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Research paper

Controls on forearc basin formation and evolution: Insights from Oligocene to Recent tectono-stratigraphy of the Lower Magdalena Valley basin of northwest Colombia

J. Alejandro Mora[a,*], Onno Oncken[b], Eline Le Breton[c], Andrés Mora[d], Gabriel Veloza[a], Vickye Vélez[a], Mario de Freitas[e]

[a] Hocol S.A., Cra 7 No. 113-43, 16th Floor, Bogotá, Colombia
[b] Deutsches GeoForschungsZentrum GFZ, Telegrafenberg 14473, Potsdam, Germany
[c] Institute of Geological Sciences, Freie Universität Berlin, Malteserstraβe 74-100, 12249, Berlin, Germany
[d] Exploration Vicepresidency, Ecopetrol, Bogotá, Colombia
[e] Caravela Energy, Bogotá, Colombia

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ABSTRACT

Mechanisms of forearc basin evolution remain not very well understood, mostly because of insufficient resolution of their temporal evolution and potential drivers. The convergent margin of northwest Colombia where the San Jacinto and Lower Magdalena Valley forearc basins are located, offers a unique opportunity to study such mechanisms. The formation of the Lower Magdalena amagmatic, forearc basin occurred in a stable setting from the Oligocene to the present, characterized by the slow and nearly orthogonal, low-angle subduction of the Caribbean plateau. We use an exceptional regional database to reconstruct the subsidence, extension, sedimentation and paleo-geographic history of the Lower Magdalena forearc basin. We propose possible mechanisms controlling its evolution, in the absence of major changes in plate kinematics and in a low-angle subduction setting. Following the collapse of a pre-Oligocene magmatic arc, late Oligocene to early Miocene fault-controlled subsidence allowed initial basin fill at relatively low sedimentation rates. After the connection of the Lower and Middle Magdalena valleys, the proto-Magdalena river in the north and the proto-Cauca river in the south both started delivering high amounts of sediments in middle Miocene times. Fault controlled subsidence was gradually replaced by subsidence due to increased sedimentary load. Increase in sediment flux would have also caused the formation of an accretionary prism, weakened the plate interface through lubrication with fluid-rich sediment and initiated underplating, with the development of forearc highs in the San Jacinto area. Inherited basement structures allowed the tectonic segmentation of the basin with the formation its two depocenters (Plato and San Jorge). Our results highlight the fundamental role of sediment flux, of the basement structure and of flat subduction on the evolution of forearc basins such as the Lower Magdalena.

1. Introduction

The privileged location of forearc basins makes them suitable for providing unique insights into subduction zone dynamics. Previous research shows that mechanisms of forearc basin formation remain not very well understood, including subsidence mechanisms (Fuller et al., 2006; Noda, 2016). However, among the proposed mechanisms, previous researchers have highlighted the fundamental role that sediment flux plays on forearc evolution (Dickinson and Seely, 1979; Noda, 2016). According to Dickinson and Seely (1979), a prime factor governing forearc evolution is the quantity of sediment delivered to the forearc region, and large-scale lateral accretion can occur only if there are large quantities of trench-fill, abyssal-plain and/or slope sediments. Noda (2016) states that an increase or decrease of the sediment flux may change the type, geometry and deformation manner of the forearc basin. Furthermore, the same author also concludes that changes of the sediment flux and configuration of the subducting plate (i.e. direction, dip, velocity and roughness) can affect the condition of accretion or erosion in the outer wedge, as well as the style of deposition in the forearc basin. Nevertheless, there are only few cases (e.g. Xigaze basin, Wang et al., 2017) in which high-resolution data is available in order to analyze forearc sedimentation and to provide robust forearc

* Corresponding author.
E-mail address: alejandro.mora@hocol.com.co (J.A. Mora).

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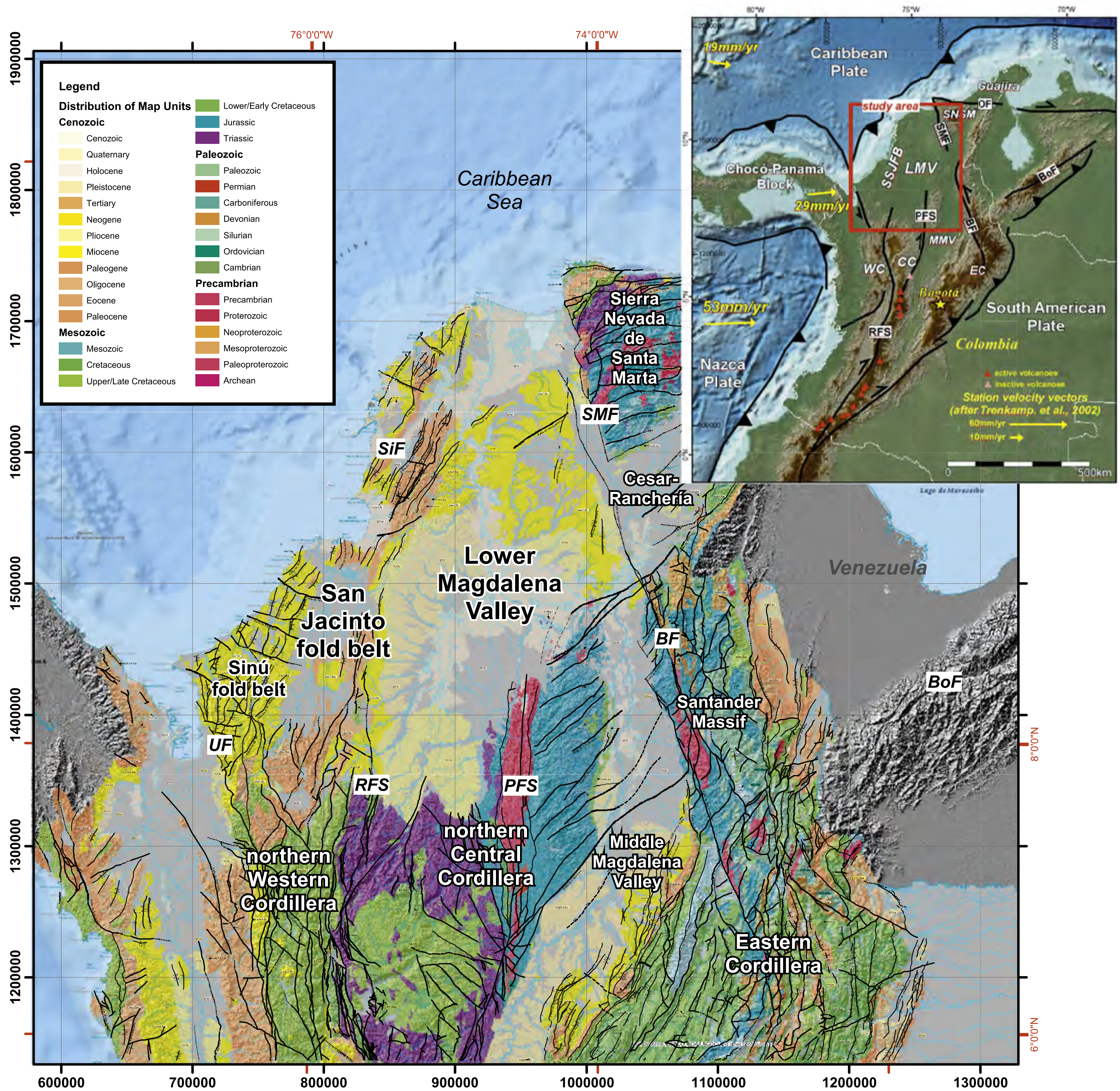

Fig. 1. Geological map of the Lower Magdalena and San Jacinto fold belt, highlighting major structural and morphologic features. RFS: Romeral Fault System; PFS: Palestina Fault System; SiF: Sinu Fault; BF: Bucaramanga Fault; SMF: Santa Marta Fault; OF: Oca Fault; UF: Uramita Fault; BoF: Bocono Fault. Geology after Gomez et al. (2015). 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. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

evolutionary models.

In this study we used a regional, reflection-seismic and well database from the Oligocene to Recent, Lower Magdalena Valley basin (LMV) of northwestern Colombia (Fig. 1) to reconstruct the sedimentary infill and tectono-stratigraphic evolution of the LMV, including estimates of subsidence (total vs tectonic) and extension, and timing of kinematic regimes and shortening/extension events. After Duque-Caro (1979) proposed his accretionary model, there have been several quite contrasting basin formation and evolution proposals for the Lower Magdalena Valley basin. These included a foreland basin setting (Macellari, 1995), backarc (Flinch, 2003), transrotational (Reyes-Harker et al., 2000; Montes et al., 2010) and forearc (Ladd et al., 1984; Mantilla et al., 2009; Bernal et al., 2015a,b,c). Due to the low seismicity and lack of magmatism, a passive margin origin has even been proposed for the LMV and San Jacinto (Rosello and Cossey, 2012), while other researchers (Ardila and Díaz, 2015) consider that the Colombia Caribbean margin developed under a transpressive regime in a tectonic setting dominated by oblique terrane accretion. Compilation and analyses of previous research (Mantilla, 2009; Bernal et al., 2015a,b,c), plus the results of our own research point towards the formation and

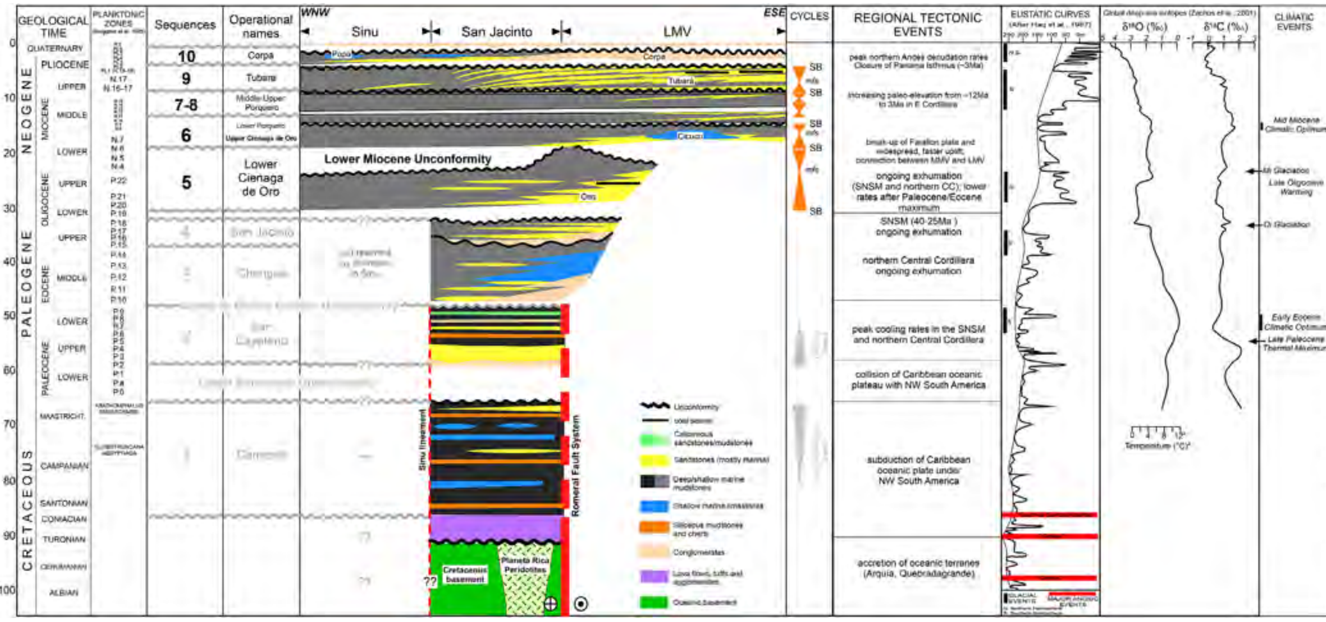

Fig. 2. WNW-ESE-trending chronostratigraphic chart of the Sinú, San Jacinto and Lower Magdalena areas, based on different sources (Hocol, 1993; Reyes-Harker et al., 2000; Guzman, 2007) and adjusted with our recent analyses of well and outcrop samples. Biostratigraphy is based on numerous papers and industry reports by Duque-Caro (1979, 1984, 1991, 2000, 2001, 2010, 2011a,b,c, 2012a,b, 2013a,b, 2014), tectonic events are after Villagómez et al. (2011a,b), Parra et al. (2012), Saylor et al. (2012), Mora et al. (2013a,b), Caballero et al. (2013a,b), Mora et al. (2015), 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). SB: Sequence boundary; mfs: maximum flooding surface. Modified from Mora et al. (2017b).

evolution of the LMV and San Jacinto fold belt (SJFB) in a forearc setting, as will be discussed here.

The objective of this contribution is to propose mechanisms that possibly controlled the evolution of the Lower Magdalena Valley forearc basin. Though the basin evolution has been previously studied, (e.g. Bernal et al., 2015c), our oil and gas industry database has allowed us to produce higher resolution reconstructions that improve the opportunities to test contrasting basin evolution hypotheses. By integrating recent results from the basement study by Mora et al. (2017a), we propose that basement structure played an important role in the formation and evolution of the LMV. Furthermore, our analyses of sedimentation rates allowed us to relate the increased sediment supply to underplating and the formation of forearc highs in San Jacinto. Through paleo-tectonic reconstructions, we studied the subduction parameters (convergence velocity and obliquity) since Oligocene times and compared the plate tectonic evolution with the basin tectono-stratigraphy. While the integration of recent biostratigraphy data provides a more precise timing of tectonic and paleogeographic events, our detailed sedimentary facies and provenance analyses also provide a stronger link between the evolution of the surrounding mountain ranges (e.g Eastern, Central and Western Cordilleras, Sierra Nevada de Santa Marta), the main drainage systems (Magdalena and Cauca) and the evolution of the LMV. Our results suggest that sediment flux, basement structure and flat subduction were the main mechanisms that controlled the formation and Oligocene to Recent evolution of the Lower Magdalena Valley basin and San Jacinto fold belt, in the absence of major variations in the plate tectonic regime.

2. Geological framework

2.1. Tectonic setting

The LMV of northwestern Colombia is located in an area in which the Caribbean oceanic plate, including the Chocó -Panamá block, and the South American continental plate have been interacting throughout the Cenozoic (Fig. 1). GPS data (e.g. Müller et al., 1999; Trenkamp et al., 2002) have shown that NW South America and the Caribbean have been converging in a nearly orthogonal fashion since Oligocene times, and that they continue to do so today (Symithe et al., 2015). Recent gravity modeling and seismic tomography (Mantilla, 2007; Mantilla et al., 2009; Bernal et al., 2015a,b), support a shallow subduction. According to this and in spite of lacking a magmatic arc, the basin has been interpreted as making part of a subduction complex (Mantilla et al., 2009) which includes an accretionary prism (Sinú) and a forearc high (San Jacinto) to the W. Mora et al. (2017a,b) proposed that the Caribbean oceanic plate is being subducted under the SJFB and LMV at a very low angle, dipping 5–9° to the SE, in agreement with Bernal et al. (2015a). Using the data presented by Mora et al. (2017b, Table 2), it appears that the western and central flat slab segments described in that paper entered the trench in Oligocene times, hence the sedimentary infill of the LMV occurred in a low-angle subduction setting.

The LMV is a lozenge-shaped basin, covering an area of 42,000 km^2 and located between two major basement terranes, the northern Central Cordillera (CC) in the S and SE and the Sierra Nevada de Santa Marta (SNSM) in the NE (Fig. 1). The Santa Marta left-lateral, strike-slip fault system is separating the northeastern part of the basin from the SNSM, while the northern extension of the Romeral Fault System (RFS) is separating the Lower Magdalena from the San Jacinto fold belt to the west. Pre-Oligocene sedimentary units are exposed in the SJFB, which has been considered the northward extension of the Western Cordillera of Colombia (Barrero et al., 1969; Duque-Caro, 1984; Cediel et al., 2003) and has been related to an oceanic to transitional-type basement (Duque-Caro, 1979; Cerón et al., 2007). The RFS, which is also considered to continue to the north to form the western boundary of the LMV, 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., 2017a). In the SJFB, located 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; Mora et al., 2017b). By contrast, Oligocene to Recent units that have been mostly eroded in the SJFB, are well preserved in the LMV and they are the focus of the tectono-stratigraphic analysis performed in this study.

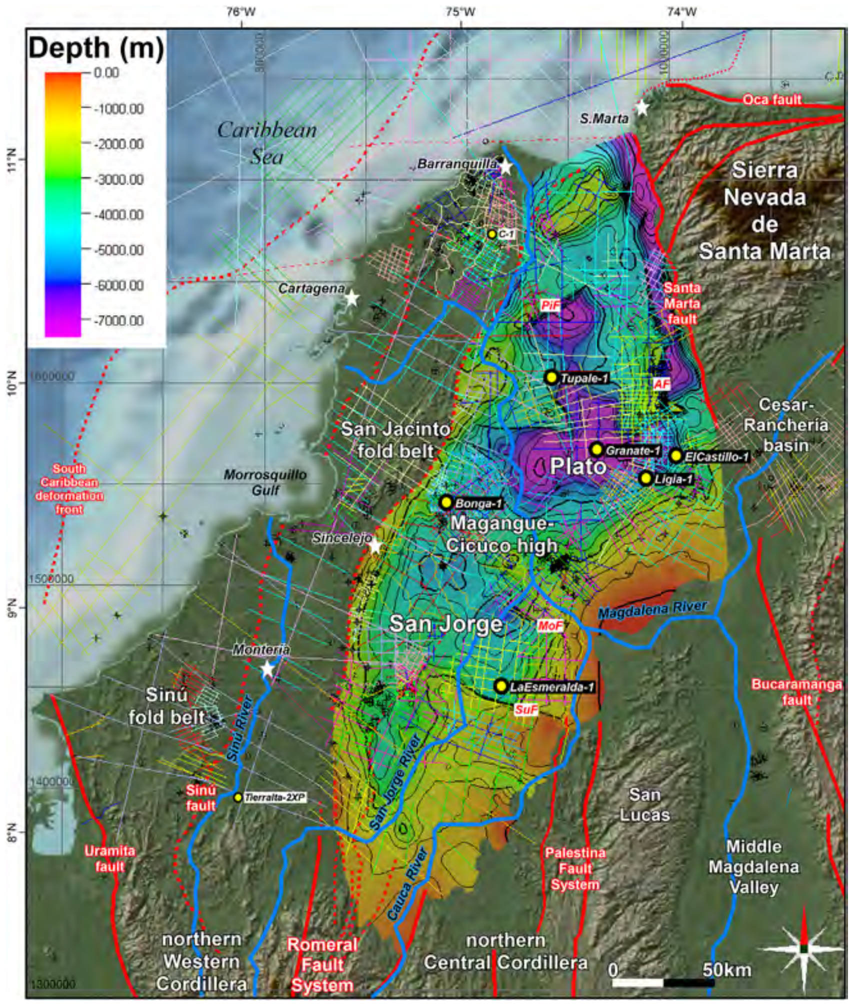

Fig. 3. Reflection seismic and well database used for this study, provided by Hocol S.A. Colors of seismic lines represent different seismic surveys. Topography and main drainages are also shown, as well as the structural map in depth of the basement under the LMV (after Mora et al., 2017a). Main wells used in this study for subsidence and sedimentation analyses are highlighted (black label: wells in LMV; white label: wells in SJFB). SuF: Sucre Fault; MoF: Mojana Fault; PiF: Pivijay Fault; AlF: Algarrobo Fault. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.2. The basement of the LMV

The basement under the LMV is considered the extension of the basement terranes that outcrop in the northern CC and consists of a core of Permo-Triassic metamorphic and igneous rocks, which were intruded by Upper Cretaceous granitoids (Montes et al., 2010; Silva et al., 2016; Mora et al., 2017a). However, the existence of an oceanic affinity terrane in the basement of the western LMV was recently proposed, based on Hf isotope geochemistry of an Upper Cretaceous pluton (Bonga pluton, Mora et al., 2017a). In terms of fabrics, the basement of the LMV comprises extensional faults with two predominant orientations, a main SE-NW trend in the western half of the basin and a secondary SW-NE trend in the northeastern part (Bernal et al., 2015c; Mora et al., 2017a). The basement structure was subdivided into four main fault families, which were studied by Mora et al. (2017a; Fig. S1). Such structural grain was formed by several mechanisms including the Romeral and Palestina dextral strike-slip displacement, Jurassic rifting and Late Cretaceous to Eocene forearc extension due to oblique convergence (Mora et al., 2017a). The extensional reactivation of the pre-existing basement fabric was crucial for the subsidence and sedimentation history of the LMV basin.

