Chapter 11

Oligocene – Miocene Coal–Bearing Successions of the Amagá Formation, Antioquia, Colombia: Sedimentary Environments, Stratigraphy, and Tectonic Implications

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Abstract The Amagá Formation is a late Oligocene – middle Miocene tropical siliciclastic succession that was deposited along several semi–isolated intramontane (pull–apart) sedimentary basins in the northernmost part of the Colombian Andes. Despite the fact that these coal–bearing sedimentary records constitute one of the most complete late Oligocene – middle Miocene continental successions deposited along the hinterland of the northern Andes convergent margin, limited geologic information is available in the literature about their sedimentology and stratigraphy. In this contribution, we report new detailed stratigraphic information from the Amagá Formation in the Santa Fe de Antioquia–San Jerónimo Sub–basin and integrate it with previously published sedimentologic, sequence stratigraphic, biostratigraphic, geochronologic, and thermochronologic information about the sedimentary successions in this formation, which crop out along the Amagá–Venecia, Fredonia–La Pintada–Valparaíso, and Santa Fe de Antioquia–San Jerónimo Sub–basins. This integrative approach allows us to assess the mechanisms controlling the sedimentologic evolution of tropical hinterland/intramontane successions along Andean–type convergent margins.

Our approach allows us to subdivide the Amagá Formation into two members, i.e., the Lower and Upper Members. Regionally, the Lower Member records a change in sedimentary environments from a braided river system to a meandering river system. This change occurred during a period of increasing sediment accommodation space, which coincides with the late Oligocene (28–25 Ma) break–up of the Farallon Plate into the Nazca and Cocos Plates. The Upper Member of the Amagá Formation displays a facies association typical of braided river systems, and it was deposited during a period of decreasing sediment accommodation space. This decrease in sediment accommodation space likely resulted from a major regional uplift event associated with the early Miocene change from oblique to orthogonal convergence between the Nazca and South American Plates and the early Miocene (23–21 Ma) docking of the Panamá–Chocó Block to northern South America.

Keywords: *Amagá Formation, sequence stratigraphy, northwestern Andes, Oligocene – Miocene tectonics, Panamá–Chocó Block.*

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Resumen La Formación Amagá es una sucesión siliciclástica tropical del Oligoceno tardío–Mioceno medio depositada a lo largo de varias cuencas sedimentarias semiaisladas intramontañosas (tracción) en la parte más septentrional de los Andes colombianos. A pesar de que estos registros sedimentarios con capas de carbón constituyen una de las sucesiones continentales del Oligoceno tardío–Mioceno medio más completas depositadas a lo largo del interior del margen convergente de los Andes del norte, la información geológica disponible sobre su sedimentología y estratigrafía es limitada. En esta contribución reportamos información estratigráfica nueva y detallada de la Formación Amagá en la Subcuenca de Santa Fe de Antioquia–San Jerónimo. Integramos esta información con datos publicados de sedimentología, estratigrafía de secuencias, bioestratigrafía, geocronología y termocronología de las sucesiones sedimentarias en esta formación, que aflora a lo largo de las subcuencas de Amagá–Venecia, Fredonia–La Pintada–Valparaíso y Santa Fe de Antioquia–San Jerónimo. Este enfoque integrador nos da la posibilidad de evaluar los mecanismos que controlan la evolución sedimentológica de sucesiones intramontañosas tropicales a lo largo de márgenes convergentes de tipo andino.

