Wells with new geochronology analyses are highlighted and the lithology legend is the same as in Figure 2.

Sandstones, conglomerates, and mudstones of upper Eocene to lower Oligocene age are locally preserved in the SJFB and unconformably overlying the middle to upper Eocene rocks of the Chengue unit (Guzman, 2007; Guzman et al., 2004). These clastic deposits have been called San Jacinto Formation (Figure 2) and were deposited in proximal deltaic fans (Guzman, 2007; Guzman et al., 2004), while upper Eocene carbonate deposits that occur in the central and southern SJFB have been called the Toluviejo Formation (Guzman et al., 2004). The lower and upper contacts of this unit are unconformities (Aleman, 1983; Guzman, 2007; Guzman et al., 2004).

Upper Oligocene to Recent deep marine to deltaic and continental units have been partially eroded in the SJFB but have been well preserved farther to the east, where they have filled the younger Lower Magdalena Valley basin (Figures 2 and 4).

3. Methodology

3.1. Construction of the Tectonostratigraphic Framework

We interpreted in two-way time (TWT) more than 3,000 km of 2-D reflection seismic, which were tied to more than 40 wells that have been drilled in the San Jacinto fold belt (Figure 3) and to the outcropping units. We identified and defined four Upper Cretaceous to lower Oligocene tectonostratigraphic sequences separated by major unconformities (Figures 2 and 4 and Text S1 in the supporting information), which according to Catuneanu et al. (2009) correspond to "depositional sequences." Sequence 1 comprises Upper Cretaceous deposits of the Cansona unit, Sequence 2 consists of upper Paleocene to lower Eocene strata of the San Cayetano unit, Sequence 3 comprises middle to upper Eocene rocks of the Chengue Group, and Sequence 4 consists of upper Eocene to lower Oligocene deposits of the San Jacinto unit. The lack of more detailed data for this study makes very difficult the identification of sequence stratigraphic surfaces other than subaerial unconformities and hampers the proposal of systems tracts (Catuneanu et al., 2009).

3.2. Detrital Zircon U-Pb Geochronology and Hf Isotope Geochemistry

In order to expand the geochronological data set for the pre-Oligocene strata in the SJFB and for correlations with basement units in northern Colombia, samples (cuttings) for petrography and detrital zircon U-Pb and Hf isotope analyses were recovered from two wells located in the northern half of the SJFB. Six samples from upper Paleocene to upper Eocene units (San Cayetano and Chengue) were collected in the C-1 well, located in the northern San Jacinto fold belt, while two more samples from an upper Eocene to lower Oligocene unit

(San Jacinto) were collected in the SamanEST-1 well, located farther south, close to the boundary between the SJFB and the LMV (Figures 3 and 4). The SamanEST-1 well is located 50 km to the north of the Bonga-1 well, which found granitic basement of Coniacian to Campanian age (Mora et al., 2017). The U-Pb geochronology and Hf isotope geochemistry detrital zircon analyses were done at the Arizona LaserChron Laboratory, and the detailed methodology is presented in Text S2. The stratigraphic succession in both wells was dated by Duque-Caro (2013a, 2013b).

3.3. Seismicity Data

We also compiled the available earthquake and seismicity data from the study area, not only to characterize the main faults and structural features in terms of seismic activity and kinematics but also to try to image the lithospheric structure of the subduction zone in the study area. Seismicity data from the study area were downloaded from the Colombian Earthquake Network (Red Sismológica Nacional, http://seisan.sgc.gov.co/RSNC/) and plotted both in map and section view, together with the seismic interpretation and maps. A total of 14,081 events was obtained, corresponding to earthquakes with M_w 1 to 9, recorded from 1 June 1993 to 26 November 2015. We interpreted and mapped the near top of the subducting oceanic plate under the SJFB, which connects with a megathrust that can be imaged in some of the regional seismic lines, as shown in Mora et al. (2017, their Figure S1). Using stacking processing velocities from reflection seismic data, we depth converted the interpreted subduction megathrust and plotted it with the earthquake and seismicity data in cross sections (Figure S1). Further procedures followed to construct our maps and plots are described in Text S3.

4. Results

4.1. Stratigraphic Framework

The general characteristics of the identified and studied tectonostratigraphic sequences are presented in Table 1, and the detailed descriptions are found in Text S1. Though our tectonostratigraphic framework is mostly based on previous research, it was built after incorporating a great deal of recent regional drill hole, seismic, and outcrop data and interpretations.

4.1.1. Sequence 1 (Cansona-Upper Cretaceous)

The oldest, second-order sequence is of Coniacian to Maastrichtian age (see Text S1) and comprises the bituminous shales, cherts, and limestones of the Cansona unit. Biostratigraphic data compiled by Duque-Caro (2000, 2001) and Guzman (2007) show an absence of lower Paleocene planktonic foraminiferal zones (P.0 to P.2) in the SJFB, indicating the existence of a regional unconformity that marks the upper limit of this sequence (Figure 4). The Cansona sequence appears to show a general coarsening and shallowing upward pattern (Guzman, 2007), similar to the pattern displayed in other Upper Cretaceous successions of northern Colombia (Villamil, 1999), all of which are in agreement with the global eustatic curve of Haq et al. (1987, Figure 2).

4.1.2. Sequence 2 (San Cayetano-Upper Paleocene to Lower Eocene)

This is also a second-order sequence that has been dated as upper Paleocene to lower Eocene (planktonic foraminiferal zones P.3 to P.9, see Text S1). The late Paleocene was characterized by a high global sea level (eustatic curves in Figure 2, Haq et al., 1987), which could have influenced the onset and extension of San Cayetano sedimentation. Biostratigraphic data show that there is a big hiatus in the center of the SJFB, where the lower Eocene is missing, while to the north the section is more complete and the contact with the overlying sequence appears to be a disconformity (Figure 4 and Table 1).

4.1.3. Sequence 3 (Chengue-Middle to Upper Eocene)

A middle to upper Eocene, second-order sequence corresponds to the Chengue Group, defined by the P.10 to P.14 planktonic foraminiferal zones of middle to late Eocene age (Text S1). Biostratigraphy indicates that the unconformity between Sequences 2 (San Cayetano) and 3 (Chengue) corresponds to the P.9 to P.10 foraminiferal zones, implying a time interval of 46 to 51 Ma that includes the limit between the lower and middle Eocene. This syntectonic sequence has been eroded in the southern part of the SJFB and is more preserved in the northern part (Figure 4).

4.1.4. Sequence 4 (San Jacinto-Upper Eocene to Lower Oligocene)

This locally preserved second-order sequence comprises the siliciclastic San Jacinto unit and the calcareous Toluviejo unit (Figures 2 and 4), which according to biostratigraphic studies (Duque-Caro, 1979;

Table 1
Main Characteristics of the Studied Upper Cretaceous to Eocene Tectonostratigraphic Sequences in the San Jacinto Fold Belt

Sequence	Lithostratigraphic unit	Planktonic foram zones (Berggren et al., 1995; Blow, 1969)	Age	Thickness and other characteristics	Facies and depositional environments
4	San Jacinto	P.15 to P.20	Upper Eocene to lower Oligocene	Highly variable facies and thicknesses, average thickness of 342 m but drilled ~1,000 m in the Saman stratigraphic well	Exhibits clastic (San Jacinto) and calcareous (Toluviejo) facies
Unconformity		*Absence of P.14 to P.16*	*Upper Eocene*		
3	Chengue	P.10 to P.14	Middle to upper Eocene	Highly variable facies and thicknesses; original syndepositional fabric comprises ESE-WNW and NNE-SSW-trending extensional faults; onlaps the basement to the ESE; thicknesses range from 150 m in paleohighs to >1,000 m in low areas	Exhibits clastic syntectonic deposits (Maco, Pendales), and local with development of carbonates in possible paleohighs (Arroyo de Piedra)
Unconformity		*Absence of P.9 to P.10*	*Lower to middle Eocene*		
2	San Cayetano	P.3 to P.9	Upper Paleocene to lower Eocene	Original fabric comprises ESE-WNW and NNE-SSW-trending extensional faults; thicknesses of >2,000 m in wells in the north and ~1,600 m in stratigraphic sections	General fining upward trend, but notorious lateral facies variations; interpreted depositional environments range from turbidites in the north and south, to fan deltas in the central part of the fold belt
Unconformity		*Absence of P.0 to P.2*	*Lower Paleocene*		
1	Cansona		Coniacian to Maastrichtian	Original syndepositional fabric affected by west verging deformation of the San Jacinto fold belt; thickness uncertain but would be ~762 m in the most complete stratigraphic section (Cacao)	Shows a general coarsening and shallowing upward pattern, deep marine environments interpreted; seismic expression is not clear, though locally presents high amplitude, parallel and continuous reflectors

Note. More information, detailed descriptions, and sources of biostratigraphic, petrographic, and organic geochemistry reports are found in Text S1.

Guzman, 2007; Guzman et al., 2004) are defined by the P.15 to P.20 planktonic foraminiferal zones of upper Eocene to lower Oligocene age.

4.1. Detrital Zircon U-Pb Geochronology and Hf Isotope Geochemistry

The detrital zircon U-Pb geochronology of samples of upper Paleocene to Eocene samples (Sequences 2 to 4, Figure 5) shows three clear provenance peaks, a main Upper Cretaceous (70–88 Ma, Coniacian-Maastrichtian) peak, a secondary peak of Permo-Triassic age (230–250 Ma), which is less evident in the SamanEST-1 well, and a minor Albian-Cenomanian peak (~100 Ma). However, the Paleocene to middle Eocene samples also evidence both Lower Paleozoic and Proterozoic provenance. Therefore, detrital zircon U-Pb geochronology indicates that the upper Paleocene to lower Oligocene sediments of Sequences 2 to 4 were mostly sourced from Upper Cretaceous and Permo-Triassic basement blocks.

Hf isotopic data show that the three dated detrital zircon populations (Coniancian-Maastrichtian, Albian-Cenomanian, and Permo-Triassic) are related to different magmatic sources (Figure 6). While the Coniacian-Maastrichtian zircons would be related to a juvenile mantle source, the older Albian-Cenomanian and Permo-Triassic zircons have much lower $\varepsilon Hf_{(t)}$ values, indicating a much older crustal source. Furthermore, in the SamánEST-1 well there are two subpopulations within the Upper Cretaceous Coniancian-Maastrichtian population (Figure 6c), and both overlap quite well with the compositions of the Bonga pluton (Mora et al., 2017), located 50 km to the south (Figure 3). The Permo-Triassic Hf isotopic compositions from the C-1 well also show a good match with the Hf compositions of the Permo-Triassic basement

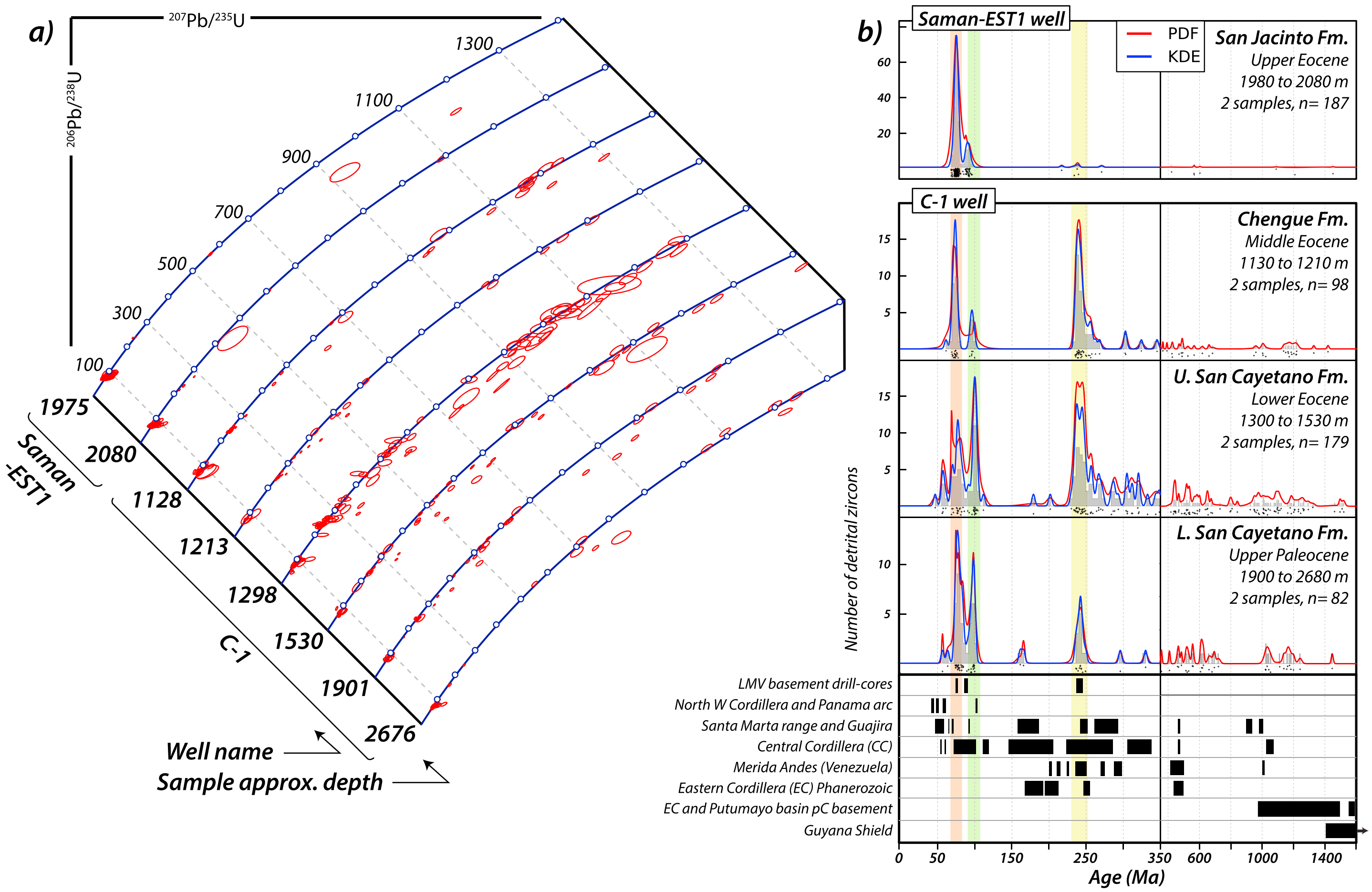

Figure 5. Results of detrital zircon U-Pb geochronology in samples of wells C-1 and SamanEST-1. Reference basement ages for possible source terranes were compiled using the data of Cordani et al. (2005), Vinasco et al. (2006), Ibañez-Mejia et al. (2015, 2011, 2007), Cardona, Chew, et al. (2010), Cardona, Valencia, et al. (2010), Horton et al. (2010), Montes et al. (2010, 2015), Restrepo-Pace and Cediel (2010), Weber et al. (2010, 2015), Cardona et al. (2011), Villagómez, Spikings, Mora et al. (2011), Bayona et al. (2012), Cardona et al. (2012, 2014), Cochrane et al. (2014), Spikings et al. (2015), Van der Lelij et al. (2016), and Mora et al. (2017).

in the HojarascaEST-1 and VIM15Est-2 wells (Mora et al., 2017) and with data from previous studies (Cardona et al., 2012; Cochrane et al., 2014).

4.2. Seismic Stratigraphy and Facies

Seismic characterization of each sequence is not an easy task considering the structural deformation, a not very dense reflection seismic coverage with poor to locally fair quality, partial erosion and notorious along-strike facies, and thickness changes of the sequences. Though the present-day SJFB is the result of at least two contraction and inversion tectonic pulses, which have obscured the original Cretaceous to Eocene structural fabric (Figure 7), in this study we document two areas in which pre-Oligocene sequences have remained deeply buried and in which their original structural fabric has been better preserved. The first area, in the southeastern SJFB, is located between the San Jerónimo anticlinorium to the west and the SJF to the east (section 3 and Figure 7), while the second area is the northernmost portion of the SJFB, located to the east of the Luruaco anticlinorium (section 1 and Figure 7). In cross section it can be seen that Sequences 1 and 2 are mostly restricted to the western side of the RFS and would be limited to the east by the San Jerónimo Fault (SJF). Sequences 3 and 4 extend farther to the east and probably into the LMV, where equivalent deposits would be preserved in the hanging wall of major extensional faults and in the deepest part of the Plato depocenter.