2.3. Upper Cretaceous to Lower Oligocene units in the SJFB

The SJFB records the existence of a Late Cretaceous to Early Eocene forearc basin, which was inverted in early to middle Eocene times and was then covered and sealed by middle Eocene to lower Oligocene units (Fig. 2 and Mora et al., 2017b). These authors divided the sedimentary succession in the SJFB into four tectono-stratigraphic sequences, bounded by regional unconformities, which are related to major tectonic events. The two oldest Upper Cretaceous to lower Eocene sequences (Sequence 1, Cansona and Sequence 2, San Cayetano) are preserved mainly to the west of the RFS, while the younger middle Eocene to lower Oligocene sequences (3 and 4, Chengue and San Jacinto) sealed the RFS as they extended farther to the east, into the western LMV, except for local Neogene to Quaternary reactivations.

2.4. Upper Oligocene to recent units in the LMV

The Oligocene to Recent stratigraphic succession in the basin has been mostly studied in drill holes and outcrops located in the western part, towards the SJFB (Fig. 1). It comprises a mainly fine-grained, marine succession in which several unconformities have been

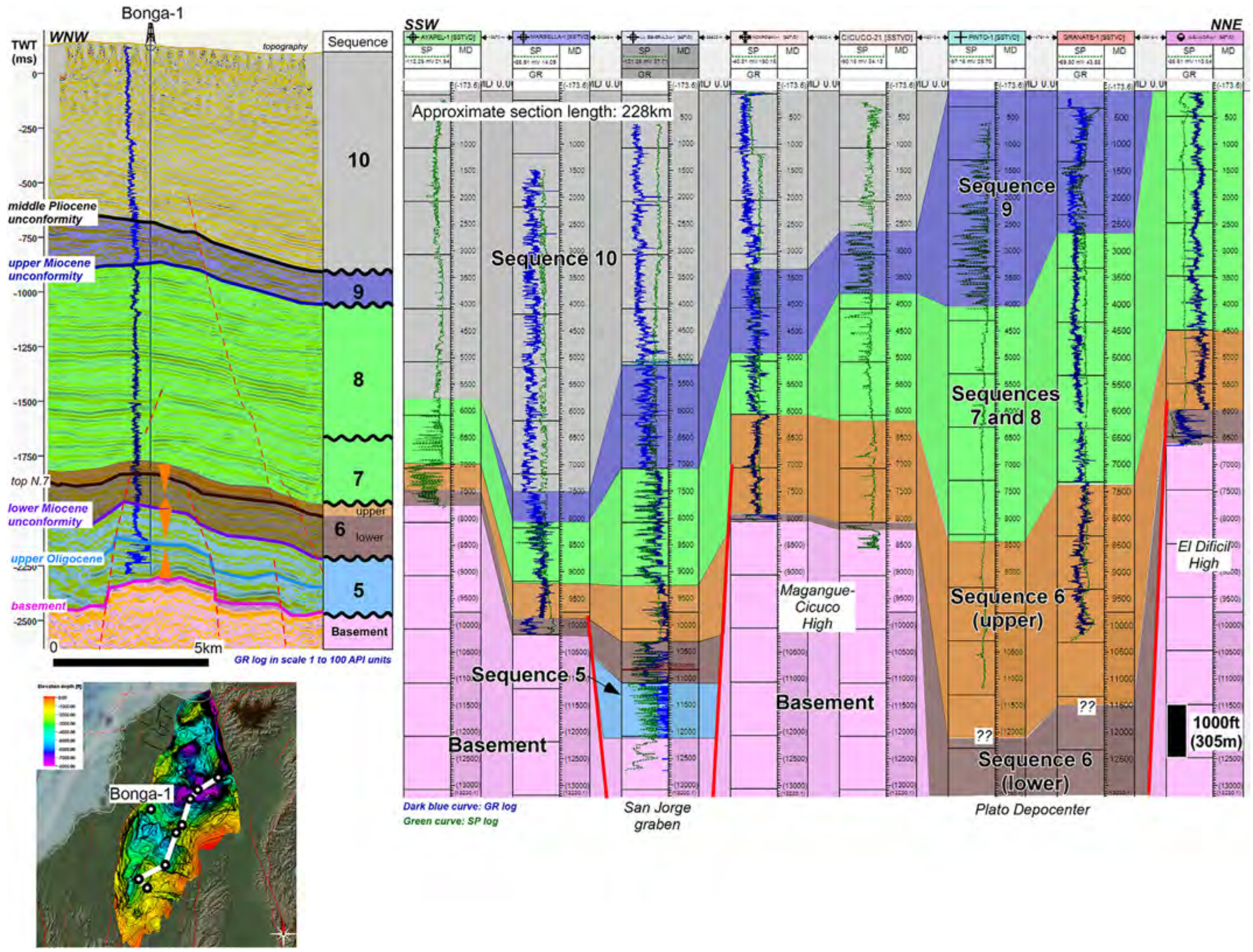

Fig. 4. Example of a well-seismic tie (left) and a regional, NNE-SSW-trending well correlation (right) in the LMV. The left panel shows the tie of the Bonga-1 well with the closest seismic line, displaying the interpreted horizons and the main stratigraphic sequences; the regional well correlation in the right panel shows the electrical facies of the studied sequences and the thickness variations. Main faults are shown as red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

identified, allowing its separation into different stratigraphic sequences (Fig. 2). The stratigraphy of the area has been studied previously by several researchers (Duque-Caro, 1972, 1979; 1984, 1991; Duque-Caro et al., 1996; Reyes-Harker et al., 2000; Guzman et al., 2004; Guzman, 2007: Bermudez, 2016), but the abundance of lithostratigraphic names has hampered a better understanding of the stratigraphic evolution of the area. For that reason, in this study we based our tectono-stratigraphic framework on the available biostratigraphic data (both published and from internal reports), tied to the reflection-seismic and drillhole data. We follow the sequence numbering proposed by Mora et al. (2017b) and propose correlations of our sequences with the most widely used lithostratigraphic and operational names (Fig. 2). According to Montes et al. (2010), the succession consists, from bottom to top, of longitudinal bars laterally adjacent to delta plain deposits, sheltered bays or lagoons near a muddy delta mouth and tidal flats and tidal channel deposits.

3. Methodology

3.1. Construction of the tectono-stratigraphic framework and paleogeographic maps

We used a regional database provided by Hocol S.A. for the construction of the tectono-stratigraphic framework of the LMV (Fig. 3), and followed the typical oil and gas industry workflow for seismic interpretation, mapping and well correlations (Figs. 4–7 and Table 1; procedure described in detail in Supplementary Text 1). The integration of seismic and well data with the published outcrop studies from the eastern SJFB (e.g. Guzman et al., 2004; Guzman, 2007; ANH-Universidad Nacional, 2009) allowed the construction of paleogeographic maps for selected time windows (Figs. 8 and 9). Structural mapping was complemented by the detailed analysis of growth strata in order to define the timing of the activity of the major faults and thus, to define the Oligocene to Recent kinematic history for the basin.

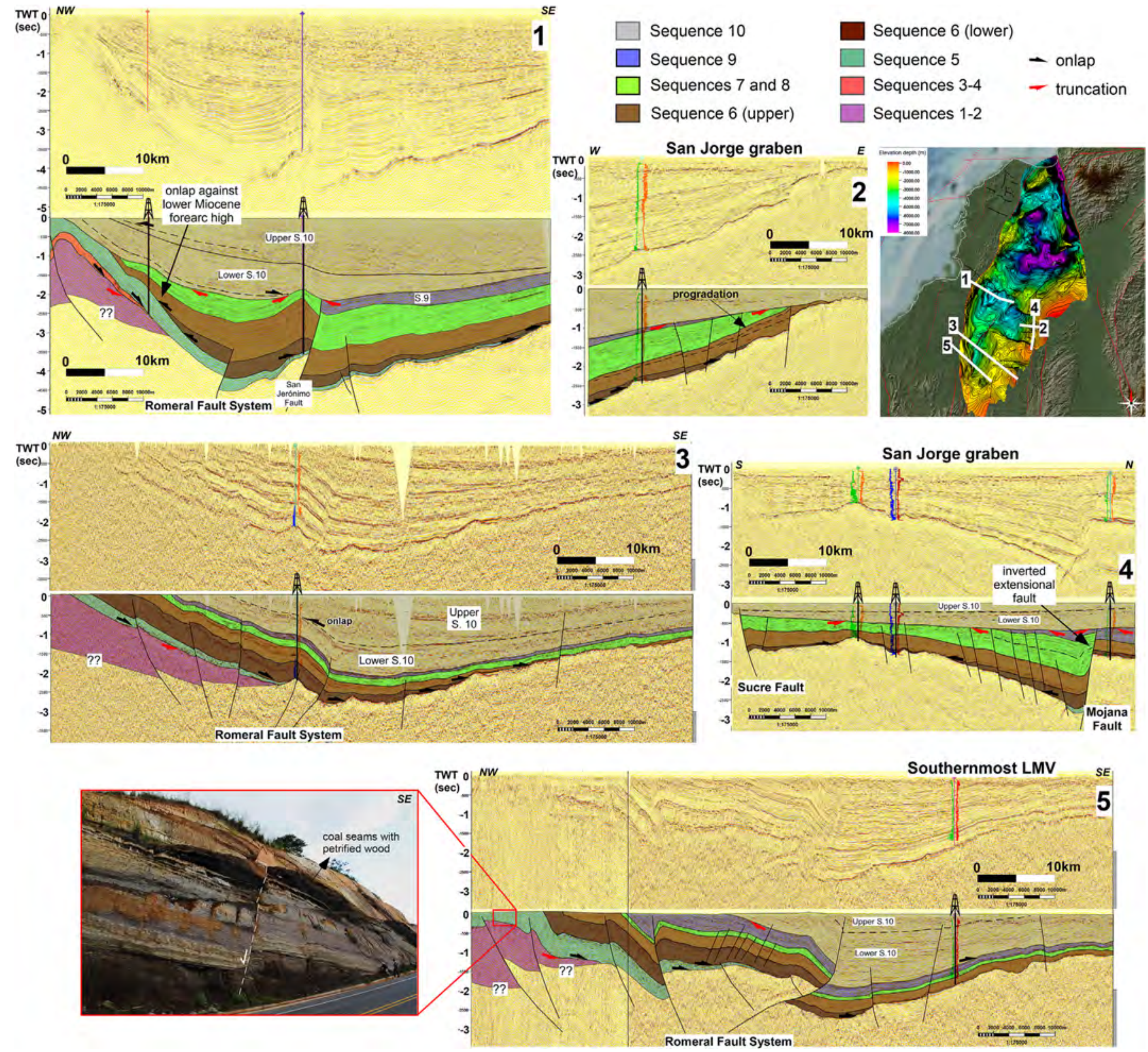

Fig. 5. Selected seismic sections from the southern LMV, showing the well ties and the seismic stratigraphic characteristics, depositional patterns and thicknesses of the Oligocene to Quaternary sequences. The onlapping pattern to the SE of sequences 5 and 6 (sections 1, 3 and 5) and the fault-controlled deposition of sequences 5 to 7 in the San Jorge graben (section 4) are illustrated. Evidence of a lower Miocene paleohigh is depicted in Section 1, with the interpreted onlap to the NW of sequences 6 to 8, while Section 2 displays the progradation of sequences 6 to 8 in the San Jorge graben. Section 3 also shows the onlap to the NW of the upper part of Sequence 10, indicative of the uplift of the SJFB. A photo of an outcrop of deltaic, coal-bearing strata of Sequence 5, affected by extensional faulting and located in the southernmost LMV, is also shown.

3.2. Subsidence history, extension and shortening in the LMV

Using the GPlates open access software, we carried out paleo-tectonic reconstructions to illustrate the relative displacement of the Caribbean plate relative ro stable South America (Fig. 10). Tectonic plate convergence velocities and obliquities since the Oligocene (Fig. 11) were estimated from available tectonic models (Boschman et al., 2014; Matthews et al., 2016), for correlation with subsidence patterns, sedimentation rates and the main regional Andean tectonic events. We carried out geohistory and subsidence analyses (Watts and Ryan, 1976; Steckler and Watts, 1978; Sclater and Christie, 1980; Allen and Allen, 2005) using available well data to estimate the amount of stretching (β-factor of McKenzie, 1978) in the LMV. We constructed a SSW-NNE-striking regional structural cross section along the LMV, perpendicular to the main structural fabric, along which we estimated the amount of crustal extension (Fig. 12). We calculated the crustal thickness without the sedimentary fill, as an alternative approach to calculate the amount of extension of the crust beneath the LMV.

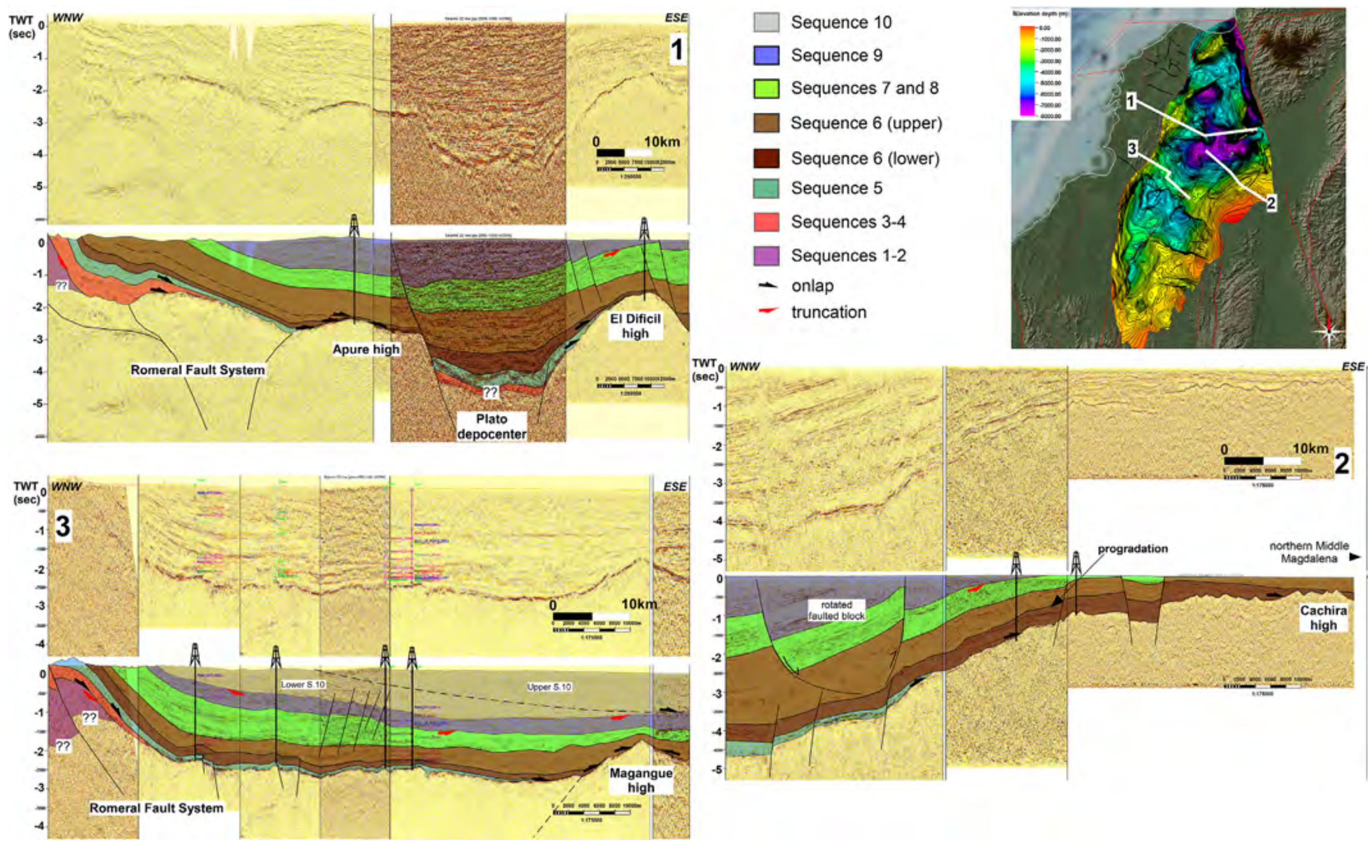

Fig. 6. Selected seismic sections from the Magangué-Cicuco high (section 3) and northern LMV (Plato depocenter), showing the well ties and the seismic stratigraphic characteristics, depositional patterns and thicknesses of the Oligocene to Quaternary sequences (5–10). The onlapping pattern to the SE and against basement highs (e.g. Apure, El Dificil and Magangue) is illustrated.