Este estudio nos permitió subdivir la Formación Amagá en dos miembros, el Miembro Inferior y el Miembro Superior. A nivel regional, el Miembro Inferior registra un cambio en los ambientes sedimentarios de un sistema de río trenzado a uno de río meándrico. Este cambio se produjo durante un período de aumento del espacio de alojamiento o acumulación de sedimentos en la cuenca, que coincide con la división de la Placa Farallon en las placas de Nazca y de Cocos en el Oligoceno tardío (28–25 Ma). El Miembro Superior de la Formación Amagá muestra asociaciones típicas de facies de sistemas de ríos trenzados, depositadas durante un período de disminución del espacio de acomodación de los sedimentos. Esta disminución de espacio probablemente se debió a un importante evento regional de levantamiento asociado al cambio mioceno temprano de convergencia oblicua a ortogonal entre la Placa de Nazca y la Placa de Suramérica y al avance y colisión del Bloque Panamá–Chocó al norte de Suramérica en el Mioceno temprano (23–21 Ma).

Palabras clave: *Formación Amagá, estratigrafía de secuencias, noroccidente de los Andes, tectónica oligocena–miocena, Bloque Panamá–Chocó.*

1. Introduction

The Cenozoic Amagá Formation is a hinterland/intramontane fluvial siliciclastic succession that crops out in the northernmost part of the Colombian Andes between what is currently known as the Central and Western Cordilleras of Colombia (Figure 1). These late Oligocene – middle Miocene tropical continental sedimentary successions, some of which display important occurrences of economically exploitable coalbeds (Grosse, 1926; Guzmán, 1991), were deposited in several semi–isolated pull–apart basins (Figures 1, 2; Guzmán & Sierra, 1984). These coal–bearing siliciclastic continental sedimentary records have been studied by several authors since the early 20th century (i.e., Grosse, 1926; Guzmán & Sierra, 1984; Delsant & Tejada, 1987; Guzmán, 1991, 2003, 2007a; Murillo, 1998; Correa & Silva–Tamayo, 1999; Hernández, 1999; González, 2001; Sierra et al., 2003; Silva–Tamayo et al., 2008; Henao, 2012; Sierra & Marín–Cerón, 2012; Páez–Acuña, 2013; Rojas–Galvis & Salazar–Franco, 2013; etc.). Although most of these works focused on investigating the evolution of the Amagá Formation, some of them have also focused on quantifying the economic exploitability of the coal reserves of the Amagá Formation.

To date, few studies have integrated sedimentologic and sequence stratigraphic analyses of the Amagá Formation (i.e., Silva–Tamayo et al., 2008), and very few published studies have focused on investigating how the Cenozoic tectonic evolution of the northern Andes controlled the evolution of these tropical intramontane siliciclastic successions, which temporally coincides with periods of major plate tectonic reconfiguration along this margin (Montes et al., 2015; Piedrahita et al., 2017; Lara et al., 2018; León, et al., 2018).

To further contribute to the knowledge of the evolution of the coal–bearing Amagá Formation, here, we report new detailed stratigraphic information from the Amagá Formation