Reflection seismic imaging of the Upper Cretaceous Sequence 1 is very poor; hence, it is very difficult to characterize it in terms of seismic facies and seismic stratigraphic relationships. The base of the sequence does

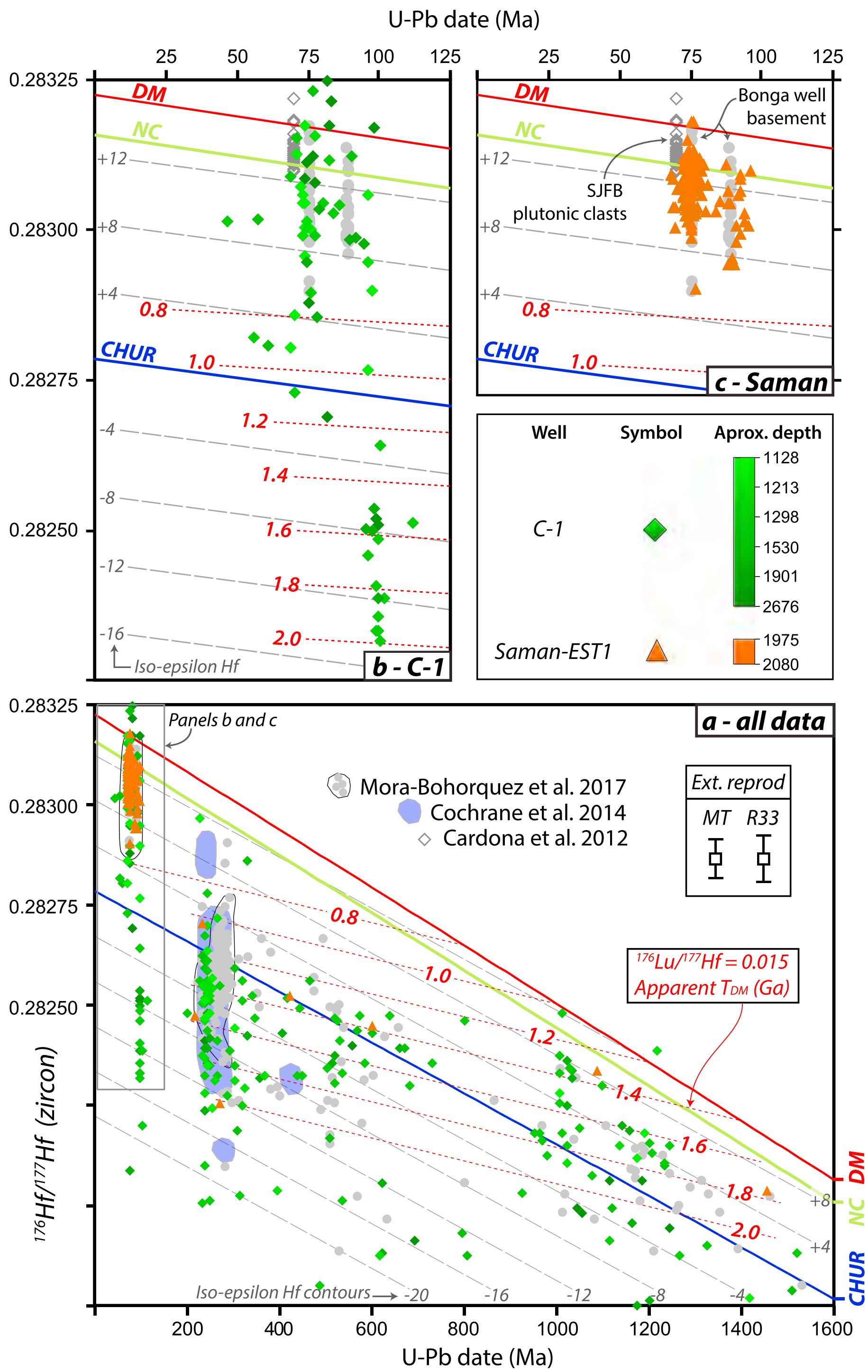

Figure 6. Results of detrital zircon Hf isotope geochemistry in samples of wells C-1 and SamanEST-1. Good matches with basement data from Mora et al. (2017), Cochrane et al. (2014), and Cardona et al. (2012) suggest a link between the analyzed pre-Oligocene sedimentary units and the Permo-Triassic and Upper Cretaceous basement terranes in the LMV and northern CC.

not have a clear expression in the seismic data (Figures 8 and 9), suggesting the absence of an acoustic impedance contrast. This is in agreement with the few descriptions of the basal portion of the sequence that report a transitional lower contact, which includes interbedded marine sediments and volcanic deposits. Imaging is extremely poor at shallow levels in which seismic facies are mainly transparent, with

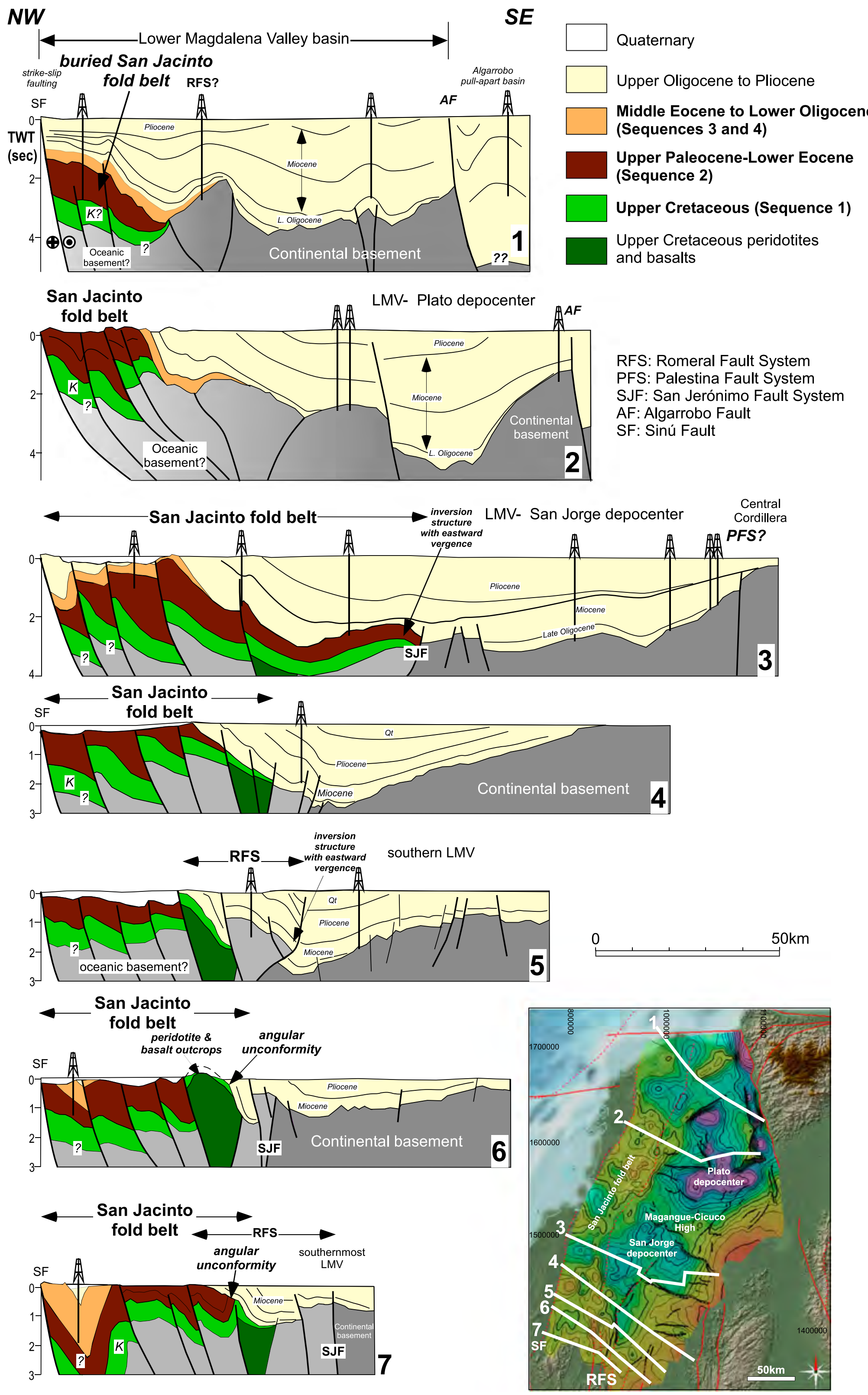

Figure 7. NW-SE trending geoseismic cross sections in two-way time (TWT), showing the along strike variation in structure of the SJFB, LMV, and RFS and highlighting tectonostratigraphic relationships among the studied sequences. The SJFB exhibits more contraction and shortening in the central and southern areas, whereas in the north (section 1), where pre-Oligocene units are buried, it displays much less contraction. The activity of the RFS also decreases from south to north. SF: Sinu Fault; SJF: San Jerónimo Fault; PFS: Palestina Fault System; and AF: Algarrobo Fault.

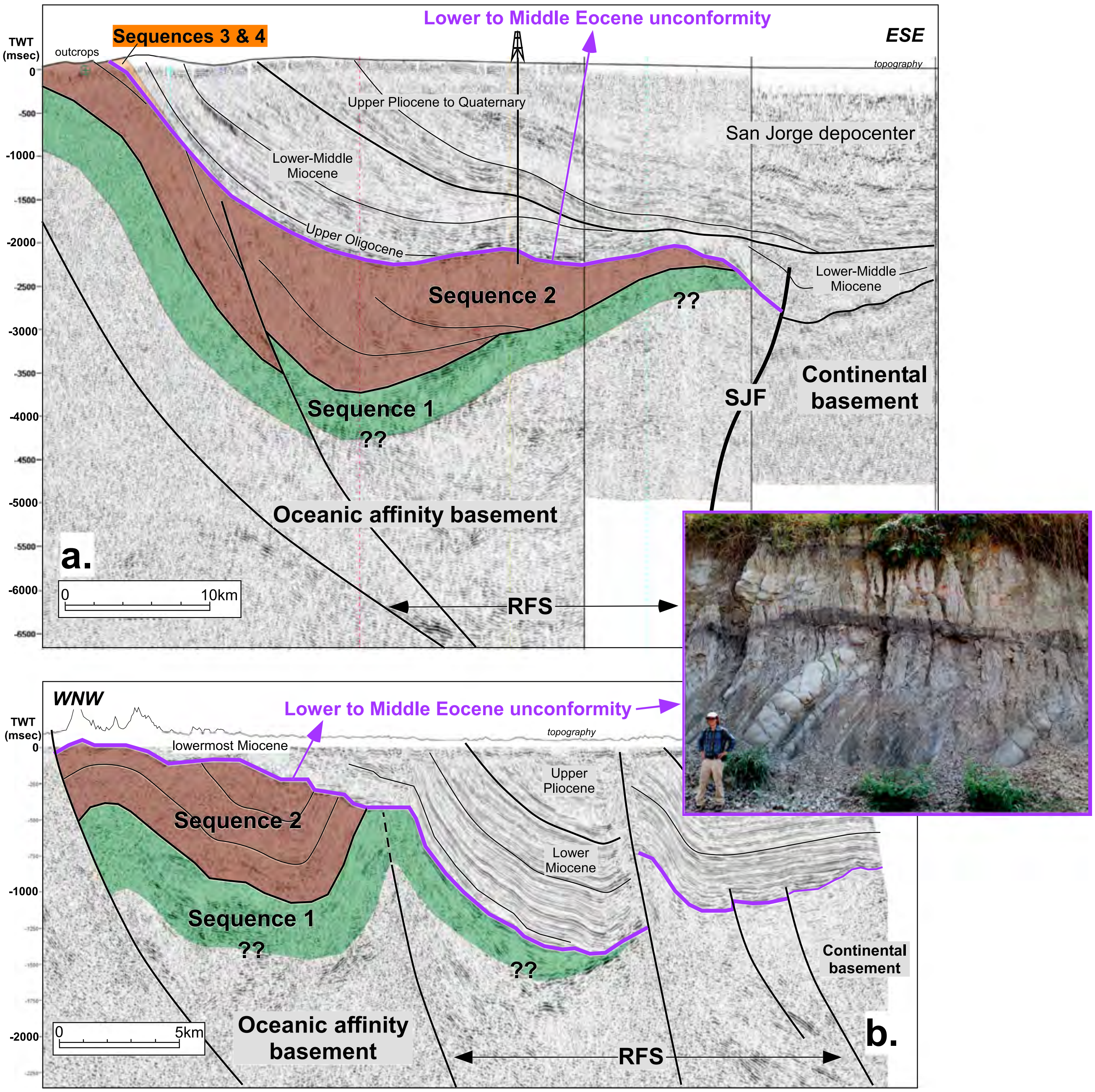

Figure 8. TWT seismic lines showing the interpreted structure of the RFS and SJFB in the southern part of the study area and the seismic and outcrop expression of the impressive, lower to middle Eocene unconformity above Sequences 1 and 2. The San Jerónimo Fault (SJF) in the southern SJFB appears to be responsible for the presence of pre-Oligocene units toward the east, into the southern LMV. Location of the sections is shown in Figure 3 and uninterpreted versions of the seismic lines are included as supporting information (Figure S2).

only local and discontinuous, east dipping, high-amplitude parallel reflectors that appear to form the steep flanks of west verging thrust blocks (Figure 8). The upper contact with Sequence 2, which has been described in outcrops as an unconformity, is very difficult to identify in the seismic data. However, in the syncline located west of the San Jorge depocenter (Figure 8a), we interpret an angular unconformity that may correspond to the contact between Sequences 1 and 2. Seismic data also suggest that Sequence 1 gets thinner to the east, either by erosion related to the lower to middle Eocene unconformity or by stratigraphic thinning of the sequence probably toward more proximal areas.

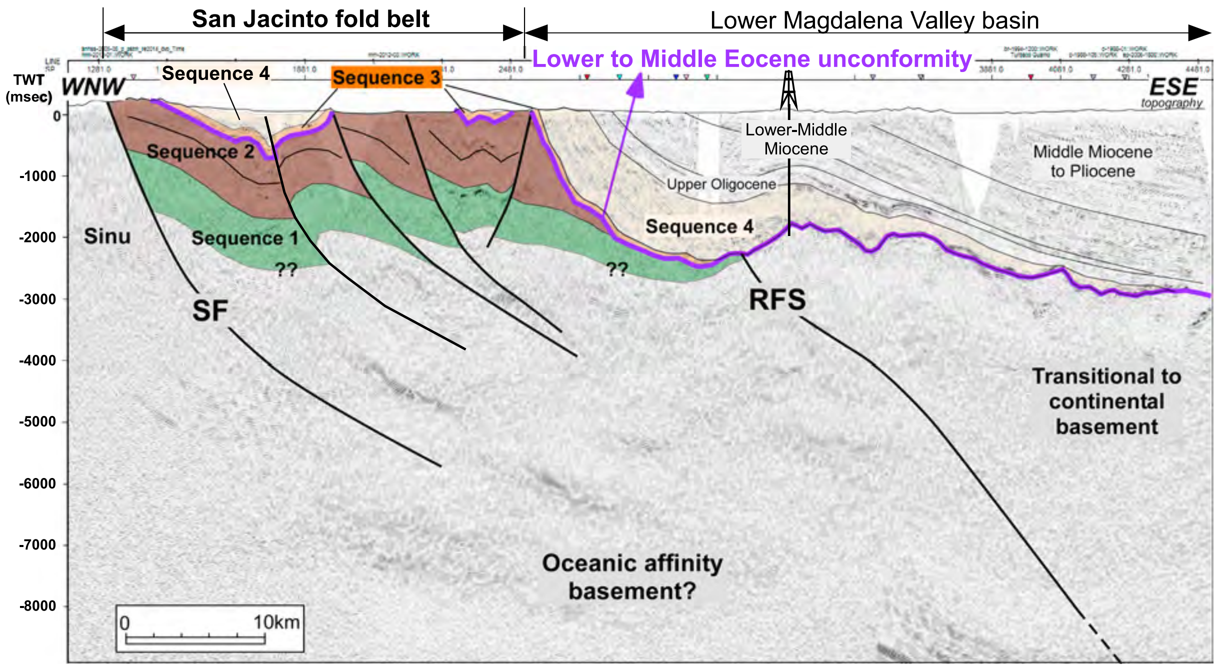

Figure 9. TWT seismic line showing the interpreted structure of the northern San Jacinto anticlinorium and of the northwestern LMV, highlighting the pre-Oligocene tectonostratigraphic sequences. Thick deposits of Sequence 4, drilled by the SamanEST-1 well, have sealed the RFS, which would only be responsible for slight folding. Main deformation of the SJFB is related to the activity of the Sinu Fault (SF) and other deeply rooted structures, which appear farther to the west, in the Sinú fold belt. The location of the section is shown in Figure 3 and an uninterpreted version of the seismic line is included as supporting information (Figure S3).

A poor seismic imaging of Sequence 2 has been obtained in the southern SJFB (Figure 8b), where Sequences 1 and 2 appear as folded strata, which are separated from younger postlower Eocene sequences by an angular unconformity. Farther north, in the syncline preserved to the west of the San Jorge depocenter (Figure 8a), Sequence 2 shows a divergent pattern with fanning toward the west and onlap toward the east, against the underlying Sequence 1. Such geometry would be related to sedimentation in very inclined surfaces, typical of slope deposits such as those interpreted in nearby outcrops. In the northern SJFB, Sequence 2 appears as a series of ESE dipping high-amplitude and low-frequency reflectors that have been interpreted as extensional rotated fault blocks (Figure 10b). Detailed mapping of such structures showed that they are forming two sets of extensional faults, one with a SSW-NNE orientation and the second one with a WNW-ESE orientation (Mora, De Freitas, et al., 2013). The upper contact of Sequence 2 is an angular unconformity, which has been imaged in several seismic sections (Figures 7–10). Considering the age of Sequences 2 and 3, the approximate age of the unconformity is marked by the planktonic zones P.9 to P.10, corresponding to the limit between the lower and middle Eocene (Figures 2 and 4). As seen in the seismic cross sections (Figures 7–11), the activity of the RFS, including the SJF, has been sealed by the lower to middle Eocene unconformity, and the eastward tilting of the whole fold belt has been caused by a deeper and younger major fault that probably extends to the deformation front of the accretionary prism, in offshore areas much farther to the west.