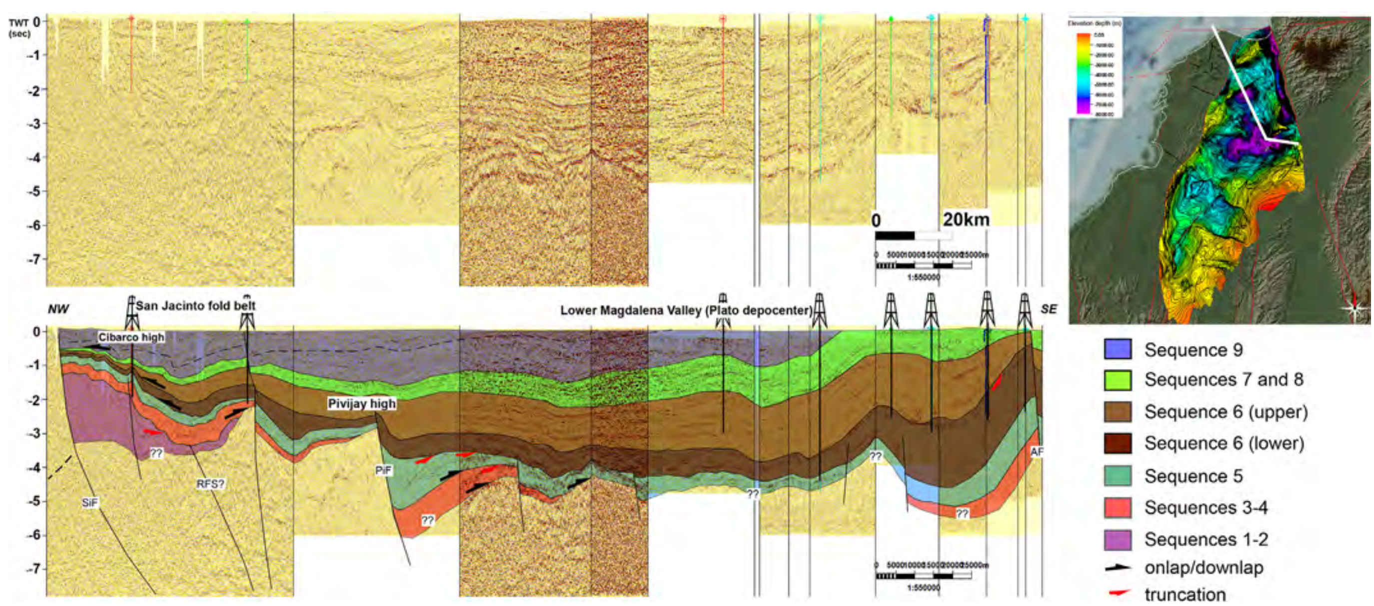

Fig. 7. Regional seismic section from the northern LMV (Plato depocenter), showing the well ties and the seismic stratigraphic characteristics, depositional patterns and thicknesses of the Oligocene to Quaternary sequences (5–10). Evidences of a Miocene paleohigh are the onlapping and downlapping patterns of low-angle clinoforms to the NW, in the area of the Cibarco high (buried San Jacinto fold belt). In the SE, the oldest sequences have not been drilled, so interpretation is based on seismic data, which has a poor image at deep levels. RFS: possible Romeral Fault System; SiF: Sinú Fault; AF: Algarrobo fault.

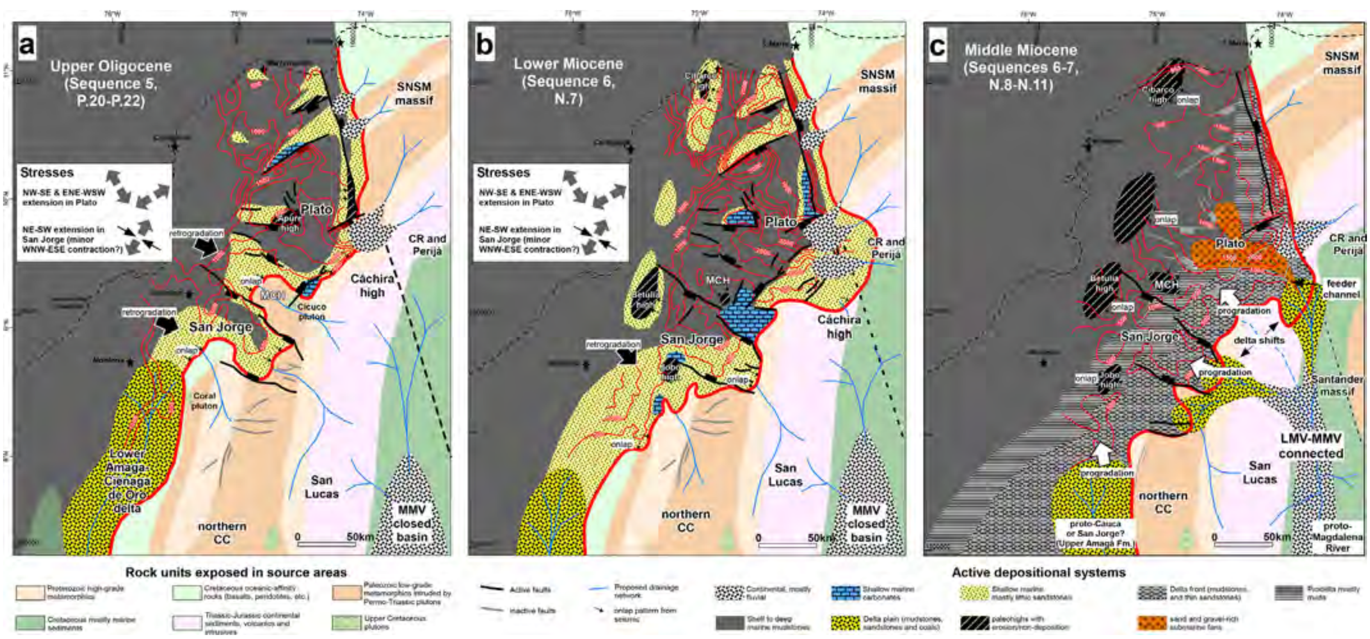

Fig. 8. Interpreted late Oligocene (a), early Miocene (b) and middle Miocene (c) paleogeography, based on regional seismic and well data interpretation, showing interpreted source areas (based on Mora et al., 2017a and others), active sedimentation areas and proposed paleo-drainages in blue; thin red contours are thicknesses in meters of each sequence and the thick red contour represents the interpreted limit of deposition of each sequence. Main stresses according to interpreted active faults are also depicted. The development of local paleohighs (e.g. Betulia, Jobo and Cibarco) in the present-day SJFB, as interpreted from seismic data, is also shown. CR: Cesar Ranchería; SNSM: Sierra Nevada de Santa Marta; CC: Central Cordillera; MMV: Middle Magdalena Valley basin. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

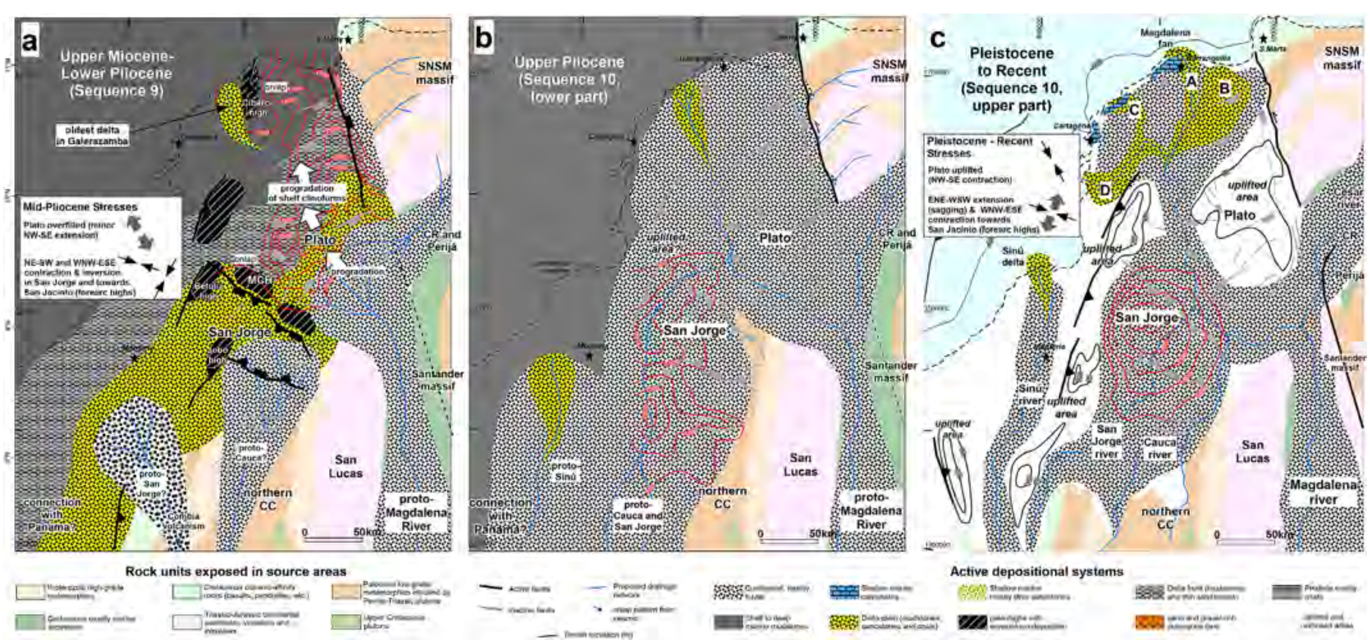

Fig. 9. Interpreted (a) late Miocene to early Pliocene, (b) late Pliocene and (c) Pleistocene to Recent paleogeography, based on regional seismic and well data interpretation, showing interpreted source areas (based on Mora et al., 2017a and others), active sedimentation areas and proposed paleo-drainages; lines, symbols and abbreviations as in Fig. 8. In (c), letters A to D represent positions of the Magdalena deltas (from Romero-Otero et al., 2015), with A representing the current position.

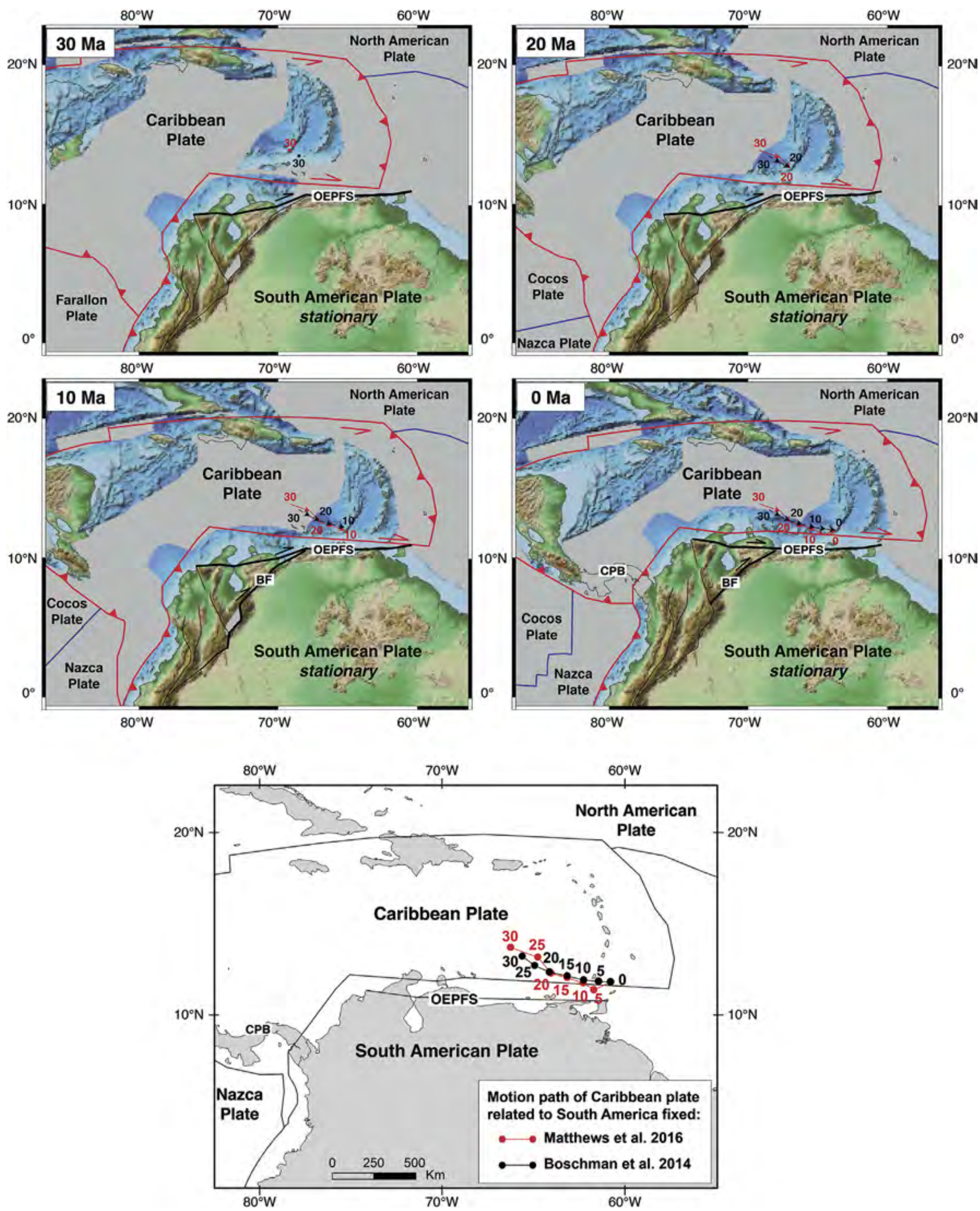

Fig. 10. Top, paleo-tectonic reconstructions at 30, 20, 10 and 0 Ma, illustrating the displacement of the Caribbean plate relative to fixed South America. The displacement vectors of the Caribbean plate relative to South America are shown in red arrows according to the model of Matthews et al. (2016, GPlates database) and in black dashed arrows according to Boschman et al. (2014). The plate boundaries (spreading ridges in blue, subduction and transform zones in red) and continent polygons are from Matthews et al. (2016). The main fault zones of NW South America are labelled and drawn in thick black lines when active. This reconstruction incorporates the "escape" of the northern Andes block along the Bocono Fault (BF) in both models. Bottom, motion paths of the Caribbean plates relative to South America according to the model of Matthews et al. (2016, GPlates database) in red and according to Boschman et al. (2014) in black. Both models shows that the overall displacement of the Caribbean plate relative to a stationary South American plate since Oligocene times is relatively stable and does not show major changes neither in convergence velocity nor in obliquity. OEPFS: Oca-El Pilar-San Sebastian Fault system. See the text for further discussion. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

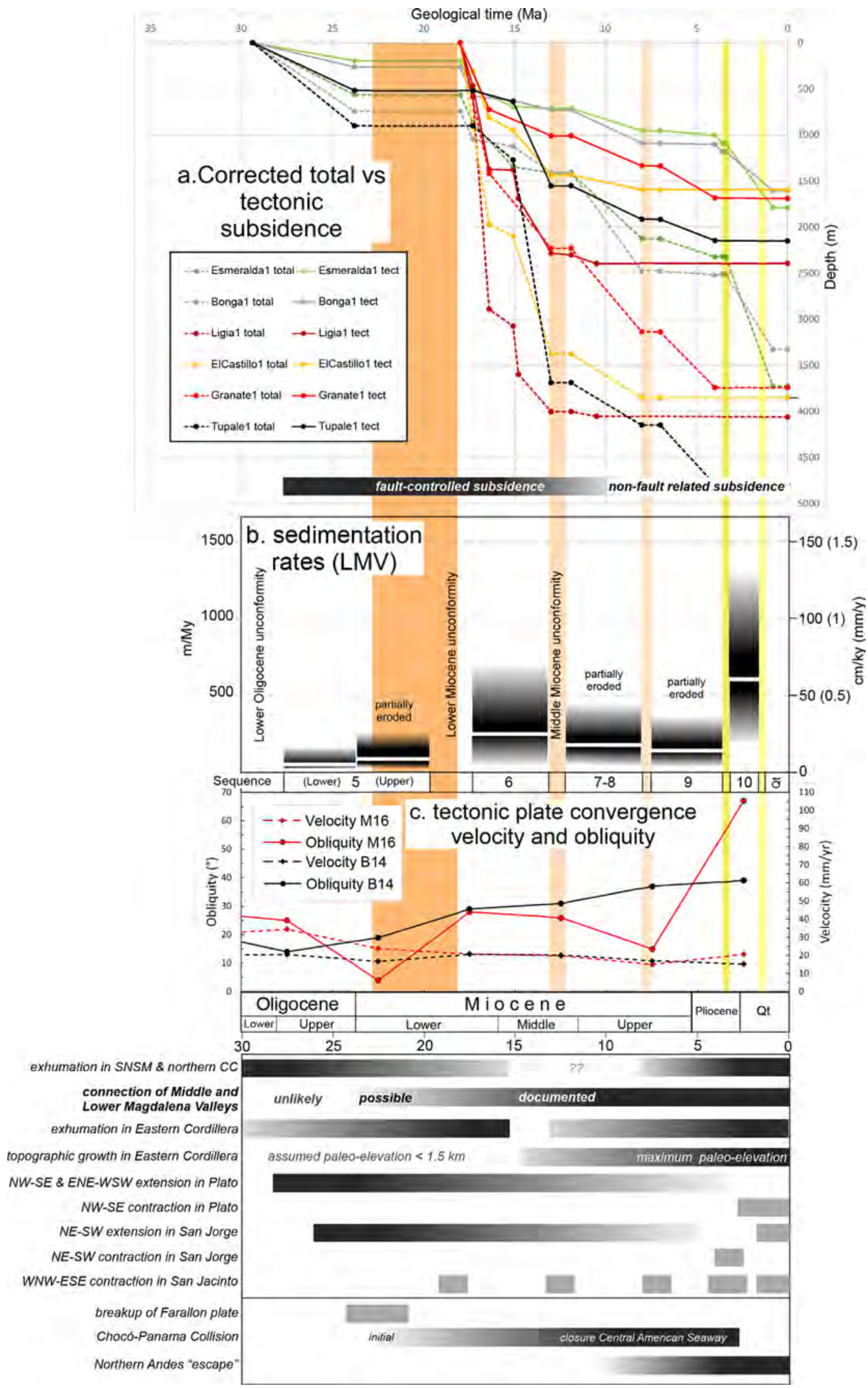

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Fig. 11. Integration of (a) subsidence (total vs tectonic), (b) sedimentation rate and (c) Oligocene to present day, tectonic plate convergence velocity and obliquity, compared with major tectonic events (colored vertical bars) and tectono-stratigraphic unconformities in the LMV. Tectonic (continuous lines) and total (dashed lines) subsidence plots of representative wells in the LMV and San Jacinto are displayed in (a). Sedimentation rates were estimated using compacted thicknesses and horizontal white lines in (b) represent average sedimentation rates; (c) displays the changes in plate convergence velocity and obliquity with time, for two different paleo-tectonic models (Boschman et al., 2014 in black, B14; Matthews et al., 2016 in red, M16), compared with the Oligocene to Quaternary tectono-stratigraphic sequences and unconformities (vertical bars of orange to yellow shades) and major tectonic events (black to grey horizontal bars in the lower panel). We calculated velocities and obliquities in time-steps of 5 Ma, hence the points in the convergence velocity and obliquity graph represent the middle of each time interval. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Thicknesses and ages from 32 wells drilled in the LMV and SJFB and 12 wells drilled in the Sinú onshore and offshore accretionary prism were compiled to calculate sedimentation rates and to carry out 1D subsidence analyses of the entire forearc area. We also used burial history charts from well data to study and illustrate the different subsidence and uplift (shortening) episodes in the LMV (Figs. 11 and 13 and Fig. S2). Further details of such procedures are included in Supplementary Text 1.