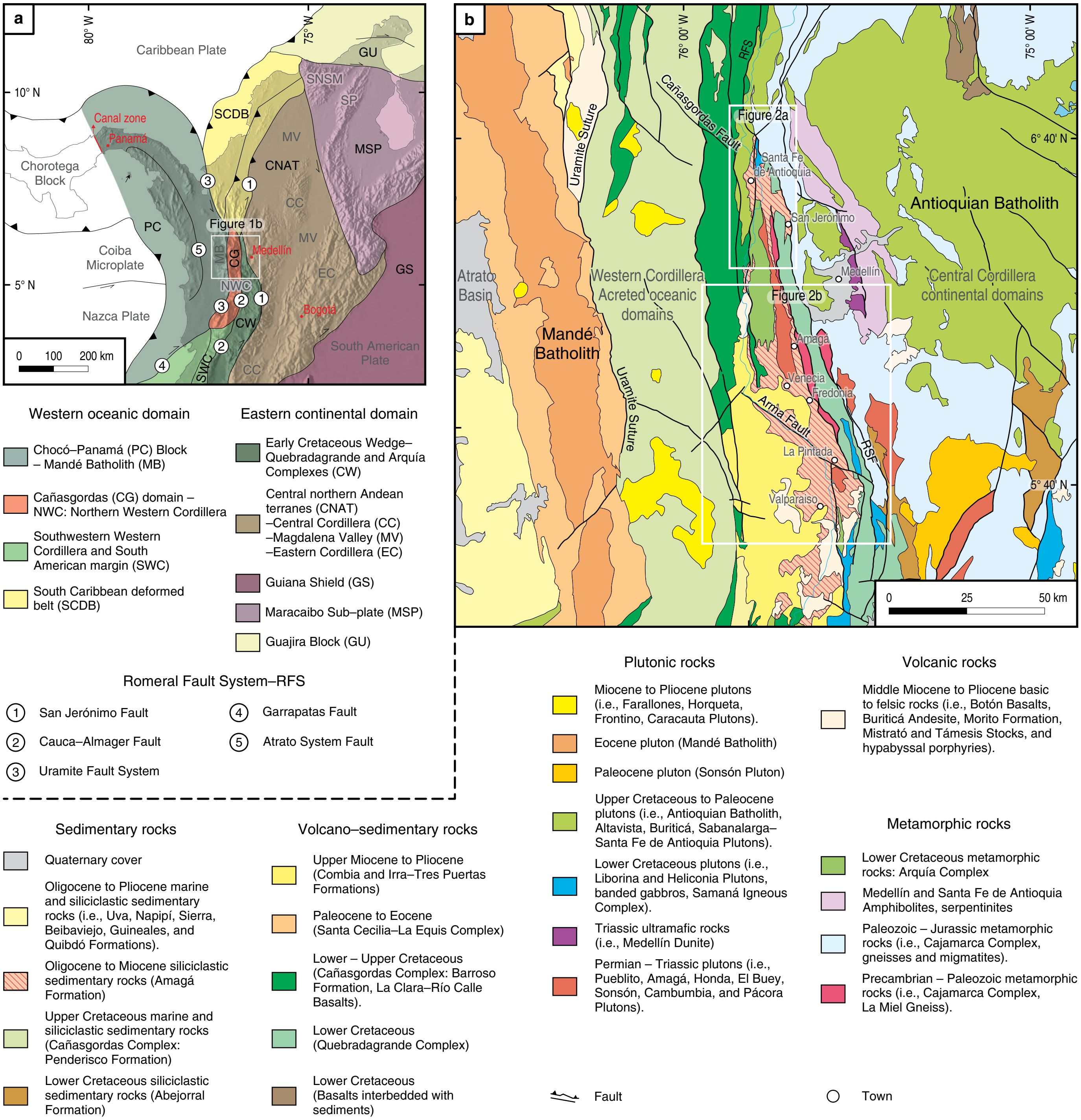


Figure 1. Geological setting and location of the study area. **(a)** Lithotectonic domains of the northwestern South America and Panamanian area (modified from Cediel et al., 2003). **(b)** Geological setting of the northwestern Andes (modified from Gómez et al., 2015). (SNSM) Sierra Nevada de Santa Marta; (SP) serranía de Perijá; (RFS) Romeral Fault System.

along the Santa Fe de Antioquia–San Jerónimo (SS) Sub–basin. We present a review of previously published studies focusing on the stratigraphy of the Amagá Formation along the Amagá–Venecia (AV) and Fredonia–La Pintada–Valparaíso (FPV) Sub–basins, which are located further south of the SS Sub–basin. Sequence stratigraphic analyses are used to propose a genetic stratigraphic correlation of those sedimentary records and to assess the stratigraphic division of the Amagá Formation. These sequence stratigraphic data, complemented with previously published biostratigraphic, geochronologic (U–Pb detrital zircon ages), and thermochronologic (zircon fission–track cooling ages) data, are used to investigate how changes in the