Sequence 3 is best preserved in the northern SJFB where it has also been well imaged by 2-D and 3-D seismic data (Figure 10) and has been drilled by wells such as the C-1. This sequence has notorious lateral thickness and facies changes. In the northern SJFB, Sequence 3 is also affected by extensional faults (Figure 10), which, when mapped in detail with 3-D seismic, were found to have two main, probably inherited structural trends, a SSW-NNE trend and a WNW-ESE trend (Mora, De Freitas, et al., 2013). The carbonates tend to be preserved in areas interpreted as paleohighs, while conglomerates appear to occur in low areas (Figure 10). In the eastern San Jacinto anticlinoria, seismic packages with medium- to high-amplitude frequency reflectors have fossilized the RFS and are onlapping the basement toward the east (Figure 11a). Sequences 3 and 4 thus represent the onset of landward stepping sedimentation in the area after the lower to middle Eocene tectonic, uplift, and erosional event. The lower contact of Sequence 3 is a clearly imaged angular unconformity, while the upper contact is also unconformable with upper Oligocene strata in the northern SJFB (Figure 10) and with upper Eocene to lower Oligocene strata of Sequence 4 (Figure 11a).

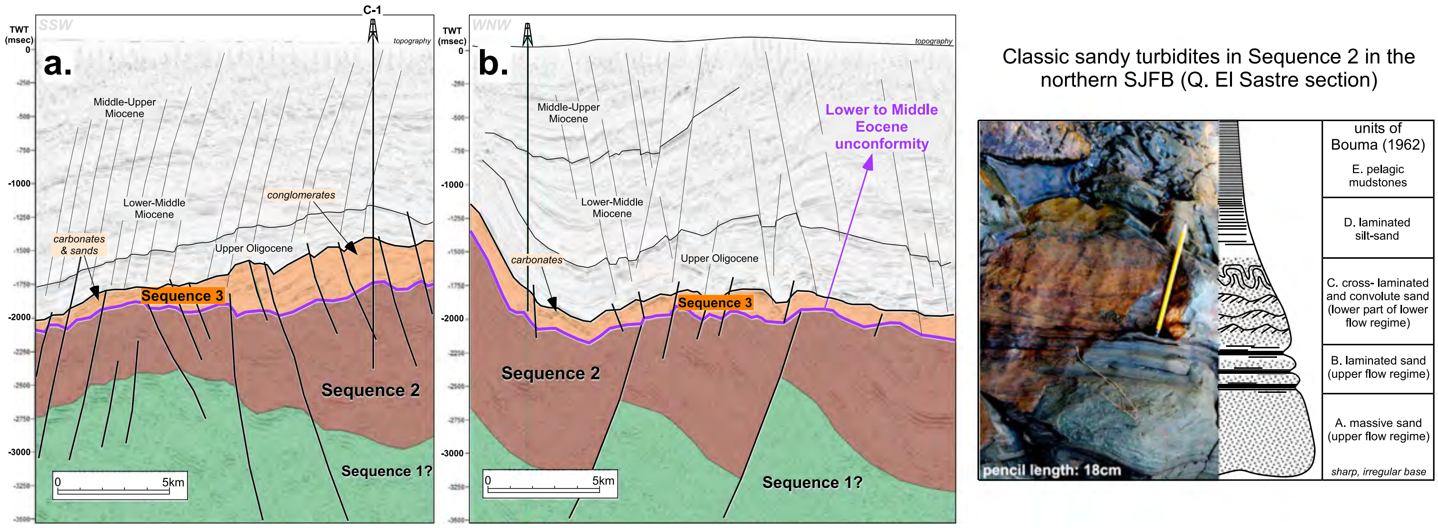

Figure 10. TWT seismic lines showing the interpreted structure of the northernmost SJFB. Extensional structures are well preserved in this area, in contrast to the central and southern areas of the fold belt where compression and strike-slip deformation is predominant. The seismic lines show how Sequence 3 delimits a lower structural domain (Sequences 1 to 3) from an upper structural domain. An example of a classic sandy turbidite, occurring in Sequence 2 and described in a stratigraphic section in the northern SJFB, is also shown. Sequence 4 is not preserved in this area. (a) A strike line, trending approximately from NE to SW and (b) a dip line, trending approximately from SE to NW. The lines are located close to the C-1 drill hole in the northern SJFB, but due to confidentiality, the exact location of the lines cannot be provided.

Sequence 4 exhibits high thicknesses in the axis of a syncline in which the T-2XP was drilled (cross-section 7 in Figure 7). This sequence is also imaged in seismic data in the central eastern part of the San Jacinto anticlinoria, where the Samán stratigraphic well was drilled (Figures 1 and 7/section 2 and Figure 11a). However, in this area, Sequences 3 and 4 were deposited on top of the basement and show moderate to high-amplitude, medium- to high-frequency reflectors, which are divergent toward the west and onlap older units at low angles toward the ESE (Figures 9 and 11a). Seismic lines oriented parallel to the belt's strike (Figures 11b and 11c) show that the clastic deposits of Sequence 4 are also affected by the WNW-ESE extensional fault family that is affecting Sequence 3 in the north.

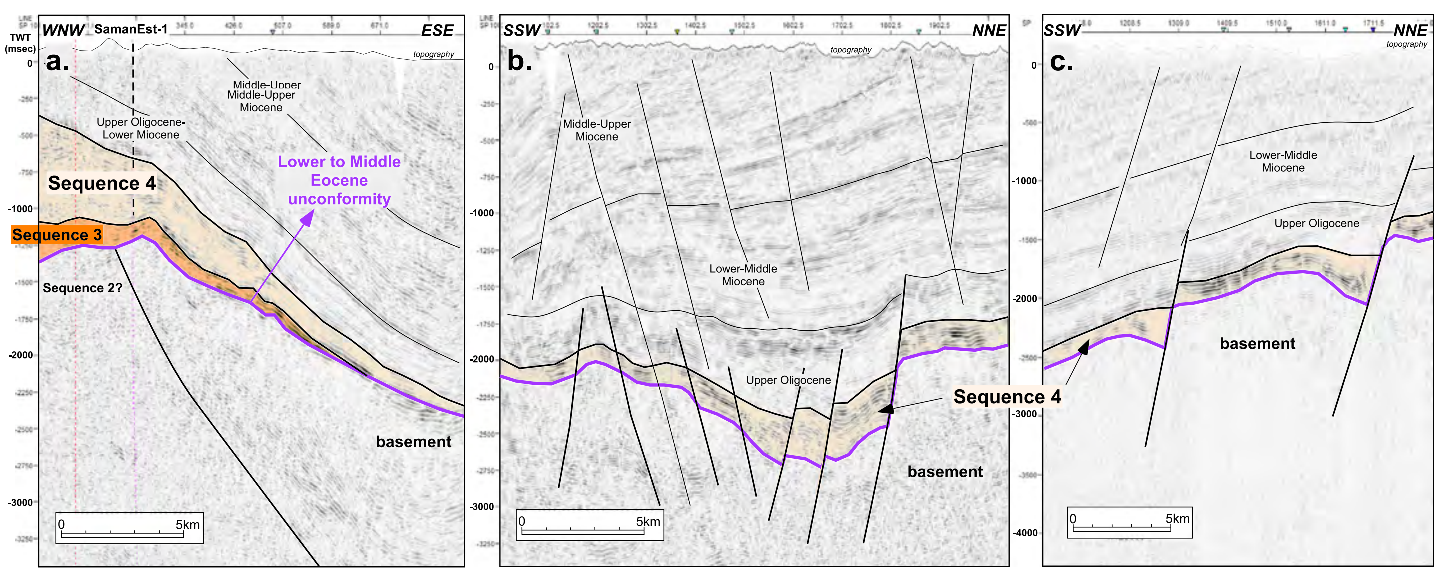

Figure 11. (a) TWT seismic lines in the central to northern SJFB (eastern San Jacinto anticlinorium) showing the onlap of Sequences 3 and 4 against the basement to the ESE, sealing the RFS. (b and c) The interpreted synextensional deposits of Sequence 4 preserved in extensional faults trending ESE-WNW. Location of the sections is shown in Figure 3, and uninterpreted versions of the seismic lines are included as supporting information (Figure S5).

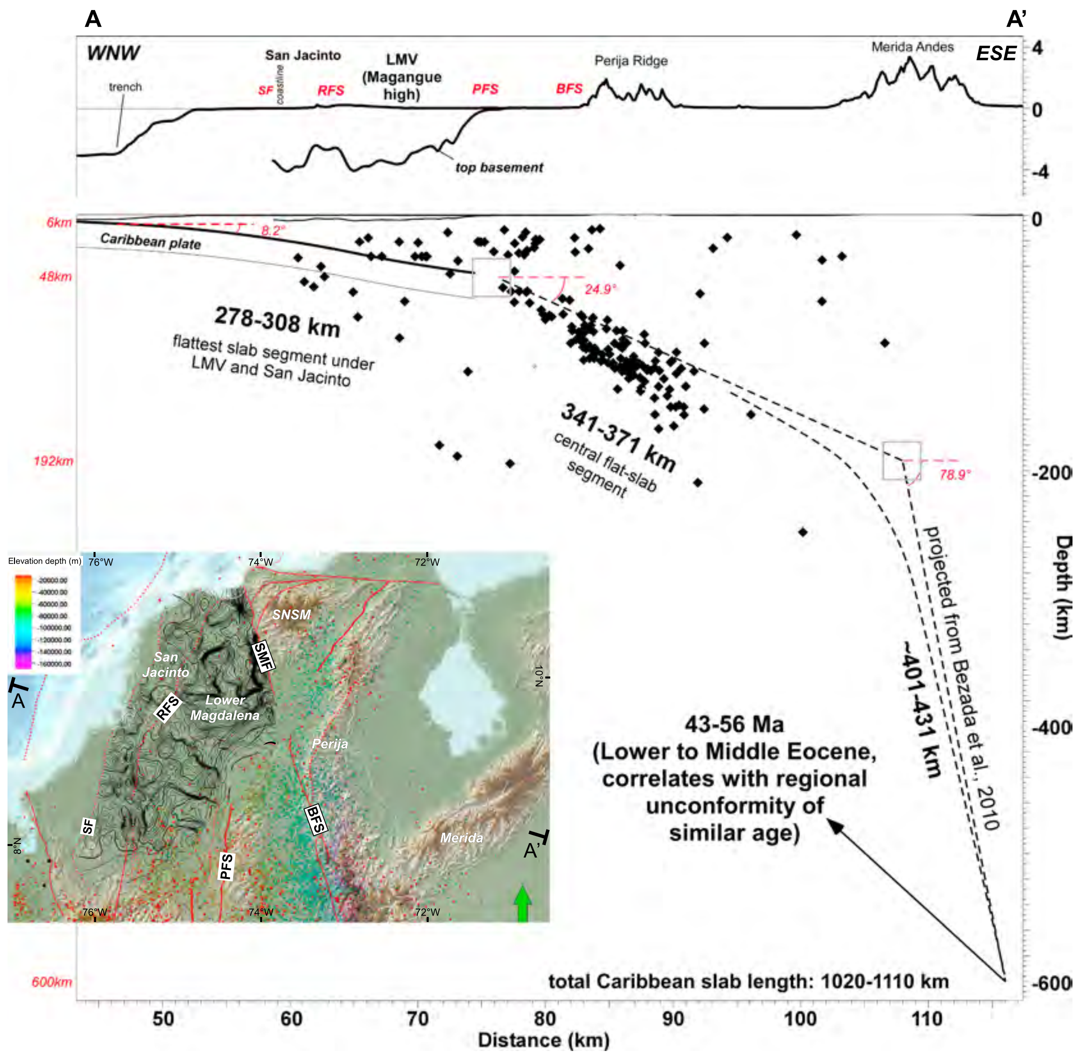

Figure 12. Regional WNW-ESE trending cross section showing the configuration of the subducted Caribbean oceanic plate, as interpreted from reflection seismic mapping for the shallowest part, intermediate-depth seismicity for the central part and from published tomography data (Bezada et al., 2010) for the deepest part of the cross section. The top of the basement under the LMV from reflection seismic mapping and the topography are also displayed. Gray squares represent the uncertainty (±15 km) in the horizontal and vertical measurements. This cross section is located farther to the north of the cross section presented by Mora et al. (2017, their Figure 13). We highlight the end of the subducted slab at a depth of ~600 km, which would have entered the trench in early to middle Eocene times, assuming convergence velocities shown in Table 2. Further explanations in the text.

4.3. Seismicity Data and Paleotectonic Reconstructions

4.4. Present-Day Lithospheric Configuration of the Convergent Margin in NW South America

We used the publicly available seismicity data and data from previous research (e.g., Bezada et al., 2010) to study the present-day geometry and configuration of the subduction zone of NW Colombia. We constructed a depth map of the top of the subducted oceanic slab beneath South America and a cross section depicting its geometry and the configuration of the subduction zone of NW Colombia (Figures 12 and 13). The detailed description of the construction of the map and cross section is included in Text S3 and Figure S1.

The study area is characterized by a low seismicity, with very few scattered, shallow (<70 km) and low magnitude (<4 M_w) events (Mora et al., 2017), and there are no focal mechanism solutions in the San Jacinto fold belt. Although it seems to be a seismically inactive area, some neotectonic fault activity has been identified by Veloza et al. (2012) in the northern part of the belt.

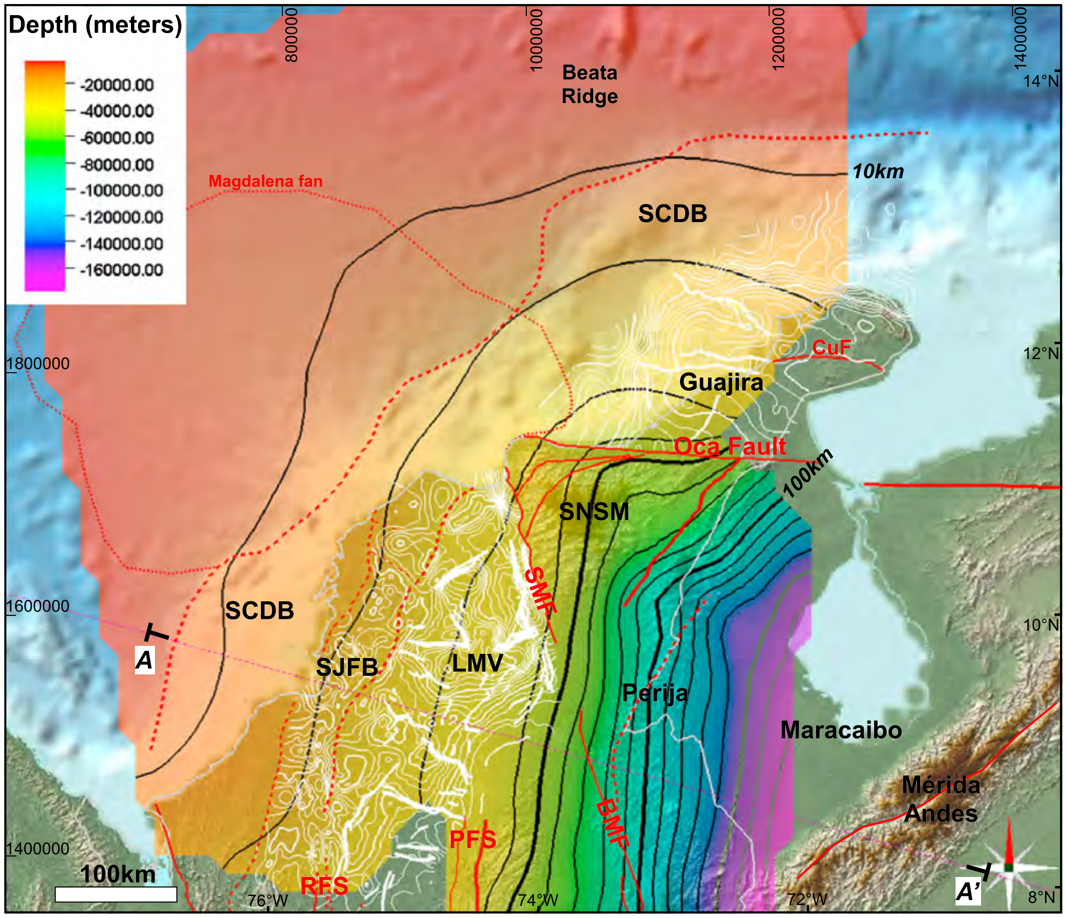

Figure 13. Integrated depth map in meters of the top of the oceanic Caribbean Plate (in colors) that has been subducted under NW South America since early to middle Eocene times. Note the change in dip of the slab in the location of the Palestina Fault System (PFS) and how it changes its strike as it approaches the Oca Fault. The white contours are the depth structure of the basement below the LMV, SJFB, and Guajira basins. SCDB: South Caribbean deformed belt (red dashed lines); RFS: Romeral Fault System; SMF: Santa Marta Fault; BMF: Bucaramanga fault; SNSM: Sierra Nevada de Santa Marta; and CuF: Cuisa Fault. Further details about the construction of this map and the related cross section (Figure 12) are found in supporting information Text S3 and in Figure S1.