In this study, we followed three different approaches in order to obtain well-supported stretching and extension estimates for the lithosphere and crust, respectively, beneath the LMV. The first approach was to do a simple line-length calculation using a NNE-SSW-trending, depth-converted structural cross-section (Fig. 12), using the Move software of Midland Valley. The second approach was a backstripping technique assuming an Airy isostasy model and using sediment thickness data from the drill holes, in order to construct the total vs tectonic subsidence curves and to calculate corresponding stretching factors (β factor, McKenzie, 1978, Fig. 13a). The third approach was to compile crustal thickness and Moho depth data from NW Colombia (e.g. Poveda et al., 2015; Bernal et al., 2015a) and use our basin floor (basement) depth map to obtain the crustal thickness beneath the LMV, after removing the sedimentary infill (Fig. 13b–d) to deduce the amount of crustal extension beneath the LMV.

At this point we must highlight the advantages and limitations of each of those methods. The line-length measurement using the depth-converted structural cross-section, constructed from reflection-seismic data, is the method that involves more uncertainty for several reasons. Due to the resolution of the seismic data, extension caused by sub-seismic features is not taken into account. In second place, analysis along a 2-D section assumes plane strain, therefore neither oblique nor ductile deformation are taken into account. Furthermore, this approach assumes correct structural geometries, and final calculations are affected by depth conversion. For these reasons, the line-length balancing method considerably underestimates the obtained amounts of extension.

The prototype uniform stretching model of McKenzie (1978) involves assumptions such as uniform stretching with depth (pure shear), instantaneous initial stretch and the operation of Airy isostasy throughout, among others. However, observations in regions of continental extension suggested re-examination of the assumptions in the uniform stretching model, and modifications to the prototype model were proposed (Allen and Allen, 2005). The calculation of the amount of stretching (beta factor) based on the model of McKenzie (1978) is used in basins with a fast initial fault-related "syn-rift" subsidence (due to stretching of the lithosphere) followed by slower thermal "post-rift" subsidence (due to thermal cooling of the lithosphere; rift basins and passive margins). Therefore, the application of this methodology to basins which show different subsidence curves with several phases of increased tectonic subsidence, such as the LMV (Fig. 11a), can lead to an overestimation of the amount of stretching (beta-factor, Fig. 13a).

Although dynamic modeling is beyond the reach of this study, our extension estimates obtained by using the crustal thickness measurements and the basement depth maps are our best approximations to extension calculations, because they allow areal and volumetric balancing and they are independent of the limitations of the other two methods (line length and uniform stretching). In spite of having a very detailed basement map, an important limitation of this method is that the crustal thickness map is very generalized because it was obtained

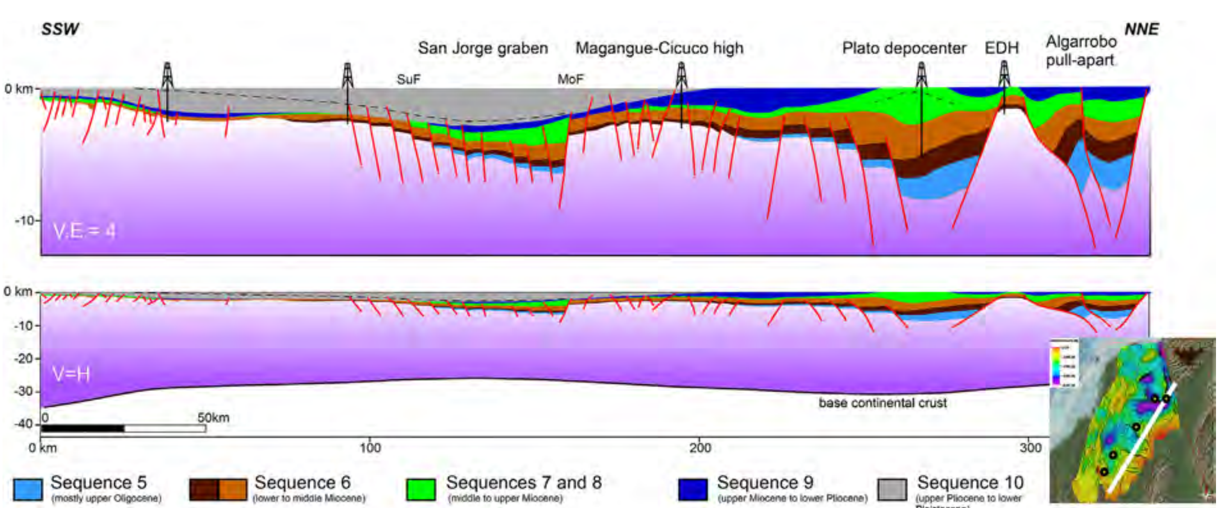

Fig. 12. Regional structural cross-section in depth (meters), in two different scales to show the stratigraphic relationships, thicknesses and preservation of the studied Oligocene to Quaternary sequences. The lower section (scale 1:1), also shows the base of the continental crust, based on data by Poveda et al. (2015) and Bernal et al., 2015a. EDH: El Dificil High; SuF: Sucre Fault; MoF: Mojana Fault. Dashed line in Sequence 10 represents clinoform progradation to the north while dashed line in green unit (sequences 7–8) represents thickening due to internal deformation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

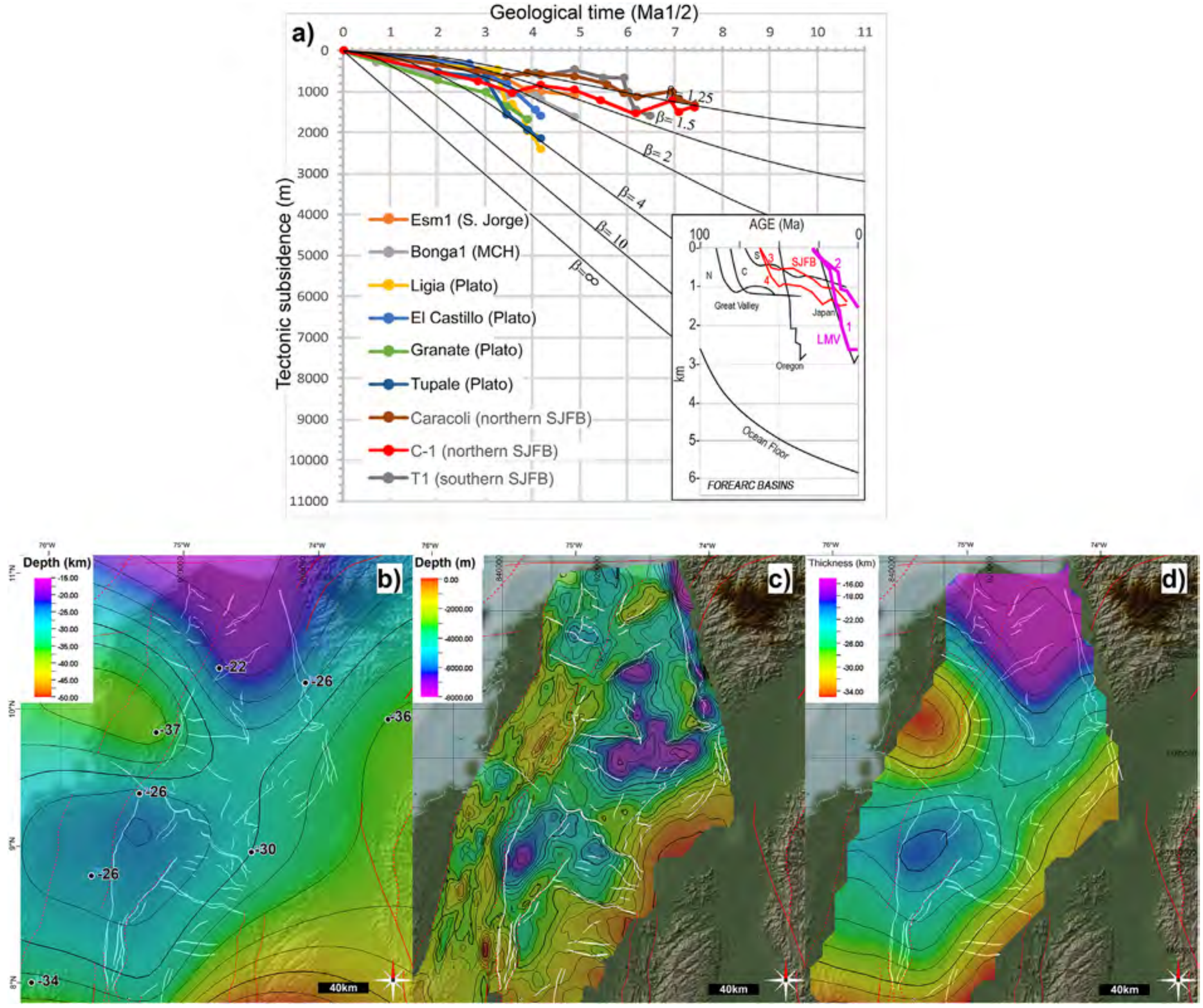

Fig. 13. (a) Tectonic subsidence data plotted against the square root of the geological time (time since end of extension), in order to estimate stretching in the LMV (β-factor; McKenzie, 1978). In most of the study area, β values range from 1.2 to 1.5, except for the Plato depocenter where they can be > 2, indicating that stretching is overestimated using this method. Inset shows a comparison of our tectonic subsidence curves for the LMV and SJFB with data from other forearc basins compiled by Angevine et al. (1990), showing a good correlation with some basins. 1. Northern LMV (Plato); 2. Southern LMV (San Jorge); 3. Southern San Jacinto; 4. Northern San Jacinto. MCH: Magangue-Cicuco high. (b) to (d), maps used to calculate extension in the LMV and SJFB. (b) Depth map of the Moho discontinuity, representing the crustal thickness, based on Poveda et al. (2015) and Bernal et al. (2015a), showing that the crust thickness ranges from 22 km in the northern LMV to > 30 km in the central and SW San Jacinto. Stations with measured values are depicted in black (values obtained from Bernal et al., 2015a were extrapolated as points from their regional gravity sections). (c) Basement map in depth (km) of the LMV, based on Mora et al., 2017a. d) Crustal thickness map without sedimentary infill, obtained by subtracting the basement map in (c) from the crustal map in (b). It must be noted that the thinner crust (< 20 km) in the NW of the LMV, where no thickness data is available, resulted from mapping extrapolation.

from data of only five stations for a receiver function approach (Poveda et al., 2015) and three cross-sections for the gravity modeling approach (Bernal et al., 2015a). There are also inherited uncertainties from each of these methods, which according to Poveda et al. (2015), would be in the order of 9 km in the Moho depth estimation, and 3–8% in thickness estimations. For the modeling of the gravity transects by Bernal et al. (2015a), the best-possible match between the calculated and observed gravity anomalies was obtained after varying the densities and geometries of pre-defined layers, but still some errors (2.27–4.38 km) are reported for such modeling.

4. Results

4.1. Stratigraphic and structural framework of the Lower Magdalena Valley basin

The pre-existing basement architecture played a crucial role in the Oligocene to Recent sedimentary evolution of the LMV, therefore we will build on the previous analyses and maps of Mora et al. (2017a,b) to study the structural and stratigraphic evolution of the basin. The main interpreted horizons are the top of the acoustic basement, the top of the upper Oligocene, the lower Miocene unconformity, the near top of the N.7 planktonic foraminifera zone (lower part of Sequence 6), the upper Miocene unconformity, the middle Pliocene unconformity, corresponding to the base of Sequence 10 (Fig. 4) and an intra-Sequence 10 reflector which does not appear in the area of the Bonga-1 well. Based on regional reflection-seismic and well data, six major Oligocene to Recent tectono-stratigraphic sequences, separated by major regional unconformities (depositional sequences sensu Catuneanu et al., 2009), were identified and defined in the LMV (Fig. 2). Numbering of the sequences starts from 5, considering that pre-Oligocene Sequences 1 to 4 were previously studied by Mora et al. (2017b) in the SJFB. The main characteristics of the studied sequences are summarized in Table 1 and a more detailed description of each sequence is found in Supplementary Text 1.

Table 1
Main characteristics of the studied Oligocene to Quaternary tectono-stratigraphic sequences in the LMV. More information, detailed descriptions and sources of biostratigraphic, petrographic and sedimentologic reports are found in Text S1.

Sequence	Lithostratigraphic and operational names	Planktonic foram zones (Berggren et al., 1995; Blow, 1969)	Age	Structural and thickness maps	Description	Kinematics	Subsidence and sedimentation in LMV
10	Corpa (Sincelejo,Betulia, Popa)	Pl.3 to Pl.6?	upper Pliocene to lower Pleistocene	Two main packages preserved in the southern LMV, the lower one is a SSW-NNE-trending elliptic depocenter and the upper one is a round depocenter on top of the San Jorge graben; total thickness close to 3 km.	In the southern LMV, corresponds to fluvio-deltaic, low-angle clinoforms prograding from S to N (paleo-Cauca deposits); in the NW SJFB, carbonates are preserved (Popa Fm.).	After Corpa deposition, NNW-SSE and SW-NE-trending extensional faults in Plato are inverted and older units are intensely eroded; onlap of the upper Corpa to the W indicates onset of recent uplift of the San Jacinto fold belt (~1.7 Ma?)	Non-fault related subsidence, much higher subsidence in San Jorge; high sedimentation rates (~500 m/My); uplift and inversion in Plato
unconformity			*middle Pliocene*				
9	Tubara (Cerrito, Zambrano)	N.17 (M.14) to Pl.2	upper Miocene to lower Pliocene	Overfilled the Plato depocenter and was highly eroded, first in the south and later in the north, where preserved thicknesses are > 2 km (Plato);	Sigmoidal, shelf margin clinoforms represent increased progradation to the NNW, of continental to shallow marine deposits of the proto-Magdalena river in the north (Plato)	After Tubara deposition, NW-SE and SW-NE-trending extensional faults in San Jorge are inverted and older units are partially eroded	Non-fault related subsidence, higher in Plato until depocenter is overfilled; low sedimentation rates (< 250 m/My, due to partial erosion)
unconformity		*absence of N.15 to N.16 (M.8 to M.9)*	*middle to upper Miocene*				
7 and 8	Middle-Upper Porquero (Mandatu, Hibacharo, Perdices, Jesus del Monte)	N.12 to N.16 (M.9-M.13)	middle to upper Miocene	Highly variable thickness due to variable preservation/erosion	Mostly fine-grained, thick deposits preserved mainly in depocenters	Less fault control, Algarrobo strike-slip fault and El Dificil fault active; local paleo-highs in San Jacinto (NW-SE contraction)	Subsidence with minor fault control, higher subsidence in Plato; low sedimentation rates (due to partial erosion)
unconformity		*absence of N.11 to N.12 (M.8 to M.9)*	*Middle Miocene*				
6	Upper Cienaga de Oro and Lower Porquero (Alférez)	N.7 to N.11 (M.4-M.8)	lower to middle Miocene	More widespread deposition focused also in topographic lows; average thickness is 400–600 m (1200–2000 ft)	Lower thin part is transgressive and onlaps the basement to the SE, while thicker upper part is progradational; Low areas were filled with clastic marine deposits while paleohighs were covered by carbonates	Active WNW-ESE-trending (Mojana, Sucre, Apure South) and SW-NE-trending (Pivijay, Pijiño, El Dificil South) extensional faults	Fault-controlled subsidence which tends to decrease with time; much higher sedimentation rates (60 to > 300 m/My)
unconformity		*absence of N.4 to N.6 (M.1 to M.3)*	*lower Miocene*				
5	Lower Cienaga de Oro (Carmen)	P.22 to N.6 (M.3)	lower Oligocene to lower Miocene	Gradually filled paleo-topographic basement lows from WNW to ESE; found at > 3.5 km in San Jorge graben and at > 5 km in Plato; thickest in the W towards the SJFB where > 1.5 km are preserved in local depocenters	Lower part shows an onlap pattern to the SE; interpreted as a retrogradational, transgressive package with a fining and deepening upwards pattern; transition from basal sandy, shallow marine facies to muddy, deeper marine facies. Upper muddy part has been mostly eroded	Active WNW-ESE-trending (Mojana, Sucre, Apure South) and SW-NE-trending (Pivijay, Pijiño, El Dificil South) extensional faults	Fault-controlled subsidence, low sedimentation rates (< 60 m/My) but would be higher due to erosion of upper part of the sequence

4.1.1. Sequence 5 (Oligocene to lower miocene)

While the upper part of Sequence 5 is not very well preserved due to erosion after the early Miocene unconformity, the lower part of the sequence is better preserved and displays an onlap pattern to the SE (Figs. 5 and 6). Seismic data shows that the Oligocene to lower Miocene deposits gradually filled the proto-San Jorge and Plato depocenters from the W and NW and that the main structural basement features, such as the Sucre, Mojana and Pivijay faults (two main fault families according to Mora et al., 2017a), were actively extending (Figs. 5–7; Fig. S1). Core analyses of the basal part of the sequence in the northwestern Magangué-Cicuco high (Salazar, 1993; Cross, 2014) show that it consists of highly bioturbated (*Cruziana* ichnofacies), sub-litharenites and subarkoses which were deposited in shallow marine, estuarine environments that show more proximal facies to the SE.