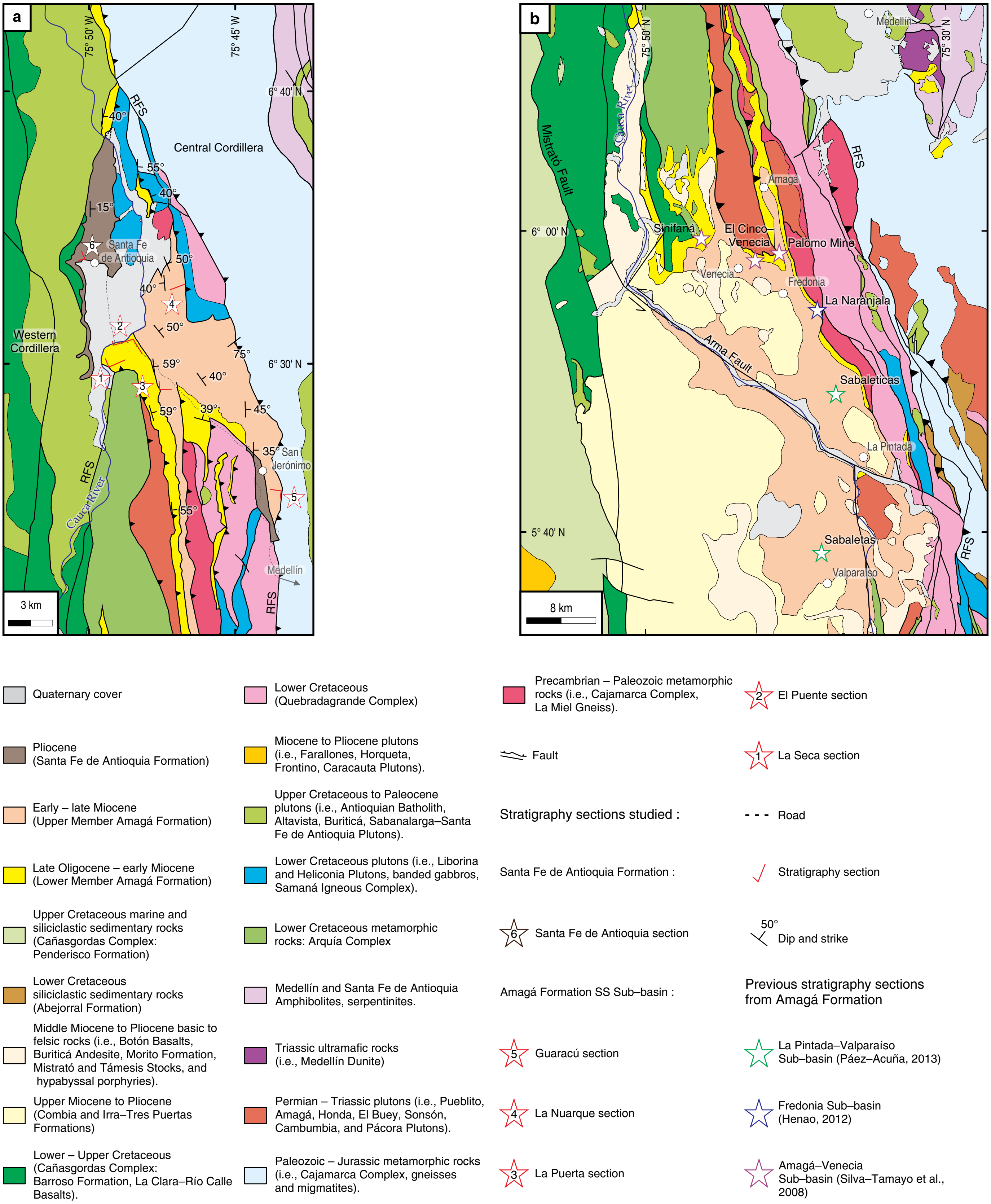


Figure 2. (a) Geological setting and location of Santa Fe de Antioquia and San Jerónimo Sub–basins of the Amagá Formation, study area (modified from González, 2001; Gómez et al., 2015; Montes et al., 2015). **(b)** Geological setting and location of Amagá–Venecia, Fredonia–La Pintada–Valparaíso Sub–basins of the Amagá Formation (modified from González, 2001; Gómez et al., 2015). (RFS) Romeral Fault System.