The Caribbean Plate subducted beneath NW South America appears to be formed by three different slab segments, separated by kinks or bends (Figure 12): a northwestern shallow and very flat slab segment, a central intermediate-depth and flat slab segment (the “Caribbean” flat slab of Syracuse et al., 2016), and a southeastern deep and very steep slab segment imaged by Bezada et al. (2010). The three slab segments could have different geometries, thicknesses, and physical properties, as deduced from Deep Sea Drilling Project, reflection seismic imaging, tomography data, and water depths in the Colombia and Venezuela basins (Driscoll & Diebold, 1999; Kroehler et al., 2011; Leroy et al., 1996; Magnani et al., 2009; Mauffret & Leroy, 1997). In general, the Colombian Basin to the west is composed of an oceanic plateau with thicknesses between 10 and 18 km (Bowland & Rosencrantz, 1988), while north of Colombia, in the area of the Beata Ridge (Figure 13), the plateau appears to be thicker (Kroehler et al., 2011). Slab segments with specific physical and chemical properties would then have specific buoyancy properties, which could explain such changes in dip.

The previously described segmented slab geometry of the subducted Caribbean Plate does not seem to continue to the north of the Oca-El Pilar-San Sebastian Fault System. In the Guajira Peninsula of northernmost Colombia, seismic interpretations and gravity modeling (Londoño et al., 2015 and this study) show that the Caribbean Plate is being subducted at low angle beneath the Southern Caribbean deformed belt. Farther to the east, in northern Venezuela, wide-angle reflection seismic and tomography data

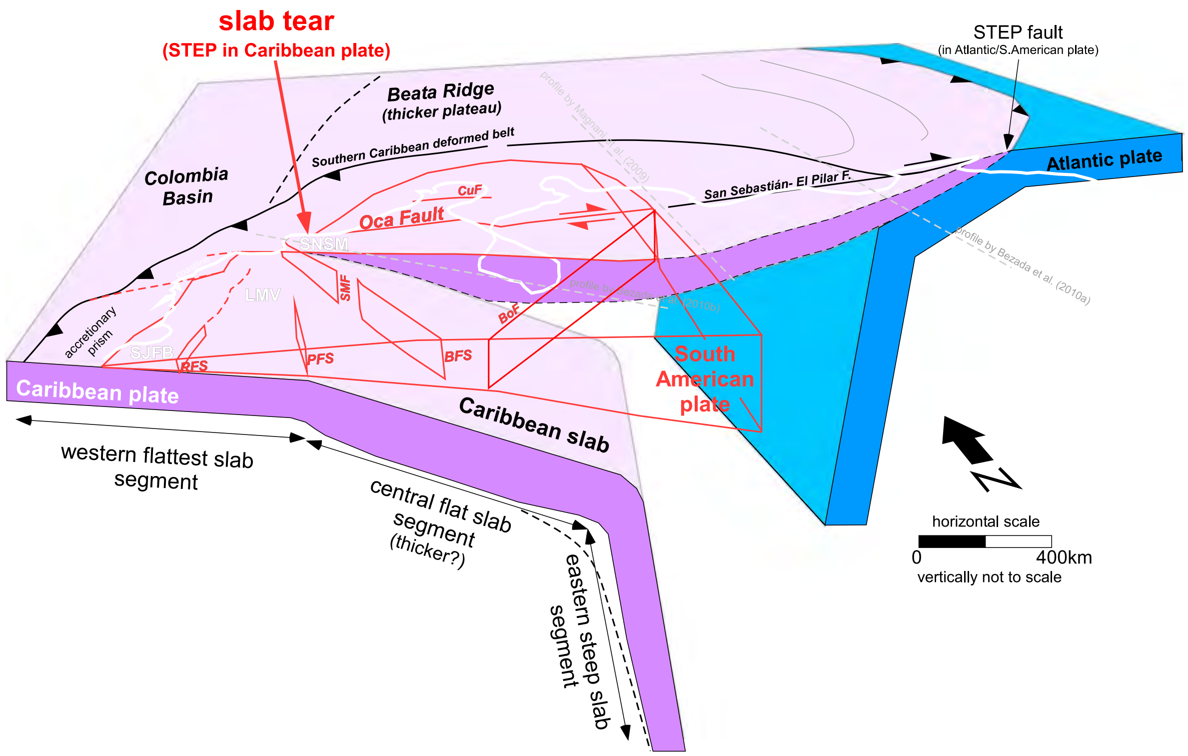

Figure 14. Proposed three-dimensional lithospheric configuration of NW South America, as interpreted from shallow reflection seismic mapping, intermediate-depth seismicity, and deep tomographic imaging from previous studies (e.g., Bezada et al., 2010); according to our interpretation, there would be a slab tear or STEP fault (subduction transform edge propagator, Govers & Wortel, 2005) in the Caribbean Plate, probably represented in the upper crust by the western tip of the Oca-El Pilar-San Sebastián dextral fault system (OEPFS).

(Bezada et al., 2010; Magnani et al., 2009) show that the boundary between northern South America and the southern Caribbean Plate is dominated by strike-slip tectonics related to the Oca-El-Pilar-San Sebastián Fault System (OEPFS) and the Caribbean Plate is clearly imaged at shallow levels in the block to the north of the fault system. Seismicity also changes abruptly from the southern block of the OEPFS, where the Wadati-Benioff zone is clearly imaged by intermediate depth seismicity, to the northern block of the fault system, where only isolated and shallow seismic events occur (Syracuse et al., 2016, and section 2 and Figure S1).

Based on the steep descent of the Caribbean Plate under Maracaibo and the Mérida Andes, previous researchers have proposed that there should be a tear in the Caribbean Plate (Bezada et al., 2010; Levander et al., 2015; Masy et al., 2011), which would be separating the steeper dipping Caribbean slabs, located to the south of the OEPFS, from the shallow Caribbean Plate that has been imaged north of the same fault system. Using data from previous research and our new depth map of the shallow subducted Caribbean oceanic segment under the San Jacinto fold belt, Lower Magdalena Valley basin and the Perijá Ridge (Figure 13), we propose a new interpretation of the three-dimensional plate tectonic configuration of northern Colombia and western Venezuela (Figure 14). This interpretation implies that the boundary between northern South America and the Caribbean Plate consists of two tears or subduction-transform edge propagator (STEP) (Govers & Wortel, 2005) faults instead of only one. The difference is that the STEP fault previously proposed by Govers and Wortel (2005) is tearing the Atlantic/South American Plate in the area of the Paria seismicity cluster, at the eastern end of the OEPFS in northeastern Venezuela (Russo et al., 1993), while the newly proposed STEP fault would be tearing the Caribbean Plate in an undefined area of the western OEPFS, probably close to the Sierra Nevada de Santa Marta (SNSM, Figure 14). This means that the Oca-San Sebastián-El Pilar dextral fault system is the tear fault that limits the Caribbean and South American/Atlantic Plates at crustal and mantle levels. Our observations are in agreement with Levander et al. (2015) who propose that the southern Caribbean Plate boundary is a complex strike-slip fault system bounded by oppositely vergent subduction zones.

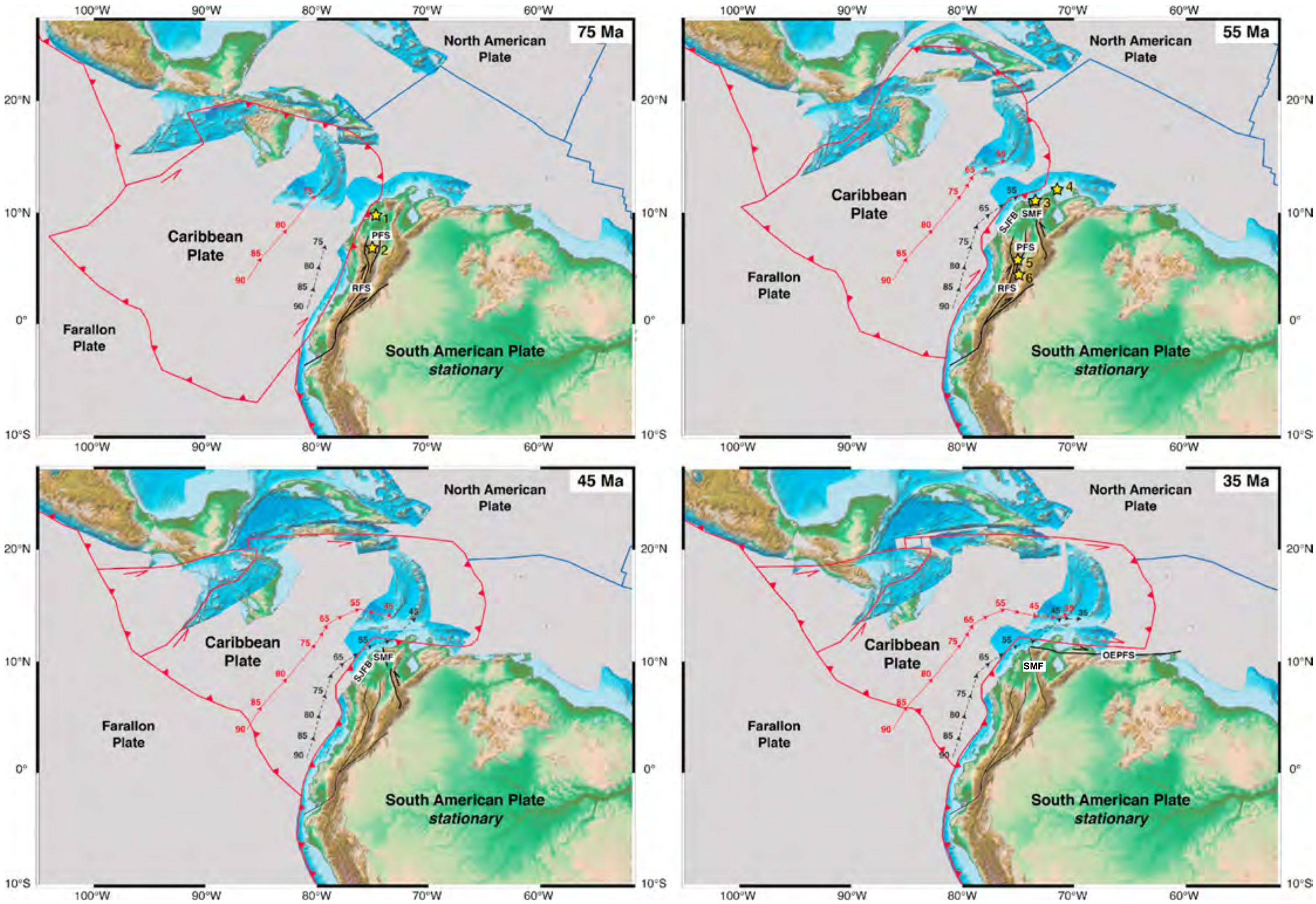

Figure 15. Paleotectonic reconstructions at 75, 55, 45, and 35 Ma, illustrating the displacement of the Caribbean Plate relative to fixed South America and the major change in convergence obliquity, which occurred between 55 and 45 Ma. The displacement vectors of the Caribbean Plate relative to South America are shown in red arrows according to the model of Matthews et al. (2016, GPlates database) and in black dashed arrows according to Boschman et al. (2014). The plate boundaries (spreading ridges in blue and subduction and transform zones in red) and continent polygons are from Matthews et al. (2016). The main fault zones of NW South America are labeled and drawn in thick black lines when active. Yellow stars indicate active magmatic arcs in our studied area: 1. Bonga and Cicuco plutons, 2. Antioquia batholith, 3. Santa Marta batholith and related plutons, 4. Parashi pluton, 5. Sonsón batholith, 6. El Bosque batholith (from ANH, 2011; Cardona et al., 2014, 2011; Bayona et al., 2012; Bustamante et al., 2017). The northwestward motion of allochthonous oceanic terranes (up to ~1077 km between 90 and 65 Ma, in Boschman et al., 2014), accreted to western Colombia along major suture zones such as the right-lateral RFS in Late Cretaceous to Paleogene times, is not shown here. Since 50 Ma, approximately 1,000 km of Caribbean oceanic crust were subducted below South America. See the text for further discussion.

4.4.1. Upper Cretaceous to Eocene Paleotectonic Reconstructions

It is expected that the onset of subduction of the irregular Caribbean Plateau had an important effect on the upper plate and that this effect should be recorded in the sedimentary basins in the area. We used the free software package GPlates (version 2.0.0, www.gplates.org; Boyden et al., 2011) and two paleotectonic models available for this area (Boschman et al., 2014, and Matthews et al., 2016, from the GPlates database) to perform Late Cretaceous to Eocene paleotectonic reconstructions (Figure 15). Our reconstructions show the motion of the Caribbean Plate relative to a fixed South American Plate, but it is important to highlight that plate tectonic processes between the Caribbean and the Americas were driven by relatively fast, westward motion of North and South America, while the Caribbean Plate has remained nearly stationary since the Eocene (Müller et al., 1999).

Using average plate convergence velocities of the Caribbean Plate relative to South America over the last 45 Ma, we calculated for both models the geological time when each of the three subducted slab segments of the Caribbean Plate imaged along cross section A–A′ (Figure 12) entered the trench (Table 2). The age of

Table 2
Compilation of the Slab Segment Lengths, Convergence Velocities and Ages of Entrance in the Trench of Each Slab Segment Shown in Figure 12

	Slab segment length (km) (±15 km error)	Calculated age of slab entrance in the trench using mean plate velocities over the last 45 Ma	
		Boschman et al., 2014	Matthews et al., 2016
		19 mm/yr	25 mm/yr
Western flat slab segment under SJFB and LMV	278–308	14.6–16.2 Ma	11.1–12.3 Ma
Central intermediate-depth flat slab segment	341–371	18–19.5 Ma	13.6–14.8 Ma
Eastern deepest and steepest slab segment	401–431	21.1–22.7 Ma	16–17.2 Ma
Western plus central flat slab segments	619–679	32.6–35.7 Ma	24.8–27.2 Ma
All three slab segments	1,020–1,110	53.7–58.4 Ma (56 ± 2 Ma)	40.8–44.4 Ma (43 ± 2 Ma)
Slab length by Van Benthem et al. (2013)[a]	900	47.4 Ma	36 Ma

Note. We calculated average velocities over the last 45 Ma according to each of the two available models (Boschman et al., 2014; Matthews et al., 2016). Using such velocities and the measured lengths of each slab segment, we could calculate the time at which each segment entered the trench. From these calculations, we found that the ~1,000 km long Caribbean slab entered the trench in early to middle Eocene times, coinciding with regional unconformities identified in the San Jacinto fold belt.
[a]They interpret three slab segments, each one 300 km long.

entrance in the trench of the whole Caribbean slab (total length of 1,065 ± 15 km) ranges from lower Eocene (circa 56 ± 2 Ma) to middle Eocene (circa 43 ± 2 Ma) depending on the model used (Boschman et al., 2014, and Matthews et al., 2016, respectively). Equivalence of the obtained age of entrance in the trench of the Caribbean slab with the identified unconformities in the stratigraphic succession in the SJFB (also shown in Figure 12) will be discussed in forthcoming sections.

5. Discussion

5.1. Late Cretaceous to Eocene Paleotectonic Reconstructions and Kinematics

In the debate about the origin and evolution of the Caribbean oceanic plate, two main models have been proposed, an in situ model that implies a short migration of the Caribbean to its present position (James, 2006) and a Pacific model that proposes an eastern Pacific origin of the plate and a long-distance migration (Boschman et al., 2014; Kennan & Pindell, 2009). The Pacific model appears to be the most robust and more widely accepted, though the migration distances of the terranes in northwestern Colombia, which show an oceanic affinity remain poorly constrained. Using the Gplates free software (Boyden et al., 2011) and the models of Boschman et al. (2014) and Matthews et al. (2016), we present modified paleotectonic reconstructions for the most relevant time slices for this study (Figure 15). Based on the model by Boschman et al. (2014), we calculated that the maximum northwestward displacement of the allochthonous oceanic (Caribbean) terranes west of the RFS was ~1077 km between 90 and 65 Ma, which can be subdivided into 691 km from 90 to 75 Ma and 386 km from 75 and 65 Ma. This means that most of the northwestward displacement of the allochthonous Caribbean terranes occurred in Late Cretaceous times, along the RFS and PFS. We also calculated the tectonic convergence velocity and obliquity curves for the Caribbean-South American margin and plotted them with the identified tectonostratigraphic unconformities in the SJFB and with the main tectonic events studied in the literature (Figure 16). The obliquity was calculated as the angle between the plate displacement vector and the orthogonal to the strike of the SW-NE South American Plate boundary, as defined by Philippon and Corti (2016).

Convergence obliquities were much higher in Late Cretaceous to early Eocene times, and they notoriously decreased in middle Eocene times (50 to 40 Ma) in both models (Figure 16), while velocities decrease earlier in the model by Matthews et al. (2016) and later (45 Ma) in the model by Boschman et al. (2014). The lower Paleocene unconformity, which would be the expression of the collision of the Caribbean oceanic plateau, appears to be related to a velocity reduction according to the model by Matthews et al. (2016). The lower to middle Eocene unconformity fits with a significant decrease in convergence obliquity and velocity (Boschman et al., 2014) and several major tectonic events, such as the end of the strike-slip activity of the RFS and PFS, the cessation of arc magmatism in NW Colombia and the onset of strike-slip displacement of the OEPFS (Gómez, 2001; Vence, 2008).