The best preserved, lower part of the sequence is interpreted as a retrogradational, transgressive package which records the advance of marine sedimentation from NW to SE and was deposited initially in shallow marine environments, which gradually changed to deeper marine and more anoxic environments (Fig. 8a). We interpret the Oligocene to lower Miocene deposits as a transgressive, 2nd-order sequence, which filled from NW to SE the lowest paleo-topographic areas formed by the basement of the LMV (Figs. 5 and 6, Table 1). Based on studies of planktonic foraminifera in wells and outcrops, this sequence, which is called “Lower Ciénaga de Oro”, has been associated to the planktonic zones P.20 to N.6 (M.3), equivalent to an early Oligocene to early Miocene age.

4.1.2. Sequence 6 (lower to middle miocene)

The lower part of this sequence, of latest Early Miocene age (planktonic zone N.7/M.4) consists of siliciclastic deposits which filled low areas (San Jorge and Plato depocenters) and calcareous deposits in the paleo-highs such as the eastern Magangué-Cicuco, El Difícil and Apure highs (Figs. 5–10). These deposits are clearly onlapping the basement farther towards the E, SE and S in the southern LMV (Fig. 5), where they have been studied in electrical logs and cores and are interpreted as shallow-marine retrogradational deposits of the transgressive systems tract of this sequence (Fig. 4). The upper part of this sequence consists of deltaic progradational deposits at San Jorge (e.g. section 2 in Fig. 5) and thicker, deeper marine progradational deposits in Plato, north of the Magangué-Cicuco high (Fig. 8c).

This sequence was deposited after a regional early Miocene tectonic event and biostratigraphic analyses indicate that it is a 3rd-order sequence of lower to middle Miocene age (Burdigalian to Serravalian, zones N.7/M.4 to N.11/M.8) (Figs. 5–7, Table 1). It displays the change from shallow marine deposits retrograding to the ESE, to deltaic to deep-marine deposits, which are prograding to the WNW. We thus consider that these early to middle Miocene (~17–14 Ma), marine packages, prograding to the WNW, are the first clear evidence of a connection with a new drainage system (proto-Magdalena river) supplying sediment from the ESE, as previously proposed by several researchers (e.g. Reyes-Santos et al., 2000; Bernal et al., 2015c). The two main extensional fault families described by Mora et al. (2017a; Fig. S1), which were actively extending since late Oligocene times, continued to be active but gradually decreased their activity through time (Figs. 5 and 6).

4.1.3. Sequences 7 and 8 (middle to upper miocene)

These sequences have been partially eroded in some areas and consist of a monotonous, fine-grained succession that has been poorly studied and characterized in wells in the LMV. In seismic data, they continue to display a progradational pattern to the NW. They have been called “Middle and Upper Porquero”, represent 3rd-order cycles of middle to upper Miocene age (Serravallian-Tortonian) and are limited by regional unconformities (Duque-Caro, 1979; Hocol, 1993; Duque-Caro et al., 1996; Reyes-Harker et al., 2000; Guzman, 2007).

4.1.4. Sequence 9 (upper miocene to lower Pliocene-Tubará)

Reflection-seismic data shows that this sequence, which is better preserved in the Plato depocenter, is composed of low-angle (0.3–0.6°) and wide (100–200 km) sigmoidal clinoforms which advanced from SSE to NNW, representing the gradual advance of the proto-Magdalena river. This 3rd-order sequence of upper Miocene to lower Pliocene age (zones N.17/M.14 to Pl.2 zones, Tortonian to Zanclean), represents the accelerated migration towards the NNW of shelf-edge clinoforms of the paleo-Magdalena river, which almost completely filled the Plato depocenter and reached the approximate position of the present-day coastline in early Pliocene times (Figs. 7 and 9a, Table 1).

4.1.5. Sequence 10 (upper pliocene to pleistocene)

This sequence, which has been very poorly studied and comprises several higher order sequences, represents renewed subsidence in the southern LMV, focused in the San Jorge graben where the thickest deposits occur (Fig. 5). It is well preserved in the southern LMV, south of the Magangué-Cicuco high, where it is called “Corpa”, while in the north, deposition appears to have been much thinner and the sedimentary record was eroded due to Pleistocene to recent deformation (Fig. 9b and c, Table 1). Taking into account the unconformities above Sequence 9 (the upper Miocene to lower Pliocene Tubará sequence), and below the upper Pleistocene to recent deposits, we infer here a late Pliocene to early Pleistocene age for Sequence 10, spanning from 3 to 1.3 Ma (3rd order cycle). We divided this sequence into two seismic packages (see Supplementary Text 1) and the area where the thickest deposits are preserved coincides with the structurally deepest area, which continues to subside today (Supplementary Fig. S3a). The expression of Sequence 10 in reflection-seismic data consists of low-angle clinoforms broadly prograding from South to North, which appear to represent the deposits of the paleo-Cauca drainage system, including fluvial channels, lakes and swamps (Figs. 9 and 12). The internal seismic-stratigraphic architecture of Sequence 10 (see onlap in section 3 of Fig. 5), reveals the time when the SJFB started to be uplifted, which appears to be close to the boundary between the Pliocene and Pleistocene.

4.2. SSW-NNE cross-section structure of the LMV

The LMV basement structure initially described by Reyes-Santos et al. (2000), has been recently described in more detail by Mora et al. (2017a), who subdivided the basement fabric in four main, extensional fault families (Fig. S1) and proposed tectonic mechanisms to explain their origin. Our seismic-stratigraphic analyses show that the two main families, trending ESE-WNW and ENE-WSW are responsible for most of the extension in the LMV, and they consist of nearly vertical extensional faults, which exhibit small heaves. They also show that deposition of the late Oligocene to early Miocene sequences (Sequences 5 and 6) had fault controlled, and that after the late Miocene, deposition was mainly due to sagging, giving rise to the classic Steer's Head model of basin geometry (Miall, 2000). This is illustrated in the regional cross-section (Fig. 12), where the majority of the extensional faults are displacing Sequences 5 to 8, with related thickness changes across the major faults. This style is very clear in the San Jorge graben of the southern LMV, which shows an asymmetric shape with thicker syntectonic deposits in the northern half of the graben, indicating that the northern Mojana fault experienced more displacement than the Sucre fault in the south (Fig. 5, section 4). By contrast, Sequences 9 and 10 filled broader depocenters in a uniform way, with only minor and localized fault displacements. The latest subsidence episode, which appears to continue active at the San Jorge graben, allowed the deposition of the very thick Pliocene to Pleistocene Sequence 10 (Corpa). Uplift and inversion in the Plato area to the north occurred probably shortly after the deposition of Sequence 10. The faults that exhibit the biggest heaves are related to the Santa Marta-Algarrobo fault system, which displays a listric style with mostly Neogene syntectonic strata and notorious fault-block rotation (Fig. 12).

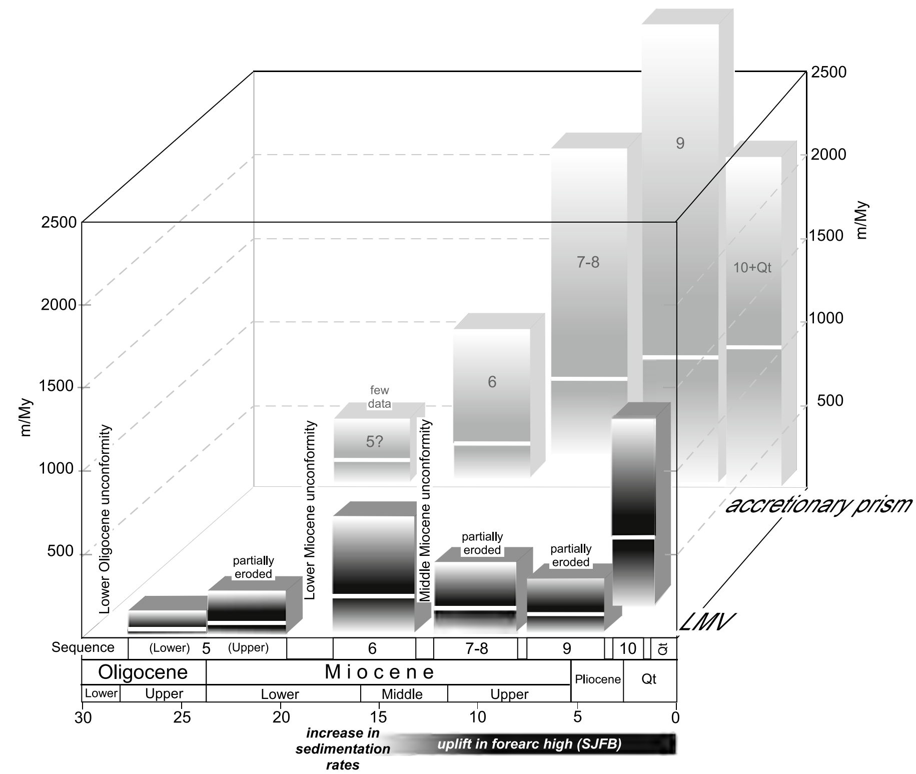

Fig. 14. Comparison of Oligocene to Recent, compacted sedimentation rates in the LMV and the accretionary prism (Sinú onshore and offshore) from well and seismic data. While there was partial erosion of middle and upper Miocene sequences in the LMV, very high sedimentation rates were measured in the accretionary prism for those sequences. The graph shows the proposed link between high sediment supply, sediment underplating and uplift in San Jacinto with the formation of forearc highs.

4.3. Sedimentation rates and subsidence in the LMV, San Jacinto and Sinú fold belts

Due to poor preservation of Oligocene to Recent deposits in the SJFB, analyses of sedimentation and subsidence rates are less reliable. In the LMV, where the succession is much more preserved, our analyses indicate that after the early Miocene tectonic event (see Text S1, description of Sequence 5), there was an increase in sedimentation and subsidence rates (panels a and b in Fig. 11 and Fig. S2). Though sedimentation rates were not corrected for compaction, the rates of the upper Oligocene to lower Miocene sequence (5) where lower than 60 m/My, though this number could be higher considering erosion of the upper part of the sequence (planktonic zones N.4/M.1 to N.6/M.3). By contrast, Sequence 6, deposited after an early Miocene unconformity, exhibits much higher sedimentation rates, generally above 60 m/My and locally exceeding 300 m/My, in some areas such as the Plato Depocenter. Sequences 7 to 9 appear to display lower sedimentation rates, generally less than 150 m/My, but considering the intense erosion suffered by these sequences, they probably also exhibited high sedimentation rates. Sequence 10 (Corpa), which is well preserved in the southern LMV, displays very high sedimentation rates, with an average of 530 m/My, exhibiting highest values in the Magangué-Cicuco high and in the western San Jorge depocenter. Our calculated sedimentation rates are in agreement with previous calculations by Molina (1978; in Reyes-Harker et al., 2000).

For the Sinú fold belt and other offshore areas, based on biostratigraphic reports by Duque-Caro (2000, 2001), we found that after middle Miocene times, there is a major increase in sedimentation, with rates in excess of 2000 m/My (Fig. 14). Though these rates are not corrected for compaction, they provide an idea for comparison with the sedimentation rates in the LMV.

Our estimates of corrected total and tectonic subsidence show important variations depending on the geographic location (Fig. 13). The highest subsidence estimates were obtained in the Plato depocenter where 4.8 km of total subsidence and 2.1 km of tectonic subsidence were calculated. However, the wells drilled in the central Plato depocenter did not drill the entire Cenozoic sequence. In the San Jorge graben, 3.7 km of total subsidence and 1.8 km of tectonic subsidence were calculated. An increase in tectonic subsidence after 18 Ma is followed by a general decrease after 13 Ma, except for the wells located in the SW (La Esmeralda and Bonga, Fig. 11a), where there's an increase in tectonic and total subsidence after 3 Ma.

4.4. Extension in the LMV

The simple line-length calculation along a SSW-NNE transect (Fig. 12) showed that the basement of the LMV has been extended 40.7 km (initial section length: 296.9 km; final length: 337.6 km), which represents 12% of extension or a stretching factor of 1.13. The Algarrobo listric fault system has been extended 26.7 km, accounting for 7% of the total extension, while the rest of the LMV including the Plato and San Jorge depocenters, experienced only 14 km of extension. This method however underestimates the total amount of extension as explained in section 3.2. According to the tectonic subsidence curves from wells located in the SJFB and in most of the LMV (except for the deep Plato depocenter), β values oscillate between 1.1 and 2, while in the deep parts of the Plato depocenter, β values range from 2 to 4, which are clearly overestimated.

Concerning the crustal thickness and Moho depth data, Poveda et al. (2015) used a receiver functions technique to obtain crustal thicknesses ranging from 26 km in the Montería area, to 50 km in the southeastern boundary of the basin against the northern Central Cordillera (Fig. 13b). Bernal et al. (2015a) reported Moho depths from gravity modeling which range from 24 km in the north of the LMV to 36 km in the south (Fig. 13b). As shown by Mora et al. (2017a), the basement beneath the LMV reaches depths of 8 km in the Plato depocenter and 6–7 km in the San Jorge graben (Fig. 13c). Removal of the sedimentary fill suggests that the crust is thinnest in the northern part of the basin where the sedimentary infill is very thick and where Bernal et al. (2015a) report crustal thicknesses close to 24 km (Fig. 13d). A thin crust was also measured in the western San Jorge depocenter (~20 km), based on the data by Poveda et al. (2015), who also measured the highest thicknesses in the northern SJFB (37 km).

Crustal thickness calculations in northern Colombia (Poveda et al., 2012) suggest that the continental crustal thickness in relatively undeformed areas such as the Middle Magdalena Valley basin ranges from 40 to 45 km. Furthermore, the weighted average thickness of the continental South American crust is 38.17 km (Chulick et al., 2013), whereas the crust in stable continental areas of Brazil has an average thickness of 39 ± 5 km and 35 km in subandean foredeeps (Assumpção et al., 2013). Therefore, if we assume an initial crustal thickness in the LMV area of 40 km and our present-day crustal thickness map (Fig. 13d), crustal thinning would be of more than 50% (β = 2) in the northwestern Plato depocenter and around 50% in the Montería-San Jorge graben area, while in the rest of the basin, there is much less crustal thinning (32 - 25 km, 20–38% thinning). This means that the LMV experienced high extension in the two depocenters (Plato and San Jorge) and low extension in the rest of the basin. However, if a lower initial crustal thickness is assumed (e.g. 35 km), thinning would have been less (maximum 16–20 km, 54-43% at depocenters, 32 - 25 km, 9–29% elsewhere). Table 2 summarizes our thinning and extension estimates using the three different approaches previously described and the previous extension calculations by Montes et al. (2010).

basin setting for the LMV and SJFB, as previously proposed by several researchers (Ladd et al., 1984; Mantilla et al., 2009; Bernal et al., 2015a).

According to paleo-tectonic reconstructions (Müller et al., 1999; Pindell and Kennan, 2009; Boschman et al., 2014; Matthews et al., 2016; Mora et al., 2017b), the plate-tectonic setting of northwestern Colombia since the Oligocene has been characterized by a slow (~2 cm/yr) and nearly orthogonal convergence and subduction of the Caribbean oceanic plate beneath the South American plate (Fig. 10). The formation and Oligocene to Recent evolution of the LMV has thus been influenced by the interaction with the Caribbean oceanic plateau, which has been considered as a flat-slab subduction (Bernal et al., 2015a; Mora et al., 2017a,b). Hence, the stratigraphic succession in the LMV must have recorded any major changes in the convergence and subduction regime. However, convergence in the last 30 Ma was characterized by low obliquities and relatively low velocities, without abrupt changes that could be related to major tectonic events (Fig. 11c). In spite of the relative stability of the Oligocene to Recent convergence between the Caribbean plate and NW South America, our results indicate that after the lower Miocene unconformity, there was an increase in subsidence and sedimentation in the LMV, which was related to the formation of the Magdalena fluvial system, when the eastern LMV was connected to the Middle Magdalena valley, as will be discussed in the following sections.

Table 2
Compilation of extension calculations in previous (Montes et al., 2010) and this study, according to the different methods that were used. Further explanation in the text.

	Stretch factor	Extension the in LMV	Comments
Line-length in cross-section	1.13	40.7 km (12.1%)	only the Algarrobo Fault system has been extended 26.7 km
Tectonic subsidence curves	β = 1.1 to 4		β values very high in depocenters (overestimated)
Crustal thickness measurements	β ≤ 2		maximum 50% in depocenters; 20–38% elsewhere[a]
Montes et al., 2010	β = 1.1 to > 4	86–115 km	both extension calculations are overestimated

[a] Assuming initial crustal thickness of 40 km.

5. Discussion

In this section we start by discussing the basin classification and tectonic regime of NW Colombia, the possible origin of the LMV and its Oligocene to Recent evolution. Then we discuss other relevant aspects of basin evolution (extension, sediment supply, underplating, subsidence) and finish by proposing mechanisms that controlled the evolution of the LMV.

5.1. LMV classification and tectonic regime

Previous data and our own support the interpretation of the LMV and SJFB as part of a convergent margin with active subduction since Late Cretaceous times. Recent studies by Mora et al. (2017a,b) and Silva et al. (2016) of the basement of the LMV have shown that there was subduction-related magmatism in Late Cretaceous to early Eocene times and that after middle Eocene times, low-angle subduction was established, shutting off the magmatism. Bernal et al. (2015c) suggested a later (middle Miocene) onset of flat subduction, but they used a unique rate of 2 cm/yr for their calculation, whereas Mora et al. (2017b) used several rates and provided more robust evidence (e.g. cessation of arc magmatism, end of activity of Romeral and Palestina Fault Systems, etc.), supporting an earlier onset of flat subduction (middle Eocene). While displacement vectors of tectonic plates indicate present-day convergence between the Caribbean and South America (Müller et al., 1999; Boschman et al., 2014; Symithe et al., 2015; Matthews et al., 2016), both tomographic and seismicity data (Bezada et al., 2010; Bernal et al., 2015a,b,c; Mora et al., 2017a,b) are clearly imaging an east-dipping Wadati-Benioff zone, requiring a slab or several slab segments beneath the LMV and SJFB (Mora et al., 2017b). Therefore, we consider that there are multiple sources of robust evidence in favor of active subduction in NW Colombia, and of a past and present forearc

5.2. Origin of the Lower Magdalena Valley basin

Mora et al. (2017a) and Silva et al. (2016) recently proposed the existence of a subduction-related, Upper Cretaceous magmatic arc that forms the basement underneath the LMV. Though no evidence has yet been found of Paleocene to Eocene arc magmatism under the LMV, there are reports of Paleocene to lower Eocene magmatic arc rocks in the northern CC and SNSM (Bayona et al., 2012; ANH, 2011; Bustamante et al., 2016), suggesting that there was a continuous, Upper Cretaceous to lower Eocene magmatic arc, extending between such areas. The existence of an Upper Cretaceous to Eocene subduction-related magmatic arc in NW Colombia is a strong evidence in favor of a forearc setting.