stratigraphic and sedimentologic characteristics of the Amagá Formation paralleled changes in Andean tectonics during the Oligocene – Miocene. The results of this work are ultimately used to further contribute to the investigation of the influence of changes in Andean tectonics on the deposition of intramontane siliciclastic successions along the northern Andes.

2. Geologic Setting

The Cenozoic evolution of the northern Andes has been influenced by important changes in tectonic setting, such as the late Oligocene break–up of the Farallon Plate into the Nazca and Cocos Plates (25–23 Ma; Pilger, 1984; Lonsdale, 2005; Pindell & Kennan, 2009; Escalona & Mann, 2011) and the early Miocene initial docking and collision of the Panamá–Chocó (PC) Block to northern South America (23–21 Ma; Montes et al., 2015; Lara et al., 2018). These changes in tectonic regime resulted in the formation of several pull–apart basins between the Central Cordillera and Western Cordillera of Colombia along what is today known as the Romeral Suture. The opening of these basins allowed for the deposition of several hinterland/intramontane siliciclastic successions, such as the Amagá Formation, which is the stratigraphic unit that is the focus of this work. The continued interaction between the PC and South American Blocks considerably increased during the middle Miocene and marked the end of the deposition of the Amagá Formation (ca. 15–13 Ma; Montes et al., 2015; Lara et al., 2018). This interaction also resulted in the emergence of the Panamá Isthmus and the subsequent closure of the Central America Seaway during the late Miocene – Pliocene (Duque–Caro, 1990; O'Dea et al., 2016; Lara et al., 2018). This event coincided with the onset of late Miocene – Pliocene arc magmatism along the different pull–apart basins where the Amagá Formation was deposited (MacDonald, 1980; Restrepo et al., 1981; Leal–Mejía, 2011; Rodríguez & Zapata, 2014). It also resulted in the deposition of several intramontane fluvial sedimentary successions, such as the Pliocene siliciclastic Santa Fe de Antioquia Formation, which unconformably overlies the Amagá Formation in the SS Sub–basin (Figures 1b, 2a; Lara et al., 2018; this work).

The Amagá Formation is an intramontane fluvial siliciclastic succession that contains important occurrences of economically exploitable coalbeds (Grosse, 1926; González, 1980). It crops out along the northwesternmost part of the northern Andes, between the Western and Central Cordilleras of Colombia, within a series of south–north–trending pull–apart basins that follow the trace of the strike of the Romeral Fault System (RFS) (Figures 1, 2; Guzmán, 1991; Sierra et al., 2003; Silva–Tamayo et al., 2008; Sierra & Marín–Cerón, 2012). The RFS is the tectonic suture that separates the allochthonous oceanic domains of western Colombia from the autochthonous continental domains located to the east (Figure 1a; Cediel et al., 2003; Moreno–Sánchez & Pardo–Trujillo, 2003; Chicangana, 2005; Cochrane et al., 2014; Spikings et al., 2015).

Ospina (1911) was the first to produce a preliminary map of the lithologic units of the Amagá Formation near Amagá town. Posada (1913) was the first to propose a formal stratigraphic hierarchical name for this siliciclastic record, i.e., "Formación Carbonífera de Amagá". Grosse (1926) renamed this sedimentary record "Terciario Carbonífero de Antioquia" and subdivided it into two units based on the presence or absence of coal–bearing layers. van der Hammen (1958), following the work of Grosse (1926), formally named it the "Antioquia Formation". González (1980) finally proposed the name "Amagá Formation", which is still in use. González (1980) and Delsant & Tejada (1987) also subdivided the Amagá Formation into three members based on the presence or absence of coal. Sierra et al. (2003) finally subdivided the Amagá Formation based on its facies associations, variations in depositional environments, and changes in the compositional modes of its major petrofacies. Silva–Tamayo et al. (2008) used high–resolution lithostratigraphic analyses to investigate the depositional style of the Amagá Formation in the AV Sub–basin and proposed a sequence stratigraphic framework for the Amagá Formation. Based on their findings, these authors also redefined the Amagá Formation and divided it into two members, i.e., the Lower and Upper Members.