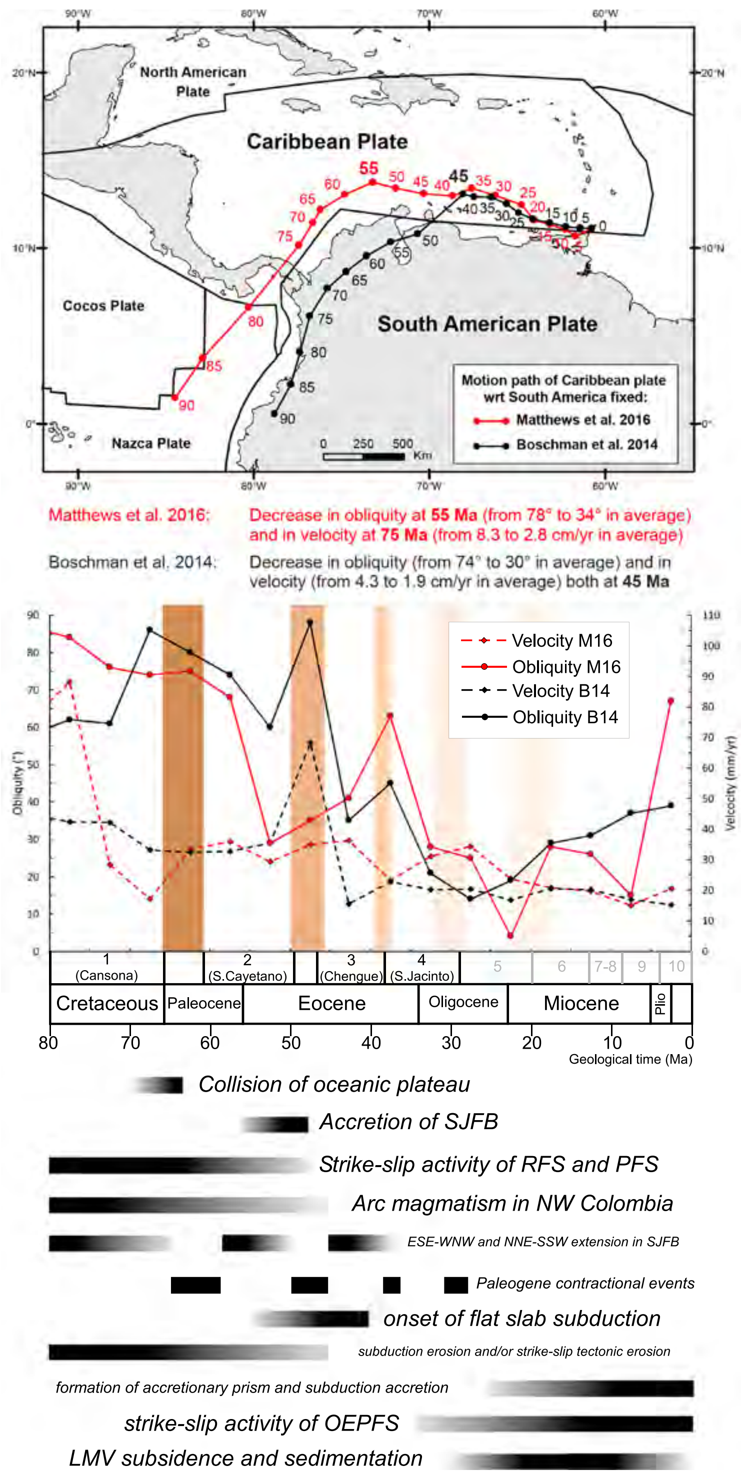

Figure 16. Evolution of Late Cretaceous to present-day tectonic plate convergence velocity and obliquity compared with major tectonic events and tectonostratigraphic unconformities. (top) The displacement vectors of the Caribbean Plate relative to a fixed South American Plate, since 90 Ma, according to two different paleotectonic models (Boschman et al., 2014, in black, B14; Matthews et al., 2016, in red, M16). (middle) The changes in plate convergence velocity and obliquity with time for both models, compared with the (bottom) pre-Oligocene tectonostratigraphic sequences and unconformities (vertical bars of brown shades) and major tectonic events (black horizontal bars). We calculated velocities and obliquities in time steps of 5 Ma, hence the points in the graph represent the middle of each time interval. The identified Paleogene unconformities correlate with major tectonic events such as the Late Cretaceous to early Paleocene collision of the Caribbean Plateau and the Eocene onset of Caribbean flat slab subduction. See text for further discussion.

5.2. Late Cretaceous Fore-Arc Basin (89 to 75 Ma, Coniacian to Campanian)

From the available information, it appears that during Late Cretaceous times, a fore-arc basin existed SW of the study area, with an intracontinental, magmatic arc to the east (called the Magangué Arc by Silva et al., 2017, Figure 15), formed by the east dipping subduction of a "normal" thickness, Caribbean oceanic plate under South America (Villagómez, Spikings, Magna, et al., 2011). Magmatism affected both continental and accreted oceanic crust (the Quebradagrande terrane or a younger, allochthonous intraoceanic arc) and supplied abundant mafic and felsic, volcaniclastic material to the proximal parts of the basin. Recent petrography analyses (see Text S1) support a Late Cretaceous magmatic arc setting in which there was also some sediment supply from more distal and older terranes, such as the Tahami-Panzenú and Chibcha terranes of the eastern LMV and northern CC (Mora et al., 2017). Gómez et al. (2005), Restrepo et al. (2009), and Caballero, Parra, et al. (2013) used apatite fission track thermochronology to propose that uplift of the CC and the San Lucas ridge began since Late Cretaceous times (Campanian-Maastrichtian); consequently, these were potential source areas, which provided sediments to surrounding basins such as the SJFB. However, according to Boschman et al. (2014) paleotectonic reconstructions, at 90 Ma the SJFB would have been as far as ~1,077 km to the SW of its present location; hence, it would have been sourced by Permo-Triassic and Cretaceous terranes located much farther south within the protocentral Cordillera. Nevertheless, several researchers (e.g., Kennan & Pindell, 2009) have suggested that the Tahami-Panzenu terrane, located between the RFS and the PFS, is para-autochthonous and that it also moved from the southwest along its limiting dextral fault systems. This would mean that the sedimentary sources and the San Jacinto basin always moved parallel to each other, thus explaining the good match we obtained in terms of provenance. Outcrop and the very few well data show that sedimentation in the area of the present-day SJFB occurred in a marine shelf in which proximal marine environments occurred in the central area (San Jacinto) while deeper marine environments occurred in the south.

5.3. Latest Cretaceous-Early Paleocene Collision of the Caribbean Oceanic Plateau

It has been proposed that in the latest Cretaceous to early Paleocene times, the Caribbean oceanic plateau collided with northwestern South America (Bayona et al., 2012; Cediel et al., 2003; Pindell et al., 2005). Paleotectonic reconstructions (Pindell & Kennan, 2009; Spikings et al., 2015) suggest that at this time, the Caribbean Plate moved toward the NE relative to the North and South American Plates and started to occupy space between them. Villagómez, Spikings, Mora, et al. (2011) and Caballero, Parra, et al. (2013) used apatite fission track thermochronology to identify an exhumation pulse in the San Lucas ridge and southernmost SNSM during early Paleocene times (Figure 15), which they relate to the collision of the Caribbean Plateau with northwestern South America. We consider that the absence of lower Paleocene deposits in northwestern Colombia (planktonic zones P.0 to P.2., 65 to 61 Ma) and the unconformity that has been reported in outcrops between Sequence 1 (Cansona) and Sequence 2 (San Cayetano, Figure 16) are the expression of a regional shortening event, which took place in latest Cretaceous to early Paleocene times and which would be related to the collision of the Caribbean Plateau. The notorious decrease in convergence velocity between 75 and 70 Ma, according to Matthews et al. (2016), could also be related to this collision event.

5.4. Late Paleocene to Early Eocene Fore-Arc Basin

After the early Paleocene shortening episode, fore-arc extension and subsidence resumed, but it is not clear if at that time the Caribbean Plateau was already being subducted under South America (Bayona et al., 2012; Bustamante et al., 2017) or if early Paleogene magmatism is more related to the final subduction stage of the normal thickness Caribbean Plate. For the deposition of Sequence 2, our integration of outcrop and well data throughout the San Jacinto fold belt shows that mud-rich and mixed sand-mud, proximal turbidite systems (in the sense of Richards, 2001) were predominant in the north and south, while sand- and gravel-rich turbidite systems prevailed in the central part.

Reflection seismic data from the central and northern SJFB show that during sedimentation of Sequence 2 (late Paleocene to early Eocene), the area experienced WNW-ESE oriented extension (Mora, De Freitas, et al., 2013; Mora et al., 2017). However, in the northern SJFB, reported lithologies are mainly fine grained and no facies changes related to the activity of extensional faults have been documented. In the central part of the fold belt, Sequence 2 shows onlap patterns toward the east and fanning toward the west, suggesting sedimentation in steep slopes. We consider that the origin of the WNW-ESE trending faults that affect

Sequence 2 relates to fore-arc extension due to oblique convergence between the Caribbean and South American Plates, as proposed by Daly (1989) in the Ecuador forearc. However, Mora et al. (2017) suggested that subduction erosion (Clift & Vannucchi, 2004) occurred in the margin in Late Cretaceous times; hence, Late Cretaceous to Paleogene subsidence and extension in the forearc could have also been related to subduction erosion.

New petrography data (Text S1) show that detrita of Sequence 2 come from similar tectonic regions that sourced Sequence 1, including a magmatic arc and older continental basement blocks. Recent analyses of drill hole samples in the San Jacinto fold belt (Sarmiento et al., 2016) provide more evidence of volcanic activity during late Paleocene to early Eocene times. According to Cardona et al. (2011), the San Cayetano sandstones fall within the transitional to dissected arc fields of Dickinson (1985), in agreement with Ecopetrol/ICP (2014).

Our new U-Pb geochronology and Hf isotope geochemistry results clearly show a main provenance from Upper Cretaceous magmatic arcs and a secondary provenance from Permo-Triassic igneous terranes such as those documented in the Tahamí-Panzenú terrane of the eastern LMV and northern CC (Mora et al., 2017). Furthermore, a very good match is seen between the Hf isotope geochemical compositions of the detrital zircons in the C-1 well and the compositions of both the Coniacian-Campanian Bonga pluton zircons and the Permo-Triassic metamorphic basement zircons from the Hojarasca and VIM15 wells reported by Mora et al. (2017). This suggests that the upper Paleocene-lower Eocene sediments of Sequence 2 were mainly sourced from Upper Cretaceous plutons of both oceanic (e.g., Bonga) and continental affinity (Magangué Arc, Silva et al., 2017; Antioquia Batholith) and from the Permo-Triassic igneous-metamorphic terranes in the LMV and northern CC. Our paleotectonic reconstructions show that after a considerable (~1,077 km) northwestward displacement of the Caribbean oceanic terranes in Late Cretaceous times, such terranes including San Jacinto, had almost reached their current position, thus supporting our provenance considerations.

These data also support a fore-arc basin setting in which both the oceanic and continental affinity, Upper Cretaceous magmatic arcs were being eroded and providing sediment for the marine basin to the northwest. Though evidence of Paleocene to early Eocene magmatism has not been yet found in the LMV and SJFB, it is likely that plutons of such ages exist, considering that Paleocene to early Eocene magmatism has been documented in surrounding areas such as the northern CC (Paleocene Sonsón Batholith, Bayona et al., 2012; Bustamante et al., 2017), the SNSM and the Guajira peninsula to the north (Cardona et al., 2014). If the SNSM and the northern CC were connected, as interpreted by Montes et al. (2010) and Mora et al. (2017), and if both the northern CC and the southern SNSM were being uplifted in the late Paleocene (Restrepo et al., 2009; Villagómez, Spikings, Mora, et al., 2011), then the most likely sources for the sediments of Sequence 2 were the ancient northern CC and southern SNSM, located to the east and southeast of the SJFB in early Eocene times. Furthermore, the presence of Permo-Triassic, Lower Paleozoic, and Mesoproterozoic to Neoproterozoic detrital zircon ages (Figure 5b), in addition to a group of Cretaceous zircons with initial εHF values <0, provide strong lines of evidence in favor of a sediment that was sourced from older continental basement blocks. Although these older sources may well derive from the core of the CC and SNSM also, it is also possible that these could be derived from farther removed sources of the Eastern and Central Cordilleras and the Putumayo basement. A far-traveled component may have also contributed reworked Cretaceous and/or Paleogene zircons (e.g., Horton et al., 2010; Nie et al., 2012) to the SJFB, but the Hf systematics of most zircons dated here and their resemblance to proximal basement sources indicate that reworking of far-traveled Cretaceous and Paleocene sources is unlikely to represent a major component (Figures 5 and 6).

Moreover, paleogeographic reconstructions of northern South America (e.g., Hoorn et al., 2010) do not support a connection between SJFB and LMV with old continental basement blocks such as the Eastern Cordillera or the Putumayo basement. This fact restricts the sediment source areas to the Central Cordillera, which was probably connected to the SNSM as suggested by Mora et al. (2017) and to the Western Cordillera.

5.5. Eocene Onset of Flat Subduction

The notorious lower to middle Eocene angular unconformity that marks the top of Sequence 2 (San Cayetano) is the most important evidence of the final episode of activity of the Romeral Fault System and of a major shortening event in northern Colombia (Figures 7–11). This event also marks the end and fossilization of the San Jacinto fore-arc basin and the birth of a new basin of middle Eocene to Recent age (Lower Magdalena).

Several researchers have related this regional angular unconformity to the accretion of the San Jacinto terrane from the south, along the RFS (Cediel et al., 2003; Duque-Caro, 1979). An equally dramatic angular unconformity produced by a middle Eocene tectonic episode has been recognized in Colombia for many years (e.g., Bayona et al., 2013; Duque-Caro, 1980; Forero, 1974; Hubach, 1957; Villamil, 1999), and it has also been identified in reflection seismic data in surrounding basins such as the Cesar-Ranchería (Mora & Garcia, 2006) and the Middle Magdalena Valley basin (MMV, Gómez et al., 2005). The Santa Marta-Bucaramanga Fault System, which is considered the northeastern boundary of the LMV against the Cesar-Ranchería basin, also experienced a middle Eocene tectonic episode as revealed by reflection seismic data (Mora & Garcia, 2006).

Using apatite (U-Th)/He thermochronology, Restrepo et al. (2009) and Villagómez, Spikings, Mora, et al. (2011) identified middle Eocene exhumation pulses in the northern CC (Antioqueño Plateau) and in the southern SNSM. However, while Restrepo et al. (2009) related the middle Eocene exhumation of the northern CC to a change in the rate of convergence between Nazca (Farallon) and South America, Villagómez, Spikings, Mora, et al. (2011) relate it to underthrusting of the Caribbean Plate beneath northern South America. Paleotectonic reconstructions (Boschman et al., 2014; Kroehler et al., 2011; Matthews et al., 2016; Müller et al., 1999; Pindell & Kennan, 2009; Ross & Scotese, 1988) show that between 56 and 45 Ma there was a major readjustment in the configuration of the South American, Caribbean, and North American Plates (Figure 15). The model by Boschman et al. (2014), in which there is a large decrease in both velocity and obliquity at ~ 48 Ma, correlates better with the identified lower to middle Eocene regional unconformity and with a regional shortening event, in agreement with the proposed major change in convergence velocity and obliquity between the Caribbean and South American Plates (Figure 16). Though the model by Matthews et al. (2016) also shows a minor decrease in convergence velocity after 48 Ma, obliquity decreased earlier, at ~58 Ma. Hence, correlations with the middle Eocene unconformity and the proposed major tectonic readjustment are not as clear as with the model by Boschman et al. (2014).

Furthermore, the cessation of magmatism in northern Colombia would also be related to this plate tectonic readjustment, which probably took place between 56 and 45 Ma. Previous studies in the Guajira peninsula (Parashi intrusive, Cardona et al., 2014), in the SNSM (Santa Marta batholith, Mejía et al., 2008), and in the northern Central Cordillera (ANH, 2011) concluded that subduction-related magmatism in northwestern Colombia occurred only until early middle Eocene times (50–45 Ma, Bayona et al., 2012). Post-Eocene magmatism has been documented only in the central and southern Colombian Andes, where it is related to the subduction of the Nazca (Farallón) Plate under western South America. It is then possible that arc magmatism ended due to an early to middle Eocene plate tectonic readjustment, consisting of a reduction in both convergence velocity and obliquity, and its expression in the stratigraphic record would be the lower to middle Eocene unconformity.

The lack of arc volcanism has been related to flat subduction of thickened and buoyant slabs (Gutscher et al., 2000; Manea et al., 2017; Ramos & Folguera, 2009; Syracuse et al., 2016). Flat slab subduction of thick oceanic crust results in surface uplift and exhumation of fore-arc basin strata and also inhibits subduction-related magmatism adjacent to the fore-arc basin (Ridgway et al., 2012). This seems to be the case of northwestern Colombia where the thick oceanic Caribbean Plateau is currently being subducted under the South American Plate, in an area where there has been no magmatism since early to middle Eocene times. Taking into account the present-day lithospheric and mantle geometry, as interpreted in Figure 12, we calculated that the onset of subduction of the Caribbean Plate occurred in early to middle Eocene times, 56 to 43 Ma ago (Table 2). Interestingly, this calculated time of onset of subduction of the Caribbean Plateau coincides with the time of plate tectonic readjustment between the Caribbean and the Americas (Figure 16) and with the estimated age of the lower to middle Eocene unconformity in the San Jacinto fold belt (planktonic foram zones P.9 to P.10, 50.4 to 45.8 Ma) and the time of cessation of magmatism in northern Colombia (50–45 Ma; Bayona et al., 2012). Though these calculations are very sensitive to slab angles, lengths, and convergence rates, the slab length measurements by Van Benthem et al. (2013) are quite similar (900 km) and hence are the obtained ages of plateau subduction (Table 2). Boschman et al. (2014) also estimated 850 km of subduction beneath Colombia since 50 Ma from their tectonic reconstructions. According to this, the onset of the low-angle subduction of the Caribbean Plateau would have occurred in early to middle Eocene times, and it was also then when the rough geodynamic configuration that we have today in the northwestern corner of South America was formed. It is thus probable that the middle Eocene uplift pulses of the CC and SNSM (Restrepo et al., 2009; Villagómez, Spikings, Mora, et al., 2011) that produced unroofing on the order of 2 km in the northern CC and the widespread deposition of coarse-grained molasses in northern Colombia are also related to the inception of flat subduction.