Subsidence mechanisms in forearc basins have long been debated and the large variability of subsidence curves indicates a wide range of mechanisms (Xie and Heller, 2009; Noda, 2016). Noda (2016) proposed a general model of forearc basin evolution, arguing that during the infant stage of subduction, the forearc may be extensional until the sinking plate retreats the hinge to obtain a sufficient downdip motion, and that such extension possibly leads to fault controlled subsidence in the overriding crust. Cooling of the Cretaceous to Paleogene magmatic arc is another important factor which would have played a role in the extensional reactivation of the main pre-Oligocene basement features in the LMV such as the Mojana and Sucre faults that limit the San Jorge graben, and the Pivijay, Apure, Pijiño and other faults of the Plato depocenter. Extensional reactivation of inherited basement structures was crucial for the tectonic segmentation of the LMV, with the formation and development of its two basin depocenters (Plato and San Jorge). It is also possible that initial subsidence could have been caused

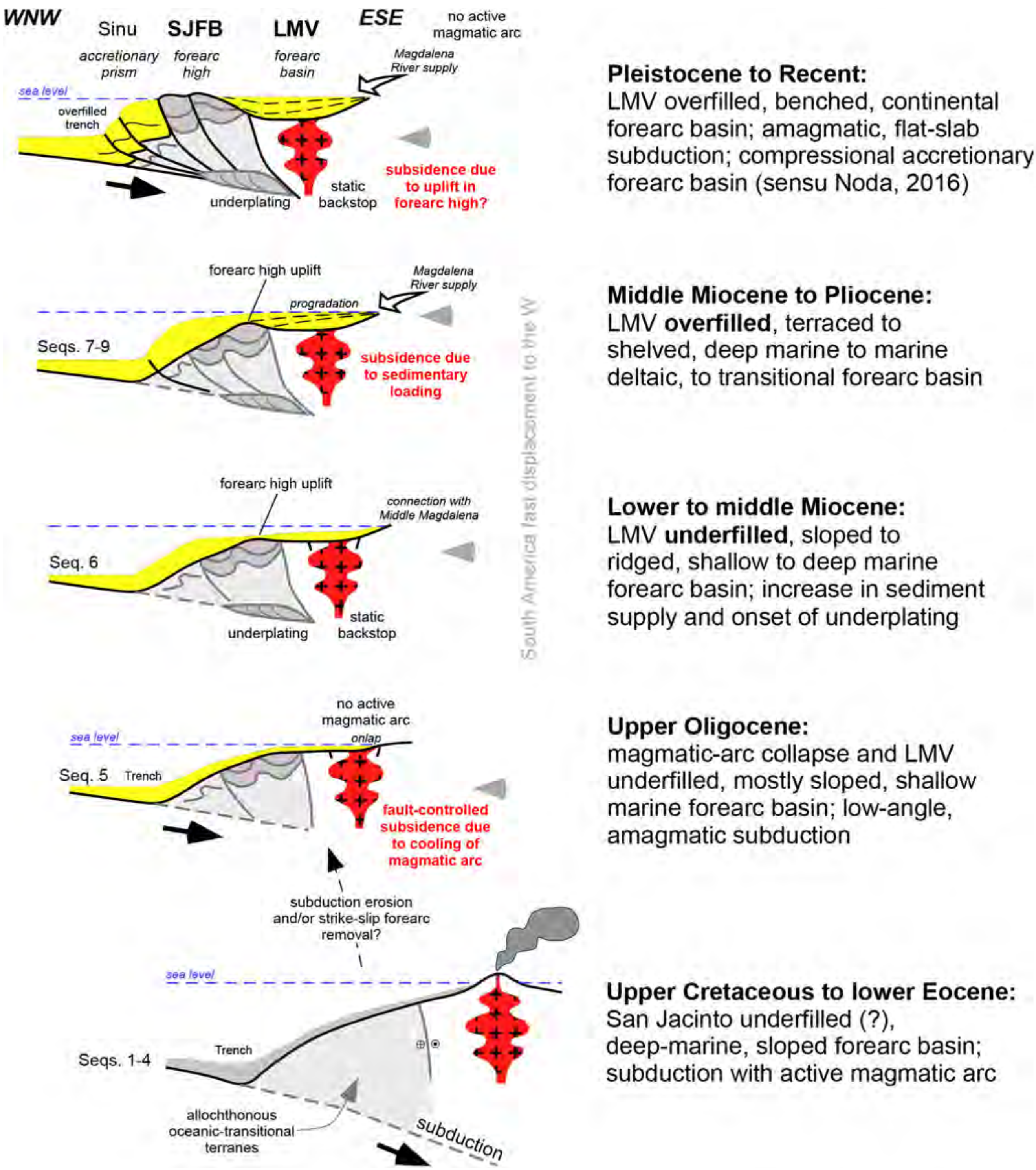

Fig. 15. Interpreted evolution of the morphology of the LMV and San Jacinto from an Upper Cretaceous to Eocene underfilled, sloped forearc basin (sensu Dickinson, 1995) with and active magmatic arc, to the current amagmatic and overfilled, benched continental forearc basin. Increased Miocene sediment flux, the inherited basement structure and a flat-slab subduction were the main controls on Oligocene to Recent forearc basin evolution, as discussed in the text.

by crustal thinning due to possible Cretaceous to Eocene subduction erosion (Clift and Vannucchi, 2004), as suggested by Mora et al. (2017a,b) after studying the position of the Upper Cretaceous to Paleogene magmatic arc relative to the trench. Final stages of pre-Oligocene clockwise tectonic-block rotation (Mora et al., 2017a) could have also exerted some influence in initial subsidence and basin formation. According to the aforementioned and as seen in other forearc basins around the world (Noda, 2016), we consider that the formation of the LMV is related to several factors such as cooling of an Upper Cretaceous to Paleogene magmatic arc, crustal thinning due to previous subduction erosion and to late stages of clockwise tectonic block rotation.

5.3. Oligocene to recent forearc basin evolution

5.3.1. Oligocene

In Oligocene times, the northern Cauca valley was probably connected to the southern LMV, as suggested by the good correlations in terms of lithology, age and depositional environments. The Amagá Formation of the northern Cauca Valley (Grosse, 1926; Van der Hammen, 1960; González, 1980; Piedrahita et al., 2017) and the Ciénaga de Oro formation of the southwestern LMV were both deposited in fluvio-deltaic environments which allowed the development of thick coal seams (photo in Fig. 5). Detrital zircon geochronology (Montes et al., 2015) and zircon fission track thermochronology (Piedrahita et al., 2017) also support a connection with Cretaceous and Paleogene terranes such as those outcropping in the present day Cauca Valley. By contrast, shallow-marine, late Oligocene deposits are only preserved in the western LMV, making a connection with the northern Middle Magdalena very unlikely. In fact, the Middle Magdalena valley was a closed intramontane basin, separated from the LMV by the Cáchira high (section 2, Fig. 6), as proposed by several researchers (Caballero et al., 2013b; Horton et al., 2015). The connection between the Middle and Lower Magdalena valleys was probably not in place in late Oligocene times.

5.3.2. The early miocene unconformity

Spanning from 23.8 to 17.3 My, the early Miocene unconformity partly overlaps in age with plate tectonic events such as the initial collision episode of the Chocó-Panamá block (Farris et al., 2011; O'Dea et al., 2016), and a tectonic inversion phase in western Caribbean basins (Escalona and Mann, 2011). Such tectonic events could have exerted some influence in the uplift of Andean terranes, which started shaping the drainage systems in northern Colombia (Hoorn et al., 2010; Caballero et al., 2013a,b; Reyes-Harker et al., 2015; Anderson et al., 2016). The late stages of deformation and exhumation which affected all the present day Eastern Cordillera (Mora et al., 2010a; Mora et al., 2013a,b), Santander Massif (Mora et al., 2015), Sierra Nevada de Santa Marta (Villagómez et al., 2011b) and most likely the Central Cordillera (Caballero et al., 2013a,b) took place in late Oligocene to early Miocene times.

5.3.3. Middle to late miocene

The first important change in sedimentation and sediment supply both to the basin (LMV) and to the accretionary prism occurred in middle Miocene times (Figs. 11 and 14). The upper part of Sequence 6 (lower to middle Miocene) starts exhibiting progradation of deltaic clinoforms to the NW, indicating connections with important drainage systems, which supplied enormous amounts of sediments from the SE and S. At a rate of ~2 cm/yr, the minimum time required for the sediments to travel from the trench areas, down the subduction channel to a position below the SJFB (60–100 km) is in the order of 3–5 Ma. This means that if the onset of high sedimentation occurred at ~18 Ma, uplift in the SJFB related to sediment underplating would have started at ~15 to 13 Ma. This time window matches the development of forearc highs in the San Jacinto area, as deduced from seismic onlapping patterns (section 1 in Figs. 5 and 14). The basin was then evolving from a sloped to ridged forearc (sensu Dickinson, 1995), due to the occurrence of mainly submerged paleohighs (Fig. 15). Fault-controlled subsidence and NE-SW and SE-NW-trending extension continued active in the LMV.

Based on detrital U/Pb data, Horton et al. (2015) suggested that an integrated proto-Magdalena drainage system can only be documented by the late Miocene time. However, according to Gomez et al. (2015) and Caballero et al. (2013b), a connection between the northern Middle Magdalena and the northeastern LMV was established in earliest middle Miocene times, when the Colorado Formation covered the Cáchira arch. In this study, we support a middle Miocene connection with the Middle Magdalena valley, based in the seismic stratigraphic patterns, tied to well data, showing the clear progradation of marine stratigraphic packages from the northern Middle Magdalena towards the NW. Furthermore, published U-Pb detrital zircon geochronology data (Montes et al., 2015) show that the upper Oligocene to middle Miocene units sampled towards the eastern LMV and northern Middle Magdalena have a Mesoproterozoic population (1000–1500 Ma) which is not present in units sampled toward the western and southern LMV. Therefore, from middle to late Miocene times (Sequences 7 and 8), deposition in the LMV was already influenced by a connection with the proto-Magdalena drainage system, which delivered abundant, mostly distal, fine-grained sediments to the basin.

In the northern Cauca Valley, a volcanic-sedimentary unit (Combia Formation, Grosse, 1926; González, 1980) of upper Miocene age (10–6 Ma, Ramirez et al., 2006), was deposited due to the activity of a late Miocene magmatic arc in the northern Central Cordillera. Though in the southernmost LMV equivalent deposits were eroded, both areas probably continued to be connected (Fig. 9a). We thus consider that the subduction channel was continuously lubricated by fluid rich sediments delivered to the trench (Fig. 14), while underplating and subsequent uplift in forearc high areas continued, as deduced from seismic data. An extensional regime prevailed in the LMV, though fault-controlled subsidence decreased with time and was gradually replaced by non-fault related subsidence due to increased sedimentary load.

Our paleo-geographic reconstructions and facies models, based on the detailed interpretation of thousands of kilometers of seismic data and hundreds of boreholes, do not support a middle Miocene connection of the northern LMV with the Panamá Arc, as proposed by Montes et al. (2015). In the northern LMV, there is no evidence of middle to late Miocene fluvial strata which could have come from the SW (Panamá), and the seismic stratigraphic patterns all indicate migration of sedimentary packages towards the WNW. Furthermore, the interpreted, SSW-NNE-trending Miocene to Recent forearc highs in the SJFB would have acted as a barrier that made very difficult a sedimentary connection with the Panamá Arc from the SW. We thus consider that geochronological analyses must be taken with extreme caution; several possible interpretations should be proposed, the analyses must be integrated with other types of methods and all the data together must be interpreted within a robust regional tectono-stratigraphic framework.

5.3.4. Latest miocene to early pliocene

A second important change in sedimentation occurred after the late Miocene tectonic event (see Text S1, description of Sequence 9), when upper Miocene to lower Pliocene Sequence 9 was deposited and partial erosion of Sequence 7 and 8 took place. Wijninga (1996), Mora et al. (2008), Hoorn et al. (2010) and Mora et al. (2010b) documented that the main phase of topographic growth in the Colombian Eastern Cordillera occurred between the middle Miocene (~15 Ma) and Plio-Pleistocene (~3 Ma) while denudation rates were the fastest (Mora et al., 2008; Caballero et al., 2013b) and deformation rates reached the Cenozoic peaks (> 8 mm/year, Mora et al., 2013a). Therefore, uplift in the eastern Cordillera and surrounding areas was increasingly more important for the shaping of the drainage systems, which continued to deliver high amounts of sediments to the basin. This is evident from the very high sedimentation rates in the accretionary prism (Fig. 14). From middle Miocene to Pliocene times, the morphology of the basin evolved from an underfilled, marine, ridged basin, to an overfilled, terraced to shelved, shallow marine forearc basin, with the occurrence of SSW-NNE-trending, submerged or locally emergent paleo-highs (Fig. 15). A recent publication (Noda, 2018) reproduced this effect of forearc basin underfilling to overfilling, due to the increase of sediment flux from the hinterland.

An important shortening event that affected the LMV, evident from seismic data, occurred shortly after the deposition of Sequence 9 (Fig. 9a), in middle Pliocene times (~3.6 Ma). Erosion of older sequences, mainly 7 to 9, occurred in areas such as the Magangué-Cicuco high and southern LMV, while normal faults such as those bounding the San Jorge graben were slightly inverted. Such inversion was related to NE-SW-trending contraction, though SE-NW-trending contraction also occurred in the forearc highs (San Jacinto).

5.3.5. Late pliocene to recent

After the middle Pliocene shortening event, the subsidence and uplift patterns in the basin depocenters changed, and the north (Plato) was uplifted while the south (San Jorge) started rapidly subsiding without an evident fault control and apparently due to increased sedimentary loading (Figs. S3 and S5). However, the increase also in tectonic subsidence (Fig. 11a) indicates that a different mechanism other than sedimentary load, would also be causing such as localized subsidence. The deposition of thick transitional to continental packages of Sequence 10 was influenced by rapid Pliocene to Recent denudation in the northern Central Cordillera (Toro et al., 2007), possibly related to the final collision of Panamá and to the closure of the Central American Seaway (Montes et al., 2015; O'Dea et al., 2016). Since the northern LMV (Plato) became a positive relief area, offshore areas such as the Magdalena fan and the trench continued to receive high amounts of sediment from the Magdalena River, and from the Sinú River farther south (Fig. 9b and c).

The San Jorge depocenter of the southern LMV continued subsiding as fluvio-deltaic deposits of the proto-Cauca and San Jorge Rivers filled the lowest areas. In Pleistocene times (~1.7 Ma), the San Jacinto fold belt was tilted to the SE due to deep, northwest-verging thrusting occurring in the accretionary prism farther west (Figs. 5–7). This tilting caused only subtle reactivation and localized inversion of structures within the Romeral Fault System. The uplift of the San Jacinto fold belt resulted in a more continuous forearc high, which would be the surface expression of continued underplating processes, driven by the high sediment supply to the trench. The development of a relatively continuous forearc high in San Jacinto was fundamental for the formation of the Sinú River valley, which became an additional and important source of sediments to the Morrosquillo Gulf offshore area. At the same time, it isolated the Cauca and San Jorge rivers and connected them to the Magdalena River in the north (Fig. 9c). Such processes produced the present-day morphology of the basin, which can be described as an overfilled, benched, continental forearc basin (sensu Dickinson, 1995, Fig. 15).

5.4. Sediment supply and extension

Sequences 5 to 7 (Oligocene to middle Miocene) represent the advance of shallow marine deposits towards the ESE, and though the upper part of Sequence 6 and Sequence 7 exhibit progradational patterns to the WNW (Fig. 8), deep marine deposits prevail (Fig. 8c) and the basin reached its maximum flooding at ~14 Ma, in agreement with a global sea level rise (Mid Miocene climatic optimum, Fig. 2; Haq et al., 1987; Zachos et al., 2001). After such maximum flooding episode and in spite of continued basin subsidence and creation of accommodation space, progradational packages of Sequences 8 and 9 advance to the NW (Fig. 9a). We interpret the fact that progradation was able to overcome increasing subsidence and creation of accommodation space in middle to late Miocene times as a clear indication of an increase in sediment supply from the SE.

Our estimates of extension in the LMV (section 4.4, Fig. 13 and Table 2) show that the basin has been moderately extended (stretching factor from 1.1 to 1.5), except for local areas where the crust has been considerably thinned (western San Jorge depocenter and northern LMV). The LMV appears to have a relatively thin crust, with thicknesses varying from 18 to 28 km, whereas a thicker crust would occur in the central SJFB (30–34 km). A relatively thin crust could be related to the location of the LMV close to the plate margin, and/or to the proposed pre-Oligocene subduction erosion (Mora et al., 2017b). A relatively thin and not very strong crust in the LMV would have made easier for sedimentary loading to become the main subsidence mechanism since middle Miocene times. Therefore, we propose that the change from fault-controlled subsidence to non-fault related subsidence, which occurred in middle to late Miocene times, is related to the onset of increased sediment supply. Crustal thickening at the central SJFB could be related to tectonic stacking of pre-Oligocene units and to underplating.