The Amagá Formation unconformably overlies and/or is often found in fault contact with the metamorphic and igneous basement of the Central Cordillera and Western Cordillera of Colombia, i.e., the Cretaceous Quebradagrande and Arquía Complexes, Cretaceous Sabanalarga Batholith, and Triassic Pueblito and Amagá Stocks, among others (Figures 1b, 2; Grosse, 1926; González, 2001). The Amagá Formation is overlain, discordantly to para–conformably, by a series of upper Miocene – Pliocene volcano–sedimentary successions from the Combia, Morito, Irra–Tres Puertas, and Santa Fe de Antioquia Formations (Leal–Mejía, 2011; Rodríguez & Zapata, 2014; Lara et al., 2018; this work). It is also intruded by late Miocene (11–6 Ma) hypabyssal porphyries (Figures 1b, 2b) and volcanic rocks (with adakitic affinity) from the Combia Formation in the AV and FPV Sub–basins (MacDonald 1980; Restrepo et al., 1981; Leal–Mejía, 2011; Rodríguez & Zapata, 2014; Borrero & Toro–Toro, 2016). The Amagá Formation has mainly been studied along the AV and FPV Sub–basins, where important coalbeds occur (Figures 1b, 2b; Grosse, 1926; González, 1980; Correa & Silva–Tamayo, 1999; Sierra et al., 2003; Silva–Tamayo et. al., 2008; Henao, 2012; Páez–Acuña, 2013; and references therein). The Amagá Formation also crops out to the north of the AV Sub–basin, along the SS Sub–basin, which is the focus of the present study (Figures 1b, 2a; Lara et al., 2018; this work).

The depositional age of the Amagá Formation is controversial. Scheibe (1919) was the first to propose a depositional age for the Amagá Formation. This author proposed a Tertiary age based on the presence of undifferentiated Tertiary palynomorphs in the Lower Member in the AV Sub–basin. Later, Grosse (1926) reported the presence of Eocene – Oligocene palynomorphs in the Lower Member of the Amagá Formation in the AV Sub–basin and interpreted those ages as the maximum depositional age of the Amagá Formation. Eocene palynomorphs have also been reported for the Lower Member of the Amagá Formation in both the SS (Ramírez et al., 2015 and references therein) and AV Sub–basins (Londoño et al., 2013 and references therein). However, the presence of Eocene palynomorphs in the Amagá Formation is controversial and has recently been attributed to the reworking of pre–existing Eocene sedimentary units that crop out along the track of the RFS (Lara et al., 2018). Although Pons (1984) reported Oligocene – Miocene palynomorphs in the Lower Member of the AV Sub–basin, the lack of stratigraphic control in that work makes it difficult to assess the reliability of this age of the Lower Member.

The upper depositional age of the Amagá Formation is less controversial. A late Miocene upper depositional age can be proposed based on the 10–7 Ma age of the overlying volcanic (adakitic affinity) deposits of the Combia and Monitos Formations (Borrero & Toro–Toro, 2016) and the occurrence of the 6 to 11 Ma hypabyssal porphyritic intrusions cross–cutting the Upper Member in the AV Sub–basin (MacDonald,1980; Restrepo et al., 1981; Leal–Mejía, 2011; Rodríguez & Zapata, 2014). The middle Miocene upper depositional age of the Amagá Formation is further supported by the presence of 13 Ma detrital zircons in the Upper Member of the Amagá Formation in the SS Sub–basin (Montes et al., 2015). In this sub–basin, the Amagá Formation is unconformably overlain by the Santa Fe de Antioquia Formation, which contains 4.8 Ma detrital zircons (Lara et al., 2018).