To summarize (Figure 16), a major lower to middle Eocene plate tectonic readjustment, consisting of a notorious decrease in both convergence velocity and obliquity in lower to middle Eocene times, seems to be the most likely cause of (1) the onset of flat slab subduction in northwestern Colombia, (2) the cessation of magmatism in northern Colombia in the middle Eocene, (3) a major shortening event with the exhumation and partial erosion of the Upper Cretaceous to lower Eocene San Jacinto fore-arc basin, (4) the end of the tectonic activity of major Cretaceous fault systems such as Romeral and Palestina, and (5) the later onset of right-lateral strike-slip displacement along the newly formed Oca-El Pilar Fault System (Boschman et al., 2014; Müller et al., 1999; Pindell & Kennan, 2009). The imprint of such tectonic readjustment in the stratigraphic record of the San Jacinto fold belt is the lower to middle Eocene unconformity, though the late Eocene unconformity could also be related.

The previous interpretation implies that the onset of flat subduction, which we correlate with the cessation of arc magmatism, occurred at lower to middle Eocene times, when convergence slowed down and became more orthogonal. Though more perpendicular convergence could tend to favor subduction with arc magmatism, several studies suggest that convergence obliquity is not among the controlling parameters of flat subduction. According to Espurt et al. (2008), two main causes have been proposed to explain the formation of flat subduction zones in South America: (1) the fast movement of South America toward the trench in the hot spot reference frame and (2) the subduction of buoyant anomalies such as oceanic plateaus. Both conditions are occurring in NW Colombia, thus supporting the proposed flat slab subduction.

5.6. Middle to Late Eocene Renewed Fore-Arc Sedimentation

After the lower to middle Eocene plate tectonic readjustment and the onset of flat subduction, the San Jacinto area experienced renewed fore-arc extension, subsidence, and sedimentation that comprised coarse-grained clastics and shallow marine carbonates of Sequences 3 and 4 (Chengue and San Jacinto). In middle Eocene times, the RFS and the northern Palestina Fault System both became inactive as seen in the cross sections in Figure 7. Reflection seismic data (Figures 10 and 11) show that the deposits of Sequence 3 and 4 are affected by SE-NW trending faults that have similar orientation as those related to Sequence 2 (San Cayetano), and therefore, they would be older inherited features, which were reactivated. Terrigenous rocks were classified as lithic arkoses to litharenites and were related to the dissected arc, transitional arc, and lithic recycled orogen provenance terranes of Dickinson (1985).

Our U-Pb geochronology and Hf isotope geochemistry results show the same Late Cretaceous and Permo-Triassic peaks as seen in samples from the sequence below (San Cayetano, Figure 5). Additionally, there seems to be a reduction in Proterozoic and Paleozoic provenance for these samples, suggesting less erosion of distant old massifs related and more erosion of younger basement massifs, though recycling of zircons is also a possibility. Considering that the SJFB had already been accreted by late Eocene times, the predominance of Upper Cretaceous and Permo-Triassic terranes suggests that sediment supply was mostly coming from the northern CC and SNSM in the SE and NE.

5.7. The Middle to Late Eocene Unconformity

The contact between Sequences 3 and 4 (Chengue and San Jacinto) is also an unconformity of middle to late Eocene age (35–40 Ma), which has been recognized in the SJFB (Duque-Caro, 1984, 1991; Guzman, 2007) as the expression of a third shortening phase, related to the plate tectonic readjustment and to the onset of flat slab subduction. Van der Lelij et al. (2016) suggested that the Santa Marta-Bucaramanga Fault was active at ~40 Ma, that rapid exhumation at that time is well documented along the western margin of South America, and that such widespread contractional phase could be related to an episode of accelerated convergence of ~15 cm/yr, between the South American margin and the Farallón Plate. However, much more data and studies are required to understand the significance of this unconformity and its possible relationship with major plate tectonic processes.

5.8. Late Eocene to Oligocene

Sequence 4 (San Jacinto) was possibly also deposited in a shallow subduction fore-arc setting, in late Eocene to early Oligocene times. It comprises shallow marine carbonate facies in the central and southern SJFB and siliciclastic deposits (fan deltas) in the central eastern part. As shown by seismic data, these deposits are affected by the same family of SE-NW trending extensional faults that affects Sequences 2 and 3.

Cardona et al. (2012) stated that the conglomerates deposited after the middle Eocene tectonism contain less igneous and metamorphic rock fragments and more sedimentary rock fragments, quartz, and stable heavy minerals compared to the pre-middle Eocene conglomerates of Sequence 2, suggesting a depletion of the more proximal volcanic sources. Petrographic analyses (Ecopetrol/ICP, 2014) revealed that the origin of siliciclastic samples of this sequence is related to transitional to quartzose recycled orogens, with few samples related to a magmatic arc. Though such data suggest less supply from magmatic arc sources, our new U-Pb geochronology and Hf isotope geochemistry results reveal that the upper Eocene to lower Oligocene sediments in the SamanEst-1 well were mainly sourced from Upper Cretaceous (Coniacian-Maastrichtian) plutons with a Hf isotopic composition very close to that of the Bonga pluton (Mora et al., 2017). The apparent contradiction between petrography analyses suggesting recycled orogen provenance versus geochronology suggesting magmatic arc provenance could also be related to zircon recycling from older sedimentary units. However, the secondary magmatic arc signature from both petrography and geochronology still suggests mixed source areas for the northern SJFB such as the present-day Magangué-Cicuco high and the northern CC, located toward the SSE (Figure 3).

Figure 16 very clearly shows that the Caribbean-NW South America convergent margin became relatively stable since Oligocene times, exhibiting low convergence velocities and obliquities. We relate this to the evolution of the margin from a highly oblique convergent margin, possibly exhibiting subduction erosion (Clift & Vannucchi, 2004) in Late Cretaceous to Eocene times, to a more orthogonal convergent margin, exhibiting subduction accretion since early Miocene times, when the accretionary prism probably started forming.

6. Conclusions

In this study we have linked the Late Cretaceous to Eocene tectonostratigraphy of the San Jacinto fold belt of NW Colombia with the plate tectonic evolution of northwestern South America, which experienced Caribbean Plateau collision and flat subduction. Using a regional geology and geophysics database, we were able to relate the deposition of four unconformity-bounded fore-arc basin sequences to specific collision/subduction stages and to relate their bounding unconformities to major tectonic episodes. The Upper Cretaceous Cansona sequence (Sequence 1) was deposited in a marine fore-arc environment in which a normal thickness Caribbean Plate was being subducted beneath northwestern South America, producing contemporaneous magmatism in the present-day northern Central Cordillera and Lower Magdalena Valley basin. Coeval strike-slip faulting by the Romeral wrench fault system accommodated right-lateral displacement due to strongly oblique convergence. In latest Cretaceous to early Paleocene times, the Caribbean oceanic plateau collided with South America causing a major shortening event and marking a change to a turbiditic marine sedimentation with abundant terrestrial input, which characterizes the upper Paleocene to lower Eocene San Cayetano sequence (Sequence 2). This sequence was also deposited in a fore-arc setting with an active volcanic arc that probably represents the final melting stage of the previously subducted normal thickness Caribbean slab. A lower to middle Eocene angular unconformity at the top of the San Cayetano sequence, a second major shortening event, the termination of the activity of the Romeral Fault System, and the cessation of arc magmatism are interpreted to indicate the onset of low-angle subduction of the thick and buoyant Caribbean oceanic plateau beneath South America, which occurred between 56 and 43 Ma. Onset of low-angle subduction was probably caused by a major change in plate convergence angle and velocity, as suggested by paleotectonic reconstructions. As low-angle subduction was gradually established, coarse-grained clastics and carbonates of the Chengue sequence (Sequence 3) were deposited in the forearc of a newly formed subduction complex. A middle to late Eocene unconformity also related to a contractional event separates the Chengue from the San Jacinto sequence (Sequence 4), which comprises similar types of terrigenous and calcareous deposits. Detrital zircon U-Pb geochronology and Hf-isotope geochemistry suggest that the upper Paleocene to upper Eocene San Cayetano and Chengue/San Jacinto Sequences were mostly sourced from Upper Cretaceous oceanic and continental-affinity magmatic arcs and from

Permo-Triassic igneous-metamorphic basement blocks. Low-angle subduction of the Caribbean Plateau has continued to the present and appears to be the main cause of the amagmatic post-Eocene deposition. Our interpreted plate tectonic configuration of northern Colombia implies the existence of a tear or STEP fault in the Caribbean Plate, located toward the western end of the Oca-San Sebastián-El Pilar Fault System.

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References

Aleman, A. (1983). Geology and hydrocarbon evaluation of northwest Colombia (Internal Rep.). Gulf Oil E&P Company.

ANH (2011). Petroleum geology of Colombia. In F. Cediel (Ed.), *Regional Geology-Phanerozoic Granitoid Magmatism in Colombia and the Tectono-Magmatic Evolution of the Colombian Andes* (Vol. I, pp. 116–190). Medellin, Colombia: Fondo Editorial Universidad Eafit.

Ares (2014). Petrografía y Datación Quimioestratigráfica del Cinturón plegado de San Jacinto en el área de Luruaco-Arroyo de Piedra. Internal report for Hocol S.A. and Lewis Energy Colombia, Bogotá.

ATG-ANH (2009). Cartografía Geológica, levantamiento de Columnas estratigráficas, toma de muestras y análisis bioestratigráficos. Sector de Chalán, Cuenca Sinú-San Jacinto. Public report for the ANH, Bogotá.

Barrero, D. (1979). Geology of the central Western Cordillera west of Buga and Roldanillo. Publicaciones Geol. Esp. No. 4, Ingeominas, Bogotá.

Barrero, D., Alvarez, J., & Kassem, T. (1969). Actividad Ignea y tectónica en la Cordillera Central. *Boletin de Geologia, Ingeominas*, *17*(1–3), 145–173.

Bayona, G., Cardona, A., Jaramillo, C., Mora, A., Montes, C., Caballero, V., … Valencia, V. (2013). Onset of fault reactivation in the Eastern Cordillera of Colombia and proximal Llanos Basin; response to Caribbean–South American convergence in early Palaeogene time. In M. Nemcok, A. Mora, & J. W. Cosgrove (Eds.), *Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion*, *Geological Society, London, Special Publications, 377* (pp. 285–314).

Bayona, G., Cardona, A., Jaramillo, C., Mora, A., Montes, C., Valencia, V., … Ibañez, M. (2012). Early Paleogene magmatism in the northern Andes: Insights on the effects of oceanic plateau–continent convergence. *Earth and Planetary Science Letters*, *331–332*, 97–111. https://doi.org/10.1016/j.epsl.2012.03.015

Berggren, W. A., Kent, D. V., Swisher, C. C. III, & Aubry, M.-P. (1995). A revised Cenozoic geochronology and chronostratigraphy. In *SEPM-Society for Sedimentary Geology, Special Publication*, 54, Tulsa, OK. pp. 129–212).

Bernal-Olaya, R., Mann, P., & Escalona, A. (2015). Cenozoic tectonostratigraphic evolution of the Lower Magdalena Basin, Colombia: An example of an under- to overfilled forearc basin. In C. Bartolini & P. Mann (Eds.), *Petroleum Geology and Potential of the Colombian Caribbean Margin*, *AAPG Memoir* (Vol. 108, pp. 345–398). Tulsa, OK: American Association of Petroleum Geologists. https://doi.org/10.1306/13531943M1083645

Bernal-Olaya, R., Mann, P., & Vargas, C. (2015). Earthquake, tomographic, seismic reflection, and gravity evidence for a shallowly dipping subduction zone beneath the Caribbean margin of northwestern Colombia. In C. Bartolini & P. Mann (Eds.), *Petroleum Geology and Potential of the Colombian Caribbean Margin*, *AAPG Memoir* (Vol. 108, pp. 247–270). Tulsa, OK: American Association of Petroleum Geologists. https://doi.org/10.1306/13531939M1083642

Beroiz, C., Lindberg, F. & Winter, S. (1986). Northwest Colombia hydrocarbon evaluation (Internal Rep.). Chevron Overseas Petroleum Inc.

Bezada, M. J., Levander, A., & Schmandt, B. (2010). Subduction in the southern Caribbean: Images from finite-frequency *P* wave tomography. *Journal of Geophysical Research*, *115*, B12333. https://doi.org/10.1029/2010JB007682

Blow, W. A. (1969). Late middle Eocene to Recent planktonic foraminiferal biostratigraphy. In P. Bronnimann & H. H. Renz (Eds). *Proceedings of First International Conference on Planktonic Microfossils* (Vol. 1, pp. 199–421). Geneva.

Boschman, L., van Hinsbergen, D., Torsvik, T., Spakman, W., & Pindell, J. (2014). Kinematic reconstruction of the Caribbean region since the Early Jurassic. *Earth-Science Reviews*, *138*(2014), 102–136. https://doi.org/10.1016/j.earscirev.2014.08.007

Bowland, C., & Rosencrantz, E. (1988). Upper crustal structure of the western Colombian Basin, Caribbean Sea. *Geological Society of America Bulletin Bulletin*, *100*(4), 534–546.

Boyden, J., Müller, R. D., Gurnis, M., Torsvik, T. H., Clark, J., Turner, M., … Cannon, J. (2011). Next-generation plate-tectonic reconstructions using GPlates. In R. Keller & C. Baru (Eds.), *Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences* (pp. 95–114). Cambridge University Press.. https://doi.org/10.1017/CBO9780511976308.008

Bustamante, C., Cardona, A., Archanjo, C., Bayona, G., Lara, M., & Valencia, V. (2017). Geochemistry and isotopic signatures of Paleogene plutonic and detrital rocks of the northern Andes of Colombia: A record of post-collisional arc magmatism. *Lithos*, *277*, 199–209. https://doi.org/10.1016/j.lithos.2016.11.025

Caballero, V., Mora, A., Quintero, I., Blanco, V., Parra, M., Rojas, L., … 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 M. Nemcok, A. Mora, & J. W. Cosgrove (Eds.), *Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion*, Geological Society, London, Special Publications (Vol. 377, pp. 315–342).

Caballero, V., Parra, M., Mora, A., Lopez, C., Rojas, L. E., & Quintero, I. (2013). Factors controlling selective abandonment and reactivation in thick-skin orogens: A case study in the Middle Magdalena Valley, Colombia. In M. Nemcok, A. Mora, & J. W. Cosgrove (Eds.), *Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion*, Geological Society, London, Special Publications (Vol. 377, pp. 343–367).

Cardona, A., Chew, D., Valencia, V. A., Bayona, G., Miskovic, A., & Ibañez-Mejia, M. (2010). Grenvillian remnants in the northern Andes: Rodinian and Phanerozoic paleogeographic perspectives. *Journal of South American Earth Sciences*, *29*(1), 92–104. https://doi.org/10.1016/j.jsames.2009.07.011

Cardona, A., Montes, C., Ayala, C., Bustamante, C., Hoyos, N., Montenegro, O., … Zapata, S. (2012). From arc-continent collision to continuous convergence, clues from Paleogene conglomerates along the southern Caribbean–South America Plate boundary. *Tectonophysics*, *580*, 58–87. https://doi.org/10.1016/j.tecto.2012.08.039

Cardona, A., Valencia, V., Bayona, G., Duque, J., Ducea, M., Gerhels, G., … Ruiz, J. (2011). Early subduction orogeny in the northern Andes: Turonian to Eocene magmatic and provenance record in the Santa Marta massif and Rancheria Basin, northern Colombia. *Terranova*, *23*, 26–34.

Cardona, A., Valencia, V., Bustamante, C., García-Casco, A., Ojeda, G., Ruiz, J., … Weber, M. (2010). Tectonomagmatic setting and provenance of the Santa Marta Schists, northern Colombia: Insights on the growth and approach of Cretaceous Caribbean oceanic terranes to the South American continent. *Journal of South American Earth Sciences*, *29*(4), 784–804. https://doi.org/10.1016/j.jsames.2009.08.012

Cardona, A., Weber, M., Valencia, V., Bustamante, C., Montes, M., Cordani, U., & Muñoz, C. (2014). Geochronology and geochemistry of the Parashi granitoid, NE Colombia: Tectonic implication of short-lived early Eocene plutonism along the SE Caribbean margin. *Journal of South American Earth Sciences*, *50*, 75–92. https://doi.org/10.1016/j.jsames.2013.12.006

Catuneanu, O., Abreu, V., Bhattacharya, J., Blum, M., Dalrymple, R., Eriksson, P., … Winker, C. (2009). Towards the standardization of sequence stratigraphy. *Earth Science Reviews*, *92*(1–2), 1–33. https://doi.org/10.1016/j.earscirev.2008.10.003

Cecil, M. R., Gehrels, G., Ducea, M. N., & Patchett, P. J. (2011). U–Pb–Hf characterization of the central Coast Mountains batholith: Implications for petrogenesis and crustal architecture. *Lithosphere*, *3*, 247–260. https://doi.org/10.1130/L134.1

Cediel, F., Shaw, R. P., & Cáceres, C. (2003). Tectonic assembly of the northern Andean block. In C. Bartolini, R. T. Buffler, & J. Blickwede (Eds.), *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation, and Plate Tectonics*, *AAPG Memoir* (Vol. 79, pp. 815–848). Tulsa, OK: The American Association of Petroleum Geologists.