5.5. Underplating and forearc uplift

The increased sediment supply which was also seen in the accretionary prism (Fig. 14) likely also strongly influenced the plate interface, by lubricating the subduction channel through subduction of porous and fluid-rich sediment, thus affecting the transmission of stresses to the upper plate and producing underplating. Crustal thickening by tectonic underplating of subducted materials has been proposed as a cause of uplift in forearc coastal terranes such as the Chile forearc (e.g. Glodny et al., 2005; Clift and Hartley, 2007), the Aleutians (Moore et al., 1991), the Hikurangi margin (Scherwath et al., 2010) and the Cascadia subduction zone (Calvert et al., 2011). At Cascadia, Calvert et al. (2011) studied an aseismic, low velocity zone, which they interpreted as fluid-rich, underplated sediments that were related to slow slip. In the Aleutians, layered reflectors beneath the Kodiak accretionary complex were interpreted as the result of underplating and may represent an antiformal stack of thrust sheets, such as those proposed by Mora et al. (2017a) based on deep seismic imaging. In this study we have identified Miocene to Recent paleo-highs in seismic sections in the current SJFB (e.g. section 1 in Fig. 5 and Cibarco high in Fig. S4), which would represent forearc highs. Therefore, uplift in the forearc as seen in the western LMV and current San Jacinto fold belt, may be related to tectonic underplating. The occurrence of a deformed outer high to the W (San Jacinto fold belt) and an undeformed forearc basin behind it, to the E (LMV), is explained if the continental basement beneath the LMV acted as a static backstop (Fig. 15), with geologically reasonable contrasts in mechanical properties compared to the sediments just trenchward of it (Byrne et al., 1993; Cerón et al., 2007; Mantilla et al., 2009).

5.6. Tectonic segmentation and depocenter evolution in the LMV

Since middle Eocene times, the domain of the later San Jacinto fold belt and the LMV became part of the same forearc basin, which deepened to the W, towards the trench area, as the accretionary prism started to develop. Upper Oligocene to upper Miocene depocenters were more developed in the N (Plato, Fig. S3b), and they migrated landward to the E, probably due to the development of forearc highs. In Pliocene times, after the north became overfilled, the southern depocenter (San Jorge) started becoming more important and migrated landward (to the E). While the landward migration of depocenters is a distinctive feature of compressional accretionary forearc basins (sensu Noda, 2016), the depocenter shifting from north to south indicates tectonic segmentation into differentially subsiding zones, as seen in several forearc basins such as the Great Valley of California (Angevine et al., 1990; Xie and Heller, 2009; inset in Fig. 13a). Forearc basin segmentation has also been related to continental forearc basins formed in flat-slab subduction settings (Ridgway et al., 2012), where marked along-strike changes in basin configuration were related to insertion of wide fragments of thick crust. Other causes of forearc basin tectonic segmentation include bathymetric changes in the underlying subducted slab that isostatically impact the overlying plate (Kobayashi, 1995), and collision of crustal fragments in the subduction zone (Clift and MacLeod, 1999).

Our results suggest that the pre-Oligocene basement fabric in the LMV, which is different beneath each depocenter (Mora et al., 2017a and Fig. S1), was probably the main cause of the tectonic segmentation of the basins. The Oligocene extensional reactivation of inherited basement faults allowed the formation of the two depocenters, while later fault reactivations controlled the response of each depocenter to the regional stress regimes. For instance, the NE-SW-trending contraction that we document in the southern LMV after the deposition of Sequence 9 (Fig. 9a) is perpendicular to the SE-NW contraction trend, which is directly related to the convergence vector of the Caribbean relative to South America (Fig. S1). Two possible tectonic events could be related to the NE-SW-trending contraction observed in the southern LMV (Fig. 9a). The first one could be the escape of the northwestern Andean block, which occurred after 11 Ma along the East Andean front fault zone in Colombia and the Boconó fault system in Venezuela, as implemented in the paleotectonic model of Matthews et al. (2016; Fig. 10). The second one would be related to collision stages of the Chocó-Panamá block with northern South America, occurring in late Miocene to Pliocene times (Montes et al., 2015; O'Dea et al., 2016), which could have also caused the selective reactivation of the basement faults in the LMV (Figs. 9c and 10).

5.7. LMV subsidence history and trends

Our results show that the inherited basement structures (reactivation of the main extensional fault families in the LMV according to Mora et al., 2017a), controlled the initial basin infill and the subsequent tectonic segmentation that formed the two depocenters (Plato and San Jorge). Fault-controlled subsidence took place in the LMV from Oligocene to middle Miocene times (29–13 Ma), spanning for 16 My, and then it was replaced by mostly non-fault related subsidence (Fig. 11a and Fig. S3). However, in the SW (San Jorge depocenter, Bonga and Esmeralda wells), there's an increase in tectonic subsidence after 3 Ma, related to the deposition of Sequence 10. Global studies of basin subsidence history (Xie and Heller, 2009) concluded that subsidence curves from forearc basins, as a group, have a diverse range of shapes, indicating that a variety of factors may contribute to basin subsidence. According to Dickinson (1995), there are four subsidence mechanisms in forearc basins: negative buoyancy of the descending slab, loading by the subduction (accretionary) complex, sediment or volcanic loading and thermal subsidence of the arc massif. Our results suggest that in the LMV, fault-controlled subsidence probably due to cooling of a pre-Oligocene arc was more important initially (late Oligocene to middle Miocene), and then it was replaced by sedimentary loading as the main subsidence mechanism in the basin during the late Miocene, except for the increase in tectonic subsidence in the SW at 3 Ma (Fig. 11a). Nevertheless, increased tectonic subsidence in the SW (Bonga and Esmeralda) after 3 Ma would not be related to sedimentary loading. Though there is no evidence of fault-controlled subsidence after 4 Ma, we consider that the increase in tectonic subsidence could be related to uplift of forearc highs, considering that most of them have been identified to the west, not far from the proposed upper Pliocene to Pleistocene depocenters (Fig. 9c and Fig. S3b). The fact that the basin experienced nearly coeval uplift in the north (Plato) and subsidence in the south (San Jorge) can be related to tectonic segmentation and to the differences in structural fabric of both depocenters, which controlled their response to different stresses. Irregularities in the subducted Caribbean plateau could have also influenced the increase in tectonic subsidence at 3 Ma. The proposal by Mora et al. (2017a) of a different type of basement (transitional to oceanic) to the west of the San Jerónimo fault of the western San Jorge depocenter could also be related to the increased tectonic subsidence that is more evident in that area.

Comparison of our subsidence curves with subsidence curves from other forearc basins in the world shows a fair match (Angevine et al., 1990, inset in Fig. 13a). However, as previously noted, the LMV curves show the opposite pattern compared to the passive rift basins considered in the stretching model of McKenzie (1978); therefore, they show that LMV is not suitable for applying the uniform stretching methodology by McKenzie (1978) and that extension using this methodology is overestimated in this basin, as previously shown by Montes et al. (2010) (Table 2). Data from the few wells in the northern SJFB show that the area experienced lower but constant subsidence rates compared to the LMV, and the SJFB curves show a similar trend to other forerarc basins in the world. The data from the deep Plato depocenter in the northern LMV (steep pink curve in the inset of Fig. 13a) matches very well the trend of the Japan forearc basin reported by Angevine et al. (1990), while the data from other shallower areas in the LMV shows a less steep curve related to the lower amount of tectonic subsidence. The marked differences in subsidence rates and trends between the SJFB and LMV in Oligocene to Recent times show that while the main depocenters in the LMV were rapidly subsiding, the SJFB experienced much less subsidence, possibly due to the development of forearc highs. The high sedimentation rates in the LMV and in the accretionary prism farther to the NW, especially after middle Miocene times, suggest that there was an important influence of sediment load in the total basin subsidence. Tectonic segmentation within both the LMV and the SJFB is also evident from the subsidence curves (inset in Fig. 13a).

5.8. Proposed mechanisms controlling LMV evolution

Our results and analyses allow us to conclude that the LMV is an amagmatic and tectonically segmented forearc basin. Among all the mechanisms controlling the evolution of forearc basins, we consider based on our results, that three mechanisms strongly controlled the evolution of the LMV. Such mechanisms are: sediment flux due to uplift and drainage evolution in hinterland areas, pre-existing basement fabric, and configuration of the subducting plate.

Our reconstruction of the extension, subsidence, sedimentation and paleogeographic history suggests that sediment flux in the LMV was an important mechanism in controlling basin evolution because, 1) it supplied sediment to the trench and as a consequence, triggered underplating and uplift in forearc high areas, 2) it rapidly filled the basin, providing sedimentary loads which kept the depocenters subsiding, as previous subsidence mechanisms became less effective, and 3) it defined the type and geometry of the basin. Due to the sediment flux, the LMV evolved from an underfilled, sloped, marine forearc basin to an overfilled, benched, terrestrial forearc basin (sensu Dickinson, 1995, Fig. 15). Considering the classification by Noda (2016), the whole margin evolved from an Oligocene extensional non-accretionary type to the present-day compressional accretionary type forearc basin, and such evolution was strongly controlled by changes in sediment flux.

The pre-existing basement structural fabric underneath the LMV was also crucial for the formation and evolution of the LMV. Inherited basement structures controlled the initial basin infill and caused the tectonic segmentation of the basin. Furthermore, differential reactivation of the inherited, basement fault families identified under the Plato depocenter in the north and the San Jorge depocenter in the south (Mora et al., 2017a; Fig. S1) influenced the subsidence and uplift history of each depocenter. It is also likely that such segmentation exerted and influence on the development of the proto-Magdalena and Cauca drainage systems and was a cause of the observed variations in terms of sedimentary thicknesses and facies from one depocenter to the other.

Concerning the configuration of the subducting plate, we have shown using paleo-tectonic models that kinematics and subduction configuration were stable throughout the evolution of the LMV (Fig. 11). However, such evolution was also probably controlled by the low-angle subduction of an irregular Caribbean oceanic plateau, which would have influenced the along-strike tectonic segmentation and stratigraphic variations observed in the LMV, as observed in other similar basins (Ridgway et al., 2012). The variations in geometry of the subducted Caribbean plateau under the LMV, described by Mora et al. (2017b) could represent irregularities, such as the Beata ridge which separates the Colombian basin from the Venezuelan basin, at the top of the plateau (Duque-Caro, 1979). Moreover, though we relate uplift in the forearc highs with high sediment supply to the trench and underplating, it is possible that flat-slab subduction also influenced exhumation in forearc high areas and produced regional and local unconformities, as proposed by Ridgway et al. (2012). Flat-slab subduction also appears to be responsible for the lack of a magmatic arc in the LMV, a condition that would otherwise have formed a completely different forearc basin. The formation and evolution of the LMV presented herein is the starting point for future petroleum system models attempting to explain the hydrocarbon occurrences and to assess the remaining oil and gas potential in the basin.

6. Conclusions

The formation of the Lower Magdalena amagmatic, forearc basin occurred in a stable setting from the Oligocene to the present, characterized by the slow and nearly orthogonal, low-angle subduction of the Caribbean plateau. In this study, we used a regional database to reconstruct the subsidence, extension, sedimentation and paleo-geographic history of the Lower Magdalena forearc basin, and to propose possible mechanisms controlling basin evolution, in the absence of major changes in plate kinematics and in a flat-slab subduction setting. Six Oligocene to Recent tectono-stratigraphic sequences were identified, comprising a general shallowing-upwards and progradational succession. We show that after the collapse of a pre-Oligocene magmatic arc, late Oligocene to early Miocene fault-controlled subsidence allowed initial basin fill at relatively low sedimentation rates. Extensional reactivation of inherited, pre-Oligocene basement faults was crucial for the tectonic segmentation of the basin. Oligocene to early Miocene uplift of Andean terranes made possible the later connection of the Lower and Middle Magdalena valleys, and the formation of the most important Colombian drainage system (Magdalena River system). The proto-Magdalena river in the north and the proto-Cauca river in the south both started delivering high amounts of sediment in middle Miocene times, as fault controlled subsidence was gradually replaced by non-fault related subsidence, due to increased sedimentary load. Such an increase in sedimentation delivered huge amounts of sediments to the trench, causing the formation of an accretionary prism farther west of San Jacinto. Associated sediment subduction probably weakened the plate interface and caused underplating, with the development of forearc highs in the San Jacinto area. Inherited basement structures and flat-slab subduction of an irregular Caribbean plateau would be related to the along-strike basin segmentation and to the formation of two main depocenters (Plato and San Jorge), each one with particular subsidence and uplift histories. A stronger backstop under the Lower Magdalena explains shortening in the forearc high and accretionary wedge areas to the W, while the Lower Magdalena remained essentially unaffected. Our results highlight the fundamental roles of sediment flux, of the inherited basement structure and of flat-slab subduction on the evolution of forearc basins such as the Lower Magdalena.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.marpetgeo.2018.06.032.

References

Allen, P., Allen, J., 2005. Basin Analysis- Principles and Applications, second ed. Blackwell Publishing Ltd., pp. 549.

Anderson, V.J., Horton, B.K., Saylor, J.E., Mora, A., Tesón, E., Breecker, D.O., Ketcham, R.A., 2016. Andean topographic growth and basement uplift in southern Colombia: implications for the evolution of the Magdalena, Orinoco, and Amazon river systems. Geosphere 12 (4), 1–22. https://doi.org/10.1130/GES01294.1.

Angevine, C.L., Heller, P.L., Paola, C., 1990. Quantitative sedimentary basin modeling. In: American Association of Petroleum Geologists Continuing Education Course Note Series, vol. 32. pp. 133.

Ardila, L., Díaz, L., 2015. Terrane accretion and transpression created new exploration frontiers in northwestern South America. In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin. vol. 108. AAPG Memoir, American Association of Petroleum Geologists, Tulsa, OK, USA, pp. 217–246.

ANH-Universidad Nacional, 2009. Informe Final de Geologia: Proyecto cartografia y modelamiento structural de las Cuencas de Urabá y Sinu-San Jacinto a partir de la interpretación de imágenes de sensores remotos y monitoreo sísmico. Public report presented to the National Hydrocarbons Agency (ANH).

ANH, 2011. Petroleum geology of Colombia. In: In: Cediel, F. (Ed.), Regional Geology-Phanerozoic Granitoid Magmatism in Colombia and the Tectono-magmatic Evolution of the Colombian Andes, vol. I.

Assumpção, M., Bianchi, M., Julia, J., Dias, F., Sand Franca, G., Nascimento, R., Drouet, S., Garcia Pavão, C., Farrapo, D., Lopes, A., 2013. Crustal Thickness map of Brazil: data compilation and main features. J. S. Am. Earth Sci. 43, 74–85. https://doi.org/10.1016/j.jsames.2012.12.009.

Barrero, D., Alvarez, J., Kassem, T., 1969. Actividad Ignea y tectónica en la Cordillera Central. Bol. Geol. Ingeominas 17 (1–3), 145–173.

Bayona, G., Cardona, A., Jaramillo, C., Mora, A., Montes, C., Valencia, V., Ayala, C., Montenegro, O., Ibañez, M., 2012. Early Paleogene magmatism in the northern Andes: insights on the effects of oceanic plateau–continent convergence. Earth Planet Sci. Lett. 331–332, 97–111.

Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.-P., 1995. A Revised Cenozoic Geochronology and Chronostratigraphy, vol. 54. Society of Economic Paleontologists and Mineralogists, Special Publication, pp. 129–212.

Bermudez, H., 2016. Esquema estratigráfico de secuencias del registro sedimentario del Cinturón Plegado de San Jacinto, Caribe colombiano. In: Extended abstract presented at the XII Simposio Bolivariano Exploración Petrolera en Cuencas Subandinas, September 26-28, 2016, Bogotá.

Bernal, Olaya R., Mann, P., Vargas, C., 2015a. Earthquake, tomographic, seismic reflection, and gravity evidence for a shallowly dipping subduction zone beneath the Caribbean Margin of Northwestern Colombia. In: In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin, vol. 108. AAPG Memoir, pp. 247–270.

Bernal, Olaya R., Sánchez, J., Mann, P., Murphy, M., 2015b. Along-strike crustal thickness variations of the subducting Caribbean plate produces two distinctive styles of thrusting in the offshore South Caribbean deformed belt, Colombia. In: In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin, vol. 108. AAPG Memoir, pp. 295–322.

Bernal, Olaya R., Mann, P., Escalona, A., 2015c. Cenozoic tectonostratigraphic evolution of the lower Magdalena basin, Colombia: an example of an under- to overfilled forearc basin. In: In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin, vol. 108. AAPG Memoir, pp. 345–398.

Bezada, M.J., Levander, A., Schmandt, B., 2010. Subduction in the southern Caribbean: images from finite-frequency P wave tomography. J. Geophys. Res. 115, B12333. https://doi.org/10.1029/2010JB007682.

Blow, W.H., 1969. Late middle Eocene to recent planktonic foraminiferal biostratigraphy. In: Bronnimann, P., Renz, H.H. (Eds.), Proceedings of the First International Conference on Planktonic Microfossils. Geneva, 1967. E.J. Brill, Leiden, pp. 199–421.

Boschman, L., van Hinsbergen, D., Torsvik, T., Spakman, W., Pindell, J., 2014. Kinematic reconstruction of the caribbean region since the early jurassic. Earth Sci. Rev. 138, 102–136.

Bustamante, C., Cardona, A., Archanjo, C., Bayona, G., Lara, M., Valencia, V., 2016. 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.

Byrne, D.E., Wang, W.H., Davis, D.M., 1993. Mechanical role of backstops in the growth of forearcs. Tectonics 12 (1), 123–144. https://doi.org/10.1029/92TC00618.

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

Caballero, V., Mora, A., Quintero, I., Blanco, V., Parra, M., Rojas, L.E., Lopez, C., Sanchez, N., Horton, B.K., Stockli, D., Duddy, I., 2013b. Tectonic controls on sedimentation in an intermontane hinterland basin adjacent to inversion structures: the Nuevo Mundo syncline, Middle Magdalena Valley, Colombia. In: In: Nemčok, M. (Ed.), Thick-Skin-dominated Orogens: from Initial Inversion to Full Accretion, vol. 377. Geological Society of London Special Publication, pp. 315–342. https://doi.org/10.1144/SP377.12.

Calvert, A., Preston, L., Farahbod, A., August 2011. Sedimentary underplating at the Cascadia mantle-wedge corner revealed by seismic imaging. Nat. Geosci. 4. https://doi.org/10.1038/NGEO1195.

Catuneanu, et al., 2009. Towards the standardization of sequence stratigraphy. Earth Sci. Rev. 92, 1–33.

Cediel, F., Shaw, R.P., Cáceres, C., 2003. Tectonic assembly of the northern andean block. In: In: Bartolini, C., Buffler, R.T., Blickwede, J. (Eds.), The Circum-gulf of Mexico and the Caribbean: Hydrocarbon Habitats, basin Formation, and Plate Tectonics, vol. 79. AAPG Memoir, pp. 815–848.

Cerón, J., Kellogg, J., Ojeda, G., 2007. Basement Configuration of the northwestern South America-Caribbean margin from recent geophysical data. Ciencia Tecnol. Fut. 3/3, 25–49.

Chulick, G., Detweiler, Sh., Mooney, W., 2013. Seismic structure of the crust and uppermost mantle of South America and surrounding oceanic basins. J. S. Am. Earth Sci. 42, 260–276. https://doi.org/10.1016/j.jsames.2012.06.002.