Cerón, J., Kellogg, J., & Ojeda, G. (2007). Basement configuration of the northwestern South America-Caribbean margin from recent geophysical data. *Ciencia Tecnología y Futuro*, *3*(3), 25–49.

Chenevart, C. (1963). Les dorsales transverses anciennes de Colombie et leurs homologues d'Amérique latine. *Eclogae Geologicae Helvetiae*, *56*(2), 907–927.

Chiarabba, C., De Gori, P., Faccena, C., Speranza, F., Deccia, D., Dionicio, V., & Pri-eto, G. A. (2015). Subduction system and flat slab beneath the Eastern Cordillera of Colombia. *Geochemistry, Geophysics, Geosystems*, *17*, 16–27. https://doi.org/10.1002/2015GC006048

Clavijo, J., & Barrera, R. (1999). *Geología de las Planchas 44, Sincelejo y 52, Sahagún*. Bogotá: Ingeominas.

Clift, P., & Vannucchi, P. (2004). Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. *Reviews of Geophysics*, *42*, RG2001. https://doi.org/10.1029/2003RG000127

Cochrane, R., Spikings, R., Gerdes, A., Ulianov, A., Mora, A., Villagómez, D., … Chiaradia, M. (2014). Permo-Triassic anatexis, continental rifting and the disassembly of western Pangaea. *Lithos*, *190–191*, 383–402. https://doi.org/10.1016/j.lithos.2013.12.020

Cordani, U. G., Cardona, A., Jimenez, D., Liu, D., & Nutman, A. P. (2005). Geochronology of Proterozoic basement inliers from the Colombian Andes: Tectonic history of remnants from a fragmented Grenville belt. In A. P. M. Vaughan, P. T. Leat, & R. J. Pankhurst (Eds.), *Terrane Processes at the Margins of Gondwana*, *Geological Society, London Special Publication* (Vol. 246, pp. 329–346).

Cross, T. (2014). Core examination summary of the Ecopetrol M-3X core. Internal report for Hocol S.A., Bogotá.

Daly, M. (1989). Correlations between Nazca/Farallón Plate kinematics and forearc basin evolution in Ecuador. *Tectonics*, *8*(4), 769–790. https://doi.org/10.1029/TC008i004p00769

De la Parra, F., Mora, A., Rueda, M., & Quintero, I. (2015). Temporal and spatial distribution of tectonic events as deduced from reworked palynomorphs in the eastern northern Andes. *AAPG Bulletin*, *99*(08), 1455–1472. https://doi.org/10.1306/02241511153

Diaz-Cañas, S. (2015). Marco bioestratigráfico y proveniencia de la Formación Penderisco, y su significado en la formación de un domo marginal a las Fallas de Romeral. BSc. Thesis, Universidad Nacional de Colombia, Bogotá, pp. 57.

Dickinson, W. R. (1985). Interpreting provenance relations from detrital modes of sandstones. In G. G. Zuffa (Ed.), *Provenance of Arenites* (pp. 333–361). Dordrecht, Netherlands: Springer. https://doi.org/10.1007/978-94-017-2809-6_15

Driscoll, N. W., & Diebold, J. B. (1999). Tectonic and stratigraphic development of the eastern Caribbean: New constraints from multichannel seismic data. In P. Mann (Ed.), *Caribbean Basins: Sedimentary Basins of the World 4* (pp. 591–626). Amsterdam: Elsevier Science B.V. https://doi.org/10.1016/S1874-5997(99)80054-9

Dueñas, H., & Gomez, C. (2013). Bioestratigrafía de las Formación Cansona en la Quebrada Peñitas, Cinturon de San Jacinto: Implicaciones Paleogeográficas. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales*, *XXXVII*(145), 527–539.

Duque-Caro, H. (1972). Ciclos tectonicos y sedimentarios en el norte de Colombia y sus relaciones con la paleoecología. *Boletin de Geologia, Ingeominas*, *19*(3), 25–68.

Duque-Caro, H. (1979). Major structural elements and evolution of northwestern Colombia. In J. S. Watkins, L. Montadert, & P. Wood Dickerson (Eds.), *Geological and Geophysical Investigations of Continental Margins*, *AAPG Memoir 29* (pp. 329–351). Tulsa, OK: The American Association of Petroleum Geologists.

Duque-Caro, H. (1980). Geotectónica y evolución de la región noroccidental Colombiana. *Boletín Geológico Ingeominas*, *23*, 4–37.

Duque-Caro, H. (1984). *Structural Style, Diapirism, and Accretionary Episodes of the Sinú-San Jacinto Terrane, Southwestern Caribbean Borderland*, *Memoir* (Vol. 162, pp. 303–316). The Geological Society of America.

Duque-Caro, H. (1991). Contributions to the geology of the Pacific and the Caribbean coastal areas of northwestern Colombia and South America. PhD Thesis, Princeton University.

Duque-Caro, H. (2000). Analisis bioestratigráficos de 400 muestras de 34 pozos y 16 muestras de superficie de las cuencas de San Jorge, Sinu, Plato y Barranquilla en el Valle Inferior del Magdalena. Internal report for Ecopetrol.

Duque-Caro, H. (2001). Analisis bioestratigráficos de 250 muestras de 5 pozos de las cuencas de San Jorge, Sinu, Plato y Barranquilla en el Valle Inferior del Magdalena. Internal report for Ecopetrol.

Duque-Caro, H. (2010). Analisis microestratigráficos de 36 muestras del pozo Saman Norte-1. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2011a). Microstratigraphic analyses of samples from the wells Caracoli-1, Manati-1 and Polonuevo-1, Barranquilla Province. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2011b). Microstratigraphic analyses of samples from the wells Molinero-1, Molinero-2 and Molinero-3X, Barranquilla Province. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2011c). Microstratigraphic analyses of 100 samples from the wells Guaruco-1, Molinero-2 and Molinero-3X and Tubará-1, Barranquilla Province. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2012a). Microstratigraphic analyses of 92 samples from the well Bonga-1, san Jorge basin. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2012b). Microstratigraphic analyses of samples from the well CurrambaEST1, Barranquilla Province. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H. (2013a). Microstratigraphic analyses of samples from the well SamanEst-1, Barranquilla Province. Internal report for Hocol S. A., Bogotá.

Duque-Caro, H. (2013b). Microstratigraphic analyses of samples from the well C-1, Barranquilla Province. Internal report for Hocol S.A., Bogotá.

Duque-Caro, H., Guzman, G., & Hernandez, R. (1996). *Mapa GeolóGico de la Plancha 38, Carmen de Bolívar*. Bogotá: Ingeominas.

Ecopetrol/ICP 2014. Proyecto "Protocolo del Pre-Neógeno del Caribe en las Cuencas Sinú-San Jacinto y Valle Inferior del Magdalena". Internal Reports. Bogotá.

Espurt, N., Funiciello, F., Martinod, J., Guillaume, B., Regard, V., Faccenna, C., & Brusset, S. (2008). Flat subduction dynamics and deformation of the South American Plate: Insights from analog modeling. *Tectonics*, *27*, TC3011. https://doi.org/10.1029/2007TC002175

ESRI/ILEX (1995). Evaluación Geológica Regional de la Cuenca Sinú-San Jacinto. Technical report for Ecopetrol. Bogotá, Colombia.

Etayo Serna, F., Renzoni, G., & Barrero, D. (1969). *Contornos Sucesivos del mar Cretáceo en Colombia. I Congreso Colombiano Geológico, Memorias*, (pp. 217–252). Bogotá: Asociación Colombiana de Geólogos y Geofísicos del Petróleo.

Faure, G., & Mensing, T. (2005). *Isotopes, Principles and Applications* (3rd ed., p. 897). New Jersey: John Wiley.

Fisher, C. M., Vervoort, J. D., & Hanchar, J. M. (2014). Guidelines for reporting zircon Hf isotopic data by LA-MC-ICPMS and potential pitfalls in the interpretation of these data. *Chemical Geology*, *363*, 125–133. https://doi.org/10.1016/j.chemgeo.2013.10.019

Flinch, J. F. (2003). Structural evolution of the Sinu-Lower Magdalena area (northern Colombia). In C. Bartolini, R. T. Buffler, & J. Blickwede (Eds.), *The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon Habitats, Basin Formation and Plate Tectonics*, *AAPG Memoir* (Vol. 79, pp. 776–796). Tulsa, OK: The American Association of Petroleum Geologists.

Forero, O. (1974). The Eocene of northwestern South America. MS thesis Tulsa, Univ. of Tulsa, pp. 81.

Gehrels, G. E., Valencia, V. A., & Ruiz, J. (2008). Enhanced precision, accuracy, efficiency, and spatial resolution of U–Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry. *Geochemistry, Geophysics, Geosystems*, *9*, Q03017. https://doi.org/10.1029/2007GC001805

GEMS Ltda (2007). Caracterizacion Geoquimica de Rocas y crudos en las cuencas de Cesar-rancheria, Sinu-San Jacinto, Choco y Area de Soapaga (Cuenca Cordillera Oriental). Final report for ANH, Bogotá.

GEMS Ltda (2014). Evaluació de los Sistemas Petrolíferos en el Bloque SSJN1 del Cinturón Plegado de San Jacinto. Internal report for Hocol S. A. and Lewis Energy Colombia, Bogota.

Geosearch Ltda (2006). Cartografía e Interpretación geológica y levantamiento estratigráfico para el Bloque Perdices, Cuenca del Valle Inferior del Magdalena. Internal report for Ecopetrol, Bogotá.

Gómez, E., Jordan, T., 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. *GSA Bulletin*, *117*(5), 547–569. https://doi.org/10.1130/B25454.1

Gómez, I. (2001). *Structural Style and Evolution of the Cuisa Fault System, Guajira* (p. 147). Colombia: University of Houston.

Gomez, J., Nivia, A., Montes, N., Tejada, M., Jimenez, D., Sepulveda, M., … Mora, M. (2007). *Geological Map of Colombia* (1st ed.). Bogota: Ingeominas (Servicio Geologico de Colombia).

Govers, R., & Wortel, M. (2005). Lithosphere tearing at STEP faults: Response to edges of subduction zones. *Earth and Planetary Science Letters*, *236*, 505–523.

Gutscher, M. A., Spakman, W., Bijwaard, H., & Engdahl, E. (2000). Geodynamics of flat subduction: Seismicity and tomographic constraints from the Andean margin. *Tectonics*, *19*(5), 814–833. https://doi.org/10.1029/1999TC001152

Guzman, G. (2007). Stratigraphy and sedimentary environment and implications in the plato basin and the San Jacinto Belt northwestern Colombia. PhD Thesis, Univ. of Liege, Belgium.

Guzman, G., Gomez, E., & Serrano, B. (2004). Geologia de los cinturones del Sinu, San Jacinto y Borde occidental del Valle Inferior del Magdalena, Caribe Colombiano. Ingeominas (Colombian Geological Survey) report, Bogotá.

Haq, B. U., Hardenbol, J., & Vail, P. R. (1987). Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science*, *235*(4793), 1156–1167. https://doi.org/10.1126/science.235.4793.1156

Hocol, S. A. (1993). Lower Magdalena Valley technical evaluation agreement. Phase I Internal report. Cartagena.

Hoorn, C., Wesselingh, F., ter Steege, H., Bermudez, M., Mora, A., Sevink, J., … Antonelli, A. (2010). Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. *Science*, *330*(6006), 927–931. https://doi.org/10.1126/science.1194585

Horton, B. K., Parra, M., Saylor, J. E., Nie, J., Mora, A., Torres, V., … Strecker, M. R. (2010). Resolving uplift of the northern Andes using detrital zircon age signatures. *GSA Today*, *20*(7), 4–9.

Hubach, E. (1957). Estratigrafía de la Sabana de Bogotá y sus alrededores. *Boletín Geológico Servicio Geológico Nacional*, *5*, 93–112.

Ibañez-Mejia, M., Pullen, A., Arenstein, J., Gehrels, G., Valley, J., Ducea, M., … Ruiz, J. (2015). Unraveling crustal growth and reworking processes in complex zircons from orogenic lower–crust: The Proterozoic Putumayo orogeny of Amazonia. *Precambrian Research*, *267*, 285–310. https://doi.org/10.1016/j.precamres.2015.06.014

Ibañez-Mejia, M., Ruiz, J., Valencia, V. A., Cardona, A., Gehrels, G. E., & Mora, A. R. (2011). The Putumayo Orogen of Amazonia and its implications for Rodinia reconstructions: New U-Pb geochronological insights into the Proterozoic tectonic evolution of northwestern South America. *Precambrian Research*, *191*(1-2), 58–77. https://doi.org/10.1016/j.precamres.2011.09.005

Ibañez-Mejia, M., Tassinari, C. C. G., & Jaramillo-Mejia, J. M. (2007). U-Pb zircon ages of the "Antioquian batholith": Geochronological constraints of Late Cretaceous magmatism in the Central Andes of Colombia. 11th Colombian Geological Congress, Extended Abstracts, pp. 11.

ICP (Instituto Colombiano del Petróleo) (2000). Evaluación Regional Integrada Cuenca Valle Inferior del Magdalena. Final Internal Report, Piedecuesta, Santander.

James, K. H. (2006). Arguments for and against the Pacific origin of the Caribbean Plate: Discussion, finding for an inter-American origin. *Geologica Acta*, *4*, 279–302.

Juliao-Lemus, T., de Araujo Carvalho, M., Torres, D., Plata, A., & Parra, C. (2016). Paleoenvironmental reconstruction based on palynofacies analyses of the Cansona Formation (Late Cretaceous), Sinú-San Jacinto Basin, northwest Colombia. *Journal of South American Earth Sciences*, *69*, 103–118. https://doi.org/10.1016/j.jsames.2016.03.009

Kennan, L., & Pindell, J. (2009). *Dextral Shear, Terrane Accretion and Basin Formation in the Northern Andes: Best Explained by the Interaction With a Pacific-Derived Caribbean Plate? Geological Society, London Special Publication* (Vol. 328, pp. 487–531).

Kroehler, M. E., Mann, P., Escalona, A., & Christeson, G. (2011). Late Cretaceous-Miocene diachronous onset of back thrusting along the South Caribbean deformed belt and its importance for understanding processes of arc collision and crustal growth. *Tectonics*, *30*, TC6003. https://doi.org/10.1029/2011TC002918

Leroy, S., Bitri, A., & Mauffret, A. (1996). Migration velocity analysis based on common-shot-depth migration applied to the seismic data of the Caribbean oceanic plateau. *Geophysical Journal International*, *125*(1), 199–213. https://doi.org/10.1111/j.1365-246X.1996.tb06546.x

Levander, A., Bezada, M., Niu, F., & Schmitz, M. (2015). The two subduction zones of the southern Caribbean: Lithosphere tearing and continental margin recycling in the east, flat slab sybduction and Laramide-style uplifts in the west. AGU Fall Meeting, San Francisco.

Llinas, R. (2012). Petrographic analyses of outcrop samples from the SSJN1 block (northern San Jacinto fold belt). Internal report for Hocol S. A., Bogotá.

Londoño, J., Schiek, C., & Biegert, E. (2015). Basement architecture of the southern Caribbean basin, Guajira offshore, Colombia. In C. Bartolini & P. Mann (Eds.), *Petroleum Geology and Potential of the Colombian Caribbean Margin*, *AAPG Memoir* (Vol. 108, pp. 85–102). Tulsa, OK: The American Association of Petroleum Geologists. https://doi.org/10.1306/13531932M1083639

Magnani, M. B., Zelt, C. A., Levander, A., & Schmitz, M. (2009). Crustal structure of the South American–Caribbean Plate boundary at 67°W from controlled source seismic data. *Journal of Geophysical Research*, *114*, B02312. https://doi.org/10.1029/2008JB005817

Manea, V., Manea, M., Ferrari, L., Orozco, T., Valenzuela, R., Husker, A., & Kostoglodov, V. (2017). A review of the geodynamic evolution of flat slab subduction in Mexico, Peru and Chile. *Tectonophysics*, *695*, 27–52. https://doi.org/10.1016/j.tecto.2016.11.037

Mantilla, A. (2007). Crustal structure of the southwestern Colombian Caribbean margin. Thesis Dr. rer. nat., Friedrich-Schiller-Universität Jena, Germany.

Mantilla, A. M., Jentszsch, G., Kley, J., & Alfonso-Pava, C. (2009). *Configuration of the Colombian Caribbean Margin: Constraints from 2D Seismic Reflection Data and Potential Fields Interpretation, Subduction Zone Geodynamics* (pp. 247–271). Dubai: Springer.