Clift, P.D., MacLeod, C.J., 1999. Slow rates of subduction erosion estimated from subsidence and tilting of the Tonga forearc. Geology 27 (5), 411–414. https://doi.org/10.1130/0091-7613(1999)027<0411:SROSEE>2.3.CO;2.

Clift, P., Vannucchi, P., 2004. Controls on Tectonic Accretion versus Erosion in subduction zones: implications for the origin and recycling of the continental crust. Rev. Geophys. 42, RG2001.

Clift, P., Hartley, A., 2007. Slow rates of subduction erosion and coastal underplating along the Andean margin of Chile and Peru. Geology 35 (6), 503–506. https://doi.org/10.1130/G23584A.1.

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

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 Bull. 99 (8), 1455–1472. https://doi.org/10.1306/02241511153.

Dickinson, W., 1995. Forearc basins. In: Busby, C., Ingersoll, R. (Eds.), Tectonics of Sedimentary Basins. Blackwell Science, Oxford, pp. 221–261.

Dickinson, W.R., Seely, D.R., 1979. Structure and stratigraphy of forearc regions. Am. Assoc. Petrol. Geol. Bull. 63 (1), 2–31.

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

Duque-Caro, H., 1979. Major structural elements and evolution of northwestern Colombia. In: In: Watkins, J.S., Montadert, L., Wood Dickerson, P. (Eds.), Geological and Geophysical Investigations of Continental Margins, vol. 29 AAPG Memoir, Tulsa.

Duque-Caro, H., 1984. Structural Style, diapirism, and accretionary episodes of the Sinú-San Jacinto terrane, southwestern Caribbean borderland. Geol. Soc. Am. Mem. 162, 303–316.

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., Guzman, G., Hernandez, R., 1996. Mapa Geológico de la Plancha 38, Carmen de Bolívar. Ingeominas, Bogotá.

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 Currulao-1, Barranquilla Province (Internal report for Hocol S.A., Bogotá).

Duque-Caro, H., 2014. Microstratigraphic Analyses of 39 Samples from the Well Calipso-1, Barranquilla Province (Internal report for Hocol S.A., Bogotá).

Escalona, A., Mann, P., 2011. Tectonics, basin subsidence mechanisms, and paleogeography of the Caribbean-South American plate boundary zone. Mar. Petrol. Geol. 28, 8–39.

Farris, D.W., Jaramillo, C.A., Bayona, G.A., Restrepo-Moreno, S.A., Montes, C., Cardona, A., Mora, A., Speakman, R.J., Glasscock, M.D., Reiners, P., Valencia, V., 2011. Fracturing of the Panamanian isthmus during initial collision with South America. Geology 39, 1007–1010. https://doi.org/10.1130/G32237.1.

Flinch, J.F., 2003. Structural evolution of the sinu-lower Magdalena area (northern Colombia). In: In: Bartolini, C., Buffler, R.T., Blickwede, J. (Eds.), The Circum-gulf of Mexico and the Caribbean: Hydrocarbon Habitats, basin Formation and Plate Tectonics, vol. 79. AAPG Memoir, pp. 776–796.

Fuller, C.W., Willett, S.D., Brandon, M.T., 2006. Formation of forearc basins and their influence on subduction zone earthquakes. Geology 34 (2), 65–68. https://doi.org/10.1130/G21828.1.

Glodny, J., Lohrmann, J., Echtler, H., Gräfe, K., Seifert, W., Collao, S., Figueroa, O., 2005. Internal Dynamics of a paleoaccretionary wedge: insights from combined isotope tectonochronology and sandbox modelling of the South-Central Chilean forearc. Earth Planet Sci. Lett. 231, 23–39.

Gomez, J., Montes, N., Nivia, A., Diederix, H., 2015. Mapa Geológico de Colombia, Scale 1:1000000. Servicio Geológico Colombiano, Bogotá.

González, H., 1980. Geología de las planchas 167 (Sonsón) y 168 (Salamina). Bol. Geol. 23, 174.

Grosse, E., 1926. El Terciario Carbonifero de Antioquia. D. Reimer-E. Vohsen, Berlin, pp. 361.

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) public report, Bogotá.

Guzman, G., 2007. Stratigraphy and Sedimentary Environment and Implications in the Plato Basin and the San Jacinto Belt Northwestern Colombia. PhD Thesis. University of Liege, Belgium.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuat¬ing sea levels since the Triassic (250 million years ago to present). Science 235, 1156–1166.

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., Sanmartin, I., Sanchez-Meseguer, A., Anderson, C., Figueiredo, J., Jaramillo, C., Riff, D., Negri, F., Hooghiemstra, H., Lundberg, J., Stadler, T., Särkinen, T., Antonelli, A., 2010. Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. Science 330, 927–931. https://doi.org/10.1126/science.1194585.

Horton, B.K., Anderson, V.J., Saylor, J.E., Parra, M., Mora, A.R., 2015. Application of detrital zircon U-Pb geochronology to surface and subsurface correlations of provenance, paleodrainage, and tectonics of the Middle Magdalena Valley Basin of Colombia. Geosphere 11, 1790–1811. https://doi.org/10.1130/GES01251.1.

Kobayashi, K., 1995. Role of subducted lithospheric slab in uplift and subsidence of the northwestern Pacific margins. Mar. Geol. 127, 119–144. https://doi.org/10.1016/0025-3227(95)00007-L.

Ladd, J., Truchan, M., Talwani, M., Stoffa, P., Buhl, P., Houtz, R., Mauffret, A., Westbrook, G., 1984. Seismic reflection profiles across the southern margin of the Caribbean. In: In: Bonini, W., Hargraves, R., Shagam, R. (Eds.), The Caribbean-south American Plate Boundary and Regional Tectonics, vol. 162 GSA Memoir, Geological Society of America.

Macellari, C., 1995. Cenozoic sedimentation and tectonics of the southwestern Caribbean pull-apart basin, Venezuela and Colombia. In: In: Tankard, A., Suarez-Soruco, R., Welsink, H. (Eds.), Petroleum Basins of South America. AAPG Memoir, vol. 62 American Association of Petroleum Geologists, Tusla, OK, USA.

Mantilla, A., 2007. Crustal Structure of the Southwestern Colombian Caribbean Margin. Thesis Dr. Rer. Nat.. Friedrich-Schiller-Universität Jena, Germany.

Mantilla, A.M., Jentzsch, 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. Springer, Dubai, pp. 247–271.

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

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth Planet Sci. Lett. 40, 25–32.

Miall, A.D., 2000. Principles of Sedimentary Basin Analysis, third ed. Springer-Verlag, Berlin Heidelberg, pp. 616.

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. J. South Am. Earth Sci. 29, 832–848.

Montes, C., Cardona, A., Jaramillo, C., Pardo, A., Silva, J.C., Valencia, V., Ayala, R., Pérez-Angel, L., Rodriguez-Parra, L., Ramirez, V., Niño, H., 2015. Middle Miocene closure of the central american Seaway. Science 348, 226–229.

Moore, J., Diebold, J., Fisher, M., Sample, J., Brocher, T., Talwani, M., Ewing, J., von Huene, R., Rowe, C., Stone, D., Stevens, C., Sawyer, D., 1991. EDGE deep seismic reflection transect of the eastern Aleutian arc-trench layered lower crust reveals underplating and continental growth. Geology 19, 420–424.

Mora, A., Parra, M., Strecker, M., Sobel, E., Hooghiemstra, H., Torres, V., Vallejo, J., 2008. Climatic forcing of asymmetric orogenic evolution in the Eastern Cordillera of Colombia. GSA Bull. 120 (7/8), 930–949. https://doi.org/10.1130/B26186.1. 13 figures, 3 tables.

Mora, A., Horton, B.K., Mesa, A., Rubiano, J., Ketcham, R.A., Parra, M., Blanco, V., Garcia, D., Stockli, D., 2010a. Cenozoic deformation migration in the Eastern Cordillera of Colombia interpreted from fission-track results and structural relationships: implications for hydrocarbon systems. AAPG Bull. 94 (10), 1543–1580.

Mora, A., Parra, M., Strecker, M., Sobel, E., Zeilinger, G., Jaramillo, C., Ferreira Da Silva, S., Blanco, M., 2010b. The eastern foothills of the Eastern Cordillera of Colombia: an example of multiple factors controlling structural styles and active tectonics. GSA Bull. 122 (11–12), 1846–1864. https://doi.org/10.1130/B30033.1.

Mora, A., Reyes, A., Rodriguez, G., Teson, E., Ramirez-Arias, J., Parra, M., Caballero, V., Mora, J., Quintero, I., Valencia, V., Ibanez-Mejia, M., Horton, B., Stockli, D., 2013a. Inversion tectonics under increasing rates of shortening and sedimentation throughout the Cenozoic. In: In: Nemcok, M., Mora, A., Cosgrove, J. (Eds.), Thick-skin-dominated Orogens, from Initial Inversion to Full Accretion, vol. 377 GSL Special Publication. https://doi.org/10.1144/SP377.6.

Mora, A., Blanco, V., Naranjo, J., Sanchez, N., Ketcham, R., Rubiano, J., Stockli, D., Quintero, I., Nemčok, M., Horton, B., Davila, H., 2013b. On the lag time between internal strain and basement involved thrust induced exhumation: the case of the Colombian Eastern Cordillera. J. Struct. Geol. 52, 96–118.

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: In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin, vol. 108. AAPG Memoir, pp. 547–586.

Mora, J.A., Ibáñez-Mejía, M., Oncken, O., De Freitas, M., Vélez, V., Mesa, A., Serna, L., 2017a. 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. J. S. Am. Earth Sci. 74, 1–26. https://doi.org/10.1016/j.jsames.2017.01.001.

Mora, J.A., Oncken, O., Le Breton, E., Ibáñez-Mejía, M., Faccena, C., Veloza, G., Vélez, V., De Freitas, M., Mesa, A., 2017b. Linking late cretaceous to Eocene tectono-stratigraphy of the san Jacinto fold belt of NW Colombia with Caribbean plateau collision and flat subduction. Tectonics 36, 2599–2629. https://doi.org/10.1002/2017TC004612.

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: Mann, P. (Ed.), Caribbean Basins. Elsevier Science, B.V., Amsterdam, The Netherlands, pp. 33–59.

Noda, A., May/June 2016. Forearc basins: types, geometries, and relationships to subduction zone dynamics. GSA Bull. 128 (5/6), 879–895. https://doi.org/10.1130/B31345.1.

Noda, A., 2018. Forearc basin stratigraphy and interactions with accretionary wedge growth according to the critical taper concept. Tectonics 37, 965–988. https://doi.org/10.1002/2017TC004744.

O'Dea, A., Lessios, H.A., Coates, A.G., Eytan, R.I., Restrepo-Moreno, S.A., Cione, A.L., Collins, L.S., de Queiroz, A., Farris, D.W., Norris, R.D., Stallard, R.F., Woodburne, M.O., Aguilera, O., Aubry, M.-P., Berggren, W.A., Budd, A.F., Cozzuol, M.A., Coppard, S.E., Duque-Caro, H., Finnegan, S., Gasparini, G.M., Grossman, E.L., Johnson, K.G., Keigwin, L.D., Knowlton, N., Leigh, E.G., Leonard-Pingel, J.S., Marko, P.B., Pyenson, N.D., Rachello-Dolmen, P.G., Soibelzon, E., Soibelzon, L., Todd, J.A., Vermeij, G.J., Jackson, J.B.C., 2016. formation of the isthmus of Panama. Sci. Adv. 2, e1600883.

Parra, M., Mora, A., Lopez, C., Rojas, L.E., Horton, B., 2012. Detecting earliest shortening and deformation advance in thrust belt hinterlands: example from the Colombian Andes. Geology 40 (2), 174–178. https://doi.org/10.1130/G32519.1. 4 figures; Data Repository item 2012032.

Piedrahita, V., Bernet, M., Chadima, M., Sierra, G., Marin-Ceron, M., Toro, G., 2017. Detrital zircon fission-track thermochronology and magnetic fabric of the Amagá Formation (Colombia): intracontinental deformation and exhumation events in the northwestern Andes. Sediment. Geol. 356, 26–42. https://doi.org/10.1016/j.sedgeo.2017.05.003.

Pindell, J., Kennan, L., 2009. Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. Geol. Soc. Lond. Specl. Publ. 328, 1–55.

Poveda, E., Monsalve, G., Vargas, C., 2012. Crustal thickness estimation beneath the northern Andes (Colombia) from teleseismic receiver functions. In: Poster Presented at the AGU Fall Meeting, San Francisco, USA, 3–7 December.

Poveda, E., Monsalve, G., Vargas, C., 2015. Receiver functions and crustal structure of the northwestern Andean region, Colombia. J. Geophys. Res. Solid Earth 120, 2408–2425. https://doi.org/10.1002/2014JB011304.

Ramirez, D., Lopez, A., Sierra, G., Toro, G., 2006. Edad y Proveniencia de las rocas volcánico sedimentarias de la Formacion Combia en el suroccidente antioqueño-Colombia. Boletin de Ciencias de la Tierra 19, 9–26.

Reyes-Santos, J., Mantilla, M., Gonzalez, J., 2000. Regiones tectono-sedimentarias del Valle Inferior del Magdalena, Colombia. In: Memoirs of the "VII Simposio Bolivariano de Cuencas Subandinas", Caracas, Sept. 10-13, 2000. Sociedad Venezolana de Geólogos, pp. 849.

Reyes-Harker, A., Montenegro, G., Gomez, P., 2000. Evolución Tectonoestratigráfica del Valle Inferior del Magdalena, Colombia. In: Memoirs of the "VII Simposio Bolivariano de Cuencas Subandinas", Caracas, Sept. 10-13, 2000. Sociedad Venezolana de Geólogos, pp. 849.

Reyes-Harker, A., Ruiz-Valdivieso, C., Mora, A., Ramirez-Arias, J., Rodriguez, G., de la Parra, F., Caballero, V., Parra, M., Moreno, N., Horton, B., Saylor, J., Silva, A., Valencia, V., Stockli, D., Blanco, V., 2015. Cenozoic paleogeography of the Andean foreland and retroarc hinterland of Colombia. AAPG Bull. 99 (8), 1407–1453. https://doi.org/10.1306/06181411110.

Ridgway, K., Trop, J., Finzel, E., 2012. Modification of continental forearc basins by flat-slab subduction processes: a case study from southern Alaska. In: Busby, C., Azor, A. (Eds.), Tectonics of Sedimentary Basins: Recent Advances, first ed. Blackwell Publishing Ltd.

Romero-Otero, G., Slatt, R., Pirmez, C., 2015. Evolution of the Magdalena deepwater fan in a tectonically active setting, offshore Colombia. In: In: Bartolini, C., Mann, P. (Eds.), Petroleum Geology and Potential of the Colombian Caribbean Margin, vol. 108. AAPG Memoir, pp. 675–708.

Rosello, E., Cossey, S., 2012. What is the evidence for subduction in the Caribbean Margin of Colombia? In: Extended abstract in Memoirs of the XII Simposio Bolivariano de Cuencas Subandinas: Cartagena, Colombia. Asociación Colombiana de Geologos y Geofisicos del Petróleo.

Salazar, A., 1993. Icnología, Facies y Ambiente de depósito de la Formación Ciénaga de Oro en el Pozo Ayombe-1 (Report presented to Ecopetrol, Bogotá).

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. J. S. Am. Earth Sci. 39, 202–215.

Scherwath, M., Kopp, H., Flueh, E., Henrys, S., Sutherland, R., Stagpoole, V., Barker, D., Reyners, M., Bassett, D., Planert, L., Dannowski, A., 2010. Fore-arc deformation and underplating at the northern Hikurangi margin, New Zealand. J. Geophys. Res. 115, B06408. https://doi.org/10.1029/2009JB006645.

Sclater, J.G., Christie, P.A., 1980. Continental stretching: an explanation of the post mid Cretaceous subsidence of the central North Sea basin. J. Geophys. Res. 85, 3711–3739.

Silva, A., Paez, L., Rincón, M., Tamara, J., Gomez, P., Lopez, E., Restrepo, S., Mantilla, L., Valencia, V., 2016. 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 Tecnol. Fut. 6 (4), 5–36.

Steckler, M., Watts, A., 1978. Subsidence of the Atlantic-type continental margin off New York. Earth Planet Sci. Lett. 41, 1–13.

Symithe, S., Calais, E., de Chabalier, J.B., Robertson, R., Higgins, M., 2015. Current block motions and strain accumulation on active faults in the Caribbean. J. Geophys. Res. Solid Earth 120, 3748–3774. https://doi.org/10.1002/2014JB011779.

Toro, G., Rendon, D., Montes, L., 2007. Levantamiento de los Andes en el norte de la Cordillera Central de Colombia: Una aproximación geomorfológica, estructural y cronológica (trazas de fisión). Boletin Ciencias de la Tierra 22, 125–126.

Trenkamp, R., Kellogg, J., Freymueller, J., Mora, H., 2002. Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. J. S. Am. Earth Sci. 15, 157–171.

Van der Hammen, T., 1960. Estratigrafía del Terciario y Maestrichtiano continentales y tectogénesis de los Andes Colombianos, Informe No. 1279. Servicio Geológico Nacional, Bogotá, pp. 128.

Villagómez, D., Spikings, R., Magna, T., Kammer, A., Winkler, W., Beltrán, A., 2011a. Geochronology, geochemistry and tectonic evolution of the western and central Cordilleras of Colombia. Lithos 125, 875–896.

Villagómez, D., Spikings, R., Mora, A., Guzmán, G., Ojeda, G., Cortés, E., van der Lelij, R., 2011b. 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.

Wang, J., Hu, X., Garzanti, E., An, W., Liu, X., 2017. The birth of the Xigaze forearc basin in southern Tibet. Earth Planet Sci. Lett. 465, 38–47. https://doi.org/10.1016/j.epsl.2017.02.036.

Watts, A., Ryan, W., 1976. Flexure of the lithosphere and continental margin basins. Tectonophysics 36, 25–44.

Wijninga, V.M., 1996. Palynology and Paleobotany of Neogene Sediments from the High plain of Bogotá (Colombia): Evolution of the Andean flora from an Ecological Perspective. Ph.D. thesis. University of Amsterdam, pp. 370.

Xie, X., Heller, P.L., 2009. Plate tectonics and basin subsidence history. Geol. Soc. Am. Bull. 121 (1–2), 55–64. https://doi.org/10.1130/B26398.1.

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, 686–693. https://doi.org/10.1126/science.1059412.