Masy, J., Niu, F., Levander, A., & Schmitz, M. (2011). Mantle flow beneath northwestern Venezuela: Seismic evidence for a deep origin of the Mérida Andes. *Earth and Planetary Science Letters*, *305*(3–4), 396–404. https://doi.org/10.1016/j.epsl.2011.03.024

Matthews, K., Maloney, K., Zahirovic, S., William, S., Seton, M., & Muller, D. (2016). Global plate boundary evolution and kinematics since the Late Paleozoic. *Global and Planetary Change*, *146*, 226–250. https://doi.org/10.1016/j.gloplacha.2016.10.002

Mauffret, A., & Leroy, S. (1997). Seismic stratigraphy and structure of the Caribbean igneous province. *Tectonophysics*, *283*(1-4), 61–104. https://doi.org/10.1016/S0040-1951(97)00103-0

McArthur, J. M., Howarth, R., & Bailey, T. (2001). Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. *The Journal of Geology*, *109*(2), 155–170. https://doi.org/10.1086/319243

Mejía, P., Santa, M., Ordóñez, O., & Pimentel, M. (2008). Consideraciones petrográficas, geoquímicas y geocronológicas de la parte occidental del Batolito de Santa Marta. *Revista Dyna*, *155*, 223–236.

Montes, C., Cardona, A., Jaramillo, C., Pardo, A., Silva, J. C., Valencia, V., … Niño, H. (2015). Middle Miocene closure of the central American seaway. *Science*, *348*(6231), 226–229. https://doi.org/10.1126/science.aaa2815

Montes, C., Guzman, G., Bayona German, A., Cardona, A., Valencia, V., & Jaramillo Carlos, A. (2010). Clockwise rotation of the Santa Marta massif and simultaneous Paleogene to Neogene deformation of the Plato-San Jorge and Cesar-Rancheria basins. *Journal of South American Earth Sciences*, *29*(4), 832–848. https://doi.org/10.1016/j.jsames.2009.07.010

Mora, A., De Freitas, M., & Velez, V. (2013). Cenozoic Tectonostratigraphy of the northern San Jacinto fold belt, northwestern Colombia. Poster presented at the AAPG International Convention and Exhibition, Cartagena, 8–11 September.

Mora, A., & Garcia, A. (2006). Cenozoic tectono-stratigraphic relationships between the Cesar subbasin and the southeastern Lower Magdalena Valley basin of northern Colombia: AAPG, search and discovery article, 30046. *Search and Discovery* 30046, 1–11.

Mora, A., Ibáñez-Mejía, M., Oncken, O., De Freitas, M., Vélez, V., Mesa, A., & Serna, L. (2017). Structure and age of the lower Magdalena Valley basement, northern Colombia: New reflection-seismic and U-Pb-Hf insights into the termination of the Central Andes against the Caribbean Basin. *Journal of South American Earth Sciences*, *74*, 1–26. https://doi.org/10.1016/j.jsames.2017.01.001

Mora, A., Parra, M., Forero, G., Blanco, V., Moreno, N., & Caballero, V. (2015). What drives orogenic asymmetry in the northern Andes?: A case study from the apex of the northern Andean orocline. In C. Bartolini & P. Mann (Eds.), *Petroleum Geology and Potential of the Colombian Caribbean Margin*, *AAPG Memoir* (Vol. 108, pp. 547–586). Tulsa, OK: The American Association of Petroleum Geologists. https://doi.org/10.1306/13531949M1083652

Mora, A., Reyes-Harker, A., Rodriguez, G., Tesón, E., Ramírez-Arias, J. C., Parra, M., … Stockli, D. (2013). Inversion tectonics under increasing rates of shortening and sedimentation: Cenozoic example from the Eastern Cordillera of Colombia. In M. Nemcok, A. Mora, & J. W. Cosgrove (Eds.), *Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion*, *Geological Society, London, Special Publications* (Vol. 377, pp. 411–442).

Müller, R. D., Royer, J.-Y., Cande, S. C., Roest, W. R., & Maschenkov, S. (1999). New constraints on the Late Cretaceous/Tertiary plate tectonic evolution of the Caribbean. In P. Mann (Ed.), *Caribbean Basins*, (pp. 33–59). Amsterdam, The Netherlands: Elseier Science B.V. https://doi.org/10.1016/S1874-5997(99)80036-7

Nie, J., Horton, B., Saylor, J., Mora, A., Mange, M., Garziones, C., … Parra, M. (2012). Integrated provenance analysis of a convergent retroarc foreland system: U–Pb ages, heavy minerals, Nd isotopes, and sandstone compositions of the Middle Magdalena Valley basin, northern Andes, Colombia. *Earth-Science Reviews*, *110*(1-4), 111–126. https://doi.org/10.1016/j.earscirev.2011.11.002

Niño, C. (2005). Sistemas Petroliferos da parte norte da Bacia de Sinu-San Jacinto, Colombia: Uma avaliacao geologica e geoquimica integrada. Masters Thesis at Federal University of Rio de Janeiro, Brazil.

Osorno, J. F., & Rangel, A. (2015). Geochemical assessment and petroleum systems in the Sinu-San Jacinto basin, northwestern Colombia. *Marine and Petroleum Geology*, *65*, 217–231. https://doi.org/10.1016/j.marpetgeo.2015.03.022

Parra, D., & Rincón, D. (2014). Foraminferal Assemblaged and Paleoenvironments of the early to middle Eocene succession in the Sinu-San Jacinto basin, Northern South America. Poster presented at the 4th International Paleontological Congress, 28th September to 3rd October, Mendoza, Argentina.

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. https://doi.org/10.1130/G32519.1

Patchett, P. J., & Tatsumoto, M. (1981). A routine high-precision method for Lu–Hf isotope geochemistry and chronology. *Contributions to Mineralogy and Petrology*, *75*, 263–267. https://doi.org/10.1007/BF01166766

Pennington, W. D. (1981). Subduction of the eastern Panama basin and seismotectonics of northwestern South America. *Journal of Geophysical Research*, *86*(B11), 10,753–10,770. https://doi.org/10.1029/JB086iB11p10753

Peters, K., & Cassa, M. R. (1994). Applied source rock geochemistry. In L. Magoon & W. Dow (Eds.), *The Petroleum System-From Source to Trap*, *AAPG Memoir* (Vol. 60, chapter 5, pp. 93–120). Tulsa, OK: The American Association of Petroleum Geologists.

Petrobras/Ecopetrol (1996). The petroleum system of the Lower Magdalena Basin, Colombia: A geochemical characterization of oils and potential source rocks. Internal report, Bogotá.

PGT (2005). Potencial Exploratorio y prospectividad de los sistemas petroliferos en la Cuenca del Sinu (Onshore y offshore). Internal report for ANH, Bogotá.

Philippon, M., & Corti, G. (2016). Obliquity along plate boundaries. *Tectonophysics*, *693*, 171–182. https://doi.org/10.1016/j.tecto.2016.05.033

Pindell, J., & Kennan, L. (2009). Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update. *Geological Society of London, Special Publication*, *328*, 1–55.

Pindell, J., Kennan, L., Maresch, W., Stanek, K., Draper, G., & Higgs, R. (2005). Plate-kinematics and crustal dynamics of circum-Caribbean arc-continent interactions: Tectonic controls on basin development in Proto-Caribbean margins. In H. Avé Lallemant & V. Sisson (Eds.), *Caribbean-South American plate interactions, Venezuela, Geological Society of America Special Paper 394*, (pp. 7–52).

Pomar, L., Esteban, M., Martinez, W., Espino, D., Castillo, V., Benkovics, L., & Castro Leyva, T. (2015). Oligocene-Miocene carbonates of the Perla field, offshore Venezuela: Depositional model and facies architecture. In C. Bartolini & P. Mann (Eds.), *Petroleum Geology and Potential of the Colombian Caribbean Margin*, *AAPG Memoir* (Vol. 108, pp. 647–674). Tulsa, OK: The American Association of Petroleum Geologists. https://doi.org/10.1306/13531952M1083655

Ramos, V., & Folguera, A. (2009). Andean flat-slab subduction through time. In J. B. Murphy, J. D. Keppie, & A. J. Hynes (Eds.), *Ancient Orogens and Modern Analogues*, *Geological Society, London, Special Publications* (Vol. 327, pp. 31–54).

Restrepo, S., Foster, D., Stockli, D., & Parra, L. (2009). Long-term erosion and exhumation of the "Altiplano Antioqueño", northern Andes (Colombia) from apatite (U–Th)/He thermochronology. *Earth and Planetary Science Letters*, *278*(1–2), 1–12. https://doi.org/10.1016/j.epsl.2008.09.037

Restrepo-Pace, P. A., & Cediel, F. (2010). Northern South America basement tectonics and implications for paleocontinental reconstructions of the Americas. *Journal of South American Earth Sciences*, *29*(4), 764–771. https://doi.org/10.1016/j.jsames.2010.06.002

Richards, M. T. (2001). Deep marine clastic systems. In D. Emery & K. Myers (Eds.), *Sequence Stratigraphy* (pp. 178–210). Oxford, UK: Blackwell Science.

Ridgway, K., Trop, J., & Finzel, E. (2012). Modification of continental forearc basins by flat-slab subduction processes: A case study from southern Alaska. In C. Busby & A. Azor (Eds.), *Tectonics of Sedimentary Basins: Recent Advances* (1st ed., pp. 327–346). Oxford: Blackwell. https://doi.org/10.1002/9781444347166.ch16

Ross, M., & Scotese, C. (1988). A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. *Tectonophysics*, *155*(1–4), 139–168. https://doi.org/10.1016/0040-1951(88)90263-6

Russo, R. M., Speed, R. C., Okal, E. A., Shepherd, J. B., & Rowley, K. C. (1993). Seismicity and tectonics of the southeastern Caribbean. *Journal of Geophysical Research*, *98*(B8), 14,299–14,319. https://doi.org/10.1029/93JB00507

Sarmiento, G., Bonilla, G., & Osorio, J. (2016). Evidencias de Vulcanismo Penecontemporáneo en la Formación San Cayetano de la Cuenca Sinu-San Jacinto e Implicaciones en el entorno geológico regional. *Abstract in the memoirs of The Colombian and Venezuelan Caribbean Geology Workshop, May 27, 2016*. (pp. 29–30). Bogotá: Universidad Nacional de Colombia.

Saylor, J., Horton, B., Stockli, D., Mora, A., & Corredor, J. (2012). Structural and thermochronological evidence for Paleogene basement-involved shortening in the axial Eastern Cordillera, Colombia. *Journal of South American Earth Sciences*, *39*, 202–215. https://doi.org/10.1016/j.jsames.2012.04.009

Silva, A., Paez, L., Rincón, M., Tamara, J., Gomez, P., Lopez, E., … Valencia, V. (2017). Basement characteristics in the Lower Magdalena Valley and the Sinu and San Jacinto fold belts: Evidence of a Late Cretaceous magmatic arc at the south of the Colombian Caribbean. *Ciencia, Tecnología y Futuro*, *6*(4), 5–36.

Spikings, R., Cochrane, R., Villagómez, D., Van der Lelij, R., Vallejo, C., Winkler, W., & Beate, B. (2015). The geological history of northwestern South America: From Pangaea to early collision of the Caribbean large igneous province (290–75 Ma). *Gondwana Research*, *27*(1), 95–139. https://doi.org/10.1016/j.gr.2014.06.004

Syracuse, E., Maceira, M., Prieto, G., Zhang, H., & Ammon, C. (2016). Multiple plates subducting beneath Colombia, as illuminated by seismicity and velocity from the joint inversion of seismic and gravity data. *Earth and Planetary Science Letters*, *444*, 139–149. https://doi.org/10.1016/j.epsl.2016.03.050

Taboada, A., Rivera, L., Fuenzalida, A., Cisternas, A., Philip, H., Bijwaard, H., … Rivera, C. (2000). Geodynamics of the northern Andes: Subductions and intracontinental deformation (Colombia). *Tectonics*, *19*(5), 787–813. https://doi.org/10.1029/2000TC900004.

Tissot, B., Durand, B., Espitalié, J., & Combaz, A. (1974). Influence of the nature and diagenesis of organic matter in the formation of petroleum. *AAPG Bulletin*, *58*, 499–506.

Trenkamp, R., Kellogg, J., Freymueller, J., & Mora, H. (2002). Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. *Journal of South American Earth Sciences*, *15*(2), 157–171. https://doi.org/10.1016/S0895-9811(02)00018-4

Vail, P. R., Mitchum, R. M. Jr., & Thompson, S. III (1977). Seismic stratigraphy and global changes of sea level, Part 3: Relative changes of sea level from coastal onlap. In C. E. Payton (Ed.), *Seismic Stratigraphy—Applications to Hydrocarbon Exploration*, *Memoir* (Vol. 26, pp. 63–81). Tulsa, OK: American Association of Petroleum Geologists.

Van Benthem, S., Govers, R., Spakman, W., & Wortel, R. (2013). Tectonic evolution and mantle structure of the Caribbean. *Journal of Geophysical Research*, *118*, 3019–3036.

Van der Hilst, R. D., & Mann, P. (1994). Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America. *Geology*, *22*(5), 451–454. https://doi.org/10.1130/0091-7613(1994)022%3C0451:TIOTIO%3E2.3.CO;2

Van der Lelij, R., Spikings, R., & Mora, A. (2016). Thermochronology and tectonics of the Mérida Andes and the Santander Massif, NW South America. *Lithos*, *248-251*, 220–239. https://doi.org/10.1016/j.lithos.2016.01.006

Van Wagoner, J. C., Mitchum, R. M. Jr., Campion, K. M., & Rahmanian, V. D. (1990). *Siliciclastic Sequence Stratigraphy in Well Logs, Core, and Cutcrops: Concepts for High-Resolution Correlation of Time and Facies*, *American Association of Petroleum Geologists Methods in Exploration Series* (Vol. 7, p. 55). Tulsa, OK: The American Association of Petroleum Geologists.

Van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S., & Hardenbol, J. (1988). An overview of sequence stratigraphy and key definitions. In C. K. Wilgus et al. (Eds.), *Sea Level Changes—An Integrated Approach*, *Special Publication* (Vol. 42, pp. 39–45). Society of Economic Paleontologists and Mineralogists (SEPM). https://doi.org/10.2110/pec.88.01.0039

Vargas, C. A., & Mann, P. (2013). Tearing and breaking off of subducted slabs as the result of collision of the Panama arc-indenter with northwestern South America. *Bulletin of the Seismological Society of America*, *103*(3), 2025–2046. https://doi.org/10.1785/0120120328

Veloza, G., Styron, R., Taylor, M., & Mora, A. (2012). Open-source archive of active faults for northwest South America. *GSA Today*, *22*(10), 4–10. https://doi.org/10.1130/GSAT-G156A.1

Vence, E. M. (2008). Subsurface structure, stratigraphy and regional tectonic controls of the Guajira margin of northern Colombia. MSc Thesis, Univ. of Texas at Austin, pp. 128.

Vervoort, J., Patchett, P., Soderlund, U., & Baker, M. (2004). Isotopic composition of Yb and the determination of Lu concentrations and Lu/Hf ratios by isotope dilution using MC-ICPMS. *Geochemistry, Geophysics, Geosystems*, *5*, Q11002. https://doi.org/10.1029/2004GC000721

Villagómez, D., Spikings, R., Magna, T., Kammer, A., Winkler, W., & Beltrán, A. (2011). Geochronology, geochemistry and tectonic evolution of the Western and Central Cordilleras of Colombia. *Lithos*, *125*(3–4), 875–896. https://doi.org/10.1016/j.lithos.2011.05.003

Villagómez, D., Spikings, R., Mora, A., Guzmán, G., Ojeda, G., Cortés, E., & van der Lelij, R. (2011). Vertical tectonics at a continental crust-oceanic plateau plate boundary zone: Fission track thermochronology of the Sierra Nevada de Santa Marta, Colombia. *Tectonics*, *30*, TC4004. https://doi.org/10.1029/2010TC002835

Villamil, T. (1999). Campanian–Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *153*(1–4), 239–275. https://doi.org/10.1016/S0031-0182(99)00075-9

Vinasco, C. J., Cordani, U., Gonzalez, H., Weber, M., & Pelaez, C. (2006). Geochronological, isotopic, and geochemical data from Permo-Triassic granitic gneisses and granitoids of the Colombian Central Andes. *Journal of South American Earth Sciences*, *21*(4), 355–371. https://doi.org/10.1016/j.jsames.2006.07.007

Weber, M., Cardona, A., Valencia, V., García-Casco, A., Tobón, M., & Zapata, S. (2010). U/Pb detrital zircon provenance from Late Cretaceous metamorphic units of the Guajira Peninsula, Colombia: Tectonic implications on the collision between the Caribbean arc and the South American margin. *Journal of South American Earth Sciences*, *29*(4), 805–816. https://doi.org/10.1016/j.jsames.2009.10.004

Weber, M., Gómez-Tapias, J., Cardona, A., Duarte, E., Pardo, A., & Valencia, V. (2015). Geochemistry of the Santa Fé batholith and Buriticá Tonalite in NW Colombia—Evidence of subduction initiation beneath the Colombian Caribbean Plateau. *Journal of South American Earth Sciences*, *62*, 257–274. https://doi.org/10.1016/j.jsames.2015.04.002

Woodhead, J. D., & Hergt, J. M. (2005). A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. *Geostandards and Geoanalytical Research*, *29*(2), 183–195. https://doi.org/10.1111/j.1751-908X.2005.tb00891.x

Zachos, J., Pagani, M., Sloan, L. C., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, *292*(5517), 686–693. https://doi.org/10.1126/science.1059412

Zarifi, Z., Havskov, J., & Hanyga, A. (2007). An insight into the Bucaramanga nest. *Tectonophysics*, *443*(1–2), 93–105. https://doi.org/10.1016/j.tecto.2007.06.004