Detrital zircon fission–track (ZFT) and magnetic susceptibility anisotropy (ASM) data suggest that several deformational and exhumation events affected both the Lower and Upper Members of the Amagá Formation in the AV Sub–basin. These events have been related to the Oligocene break–up of the Farallon Plate into the Nazca and Cocos Plates as well as to the Miocene collision of the PC Block to northern South America (Ramírez–Arias et al., 2012; Sierra & Marín–Cerón, 2012; Piedrahita et al., 2017; Lara et al., 2018). Lara et al. (2018) used the detrital zircon fission–track data and U–Pb detrital zircon ages from the Upper Member to propose a short lag time between the erosion of its sediment source areas and the sedimentation of the Upper Member.

Finally, the Amagá Formation has been regionally correlated with marginal continental and transitional siliciclastic deposits from the Cauca–Patía and San Jacinto Basins (Figure 3; references therein). However, these correlations most be regarded with caution given the lack of consensus on the ages of these formations.

3. Methods

In this contribution, we report both previously published and unpublished sedimentologic and stratigraphic information about the Amagá Formation. Four previously published composite stratigraphic columns of the Amagá Formation from the AV and FPV Sub–basins are presented in Figures 4–6 (Silva–Tamayo et al., 2008; Henao, 2012; Páez–Acuña, 2013). In addition, one new composite stratigraphic column of the Amagá Formation from the SS Sub–basin is herein reported for the first time (Figure 7). One new stratigraphic column of consolidated but uncemented sediments unconformably overlying the Amagá Formation in the SS Sub–basin (named the Santa Fe de Antioquia Formation; Lara et al., 2018) is also presented in detail here for the first time (Figure 7).

The sedimentary facies analyses of the Amagá and Santa Fe de Antioquia Formations in the SS Sub–basin were performed following Miall (1985, 1996). The sequence stratigraphic analyses were performed following Cross (1988) and Ramón & Cross (1997). These same methods were previously used by Silva–Tamayo et al. (2008) to subdivide the Amagá Formation into two members and later used by Henao (2012) and Páez–Acuña (2013) to study the sedimentary records in the AV and FPV Sub–basins. Briefly, variations in facies associations and variations in stratigraphic stacking patterns were used to define stratigraphic cycles. Variations in the preservation of geomorphic elements, such as channels, flood plains, point bars, and paleosols, were also considered when defining stratigraphic cycles. Long–term variations in stratigraphic cycles were subsequently used to define changes in the base level position along the basin, i.e., changes in the accommodation space (A)/sediment supply (S) ratio (A/S) (Cross, 1988; Ramón & Cross, 1997), and to correlate the different reported stratigraphic sections. Briefly, continental sedimentary successions displaying coarse–grained material and coarsening–upward and/or aggradational stacking patterns are considered to have been deposited during periods of low A/S. The low diversity of sedimentary facies and low preservation of fine–grained facies and geomorphic elements such as flood plains, lakes, point bars, and paleosols are also expected under low A/S conditions. Sediments deposited under low A/S conditions are also characterized by high degrees of channel amalgamation and the presence of erosional surfaces. During periods of high A/S, in turn, continental sedimentary successions display high facies diversity and especially the high preservation of fine–grained sediments and geomorphic features. The presence of coarse–grained material, i.e., conglomerates and coarse–grained sandstone, tends to decrease as the A/S increases. Enhanced accommodation space allows for the migration of rivers; therefore, the amalgamation of channels is low. This results in fining–upward stratigraphic cycles and a higher degree of symmetry between fining–upward and coarsening–upward cycles.

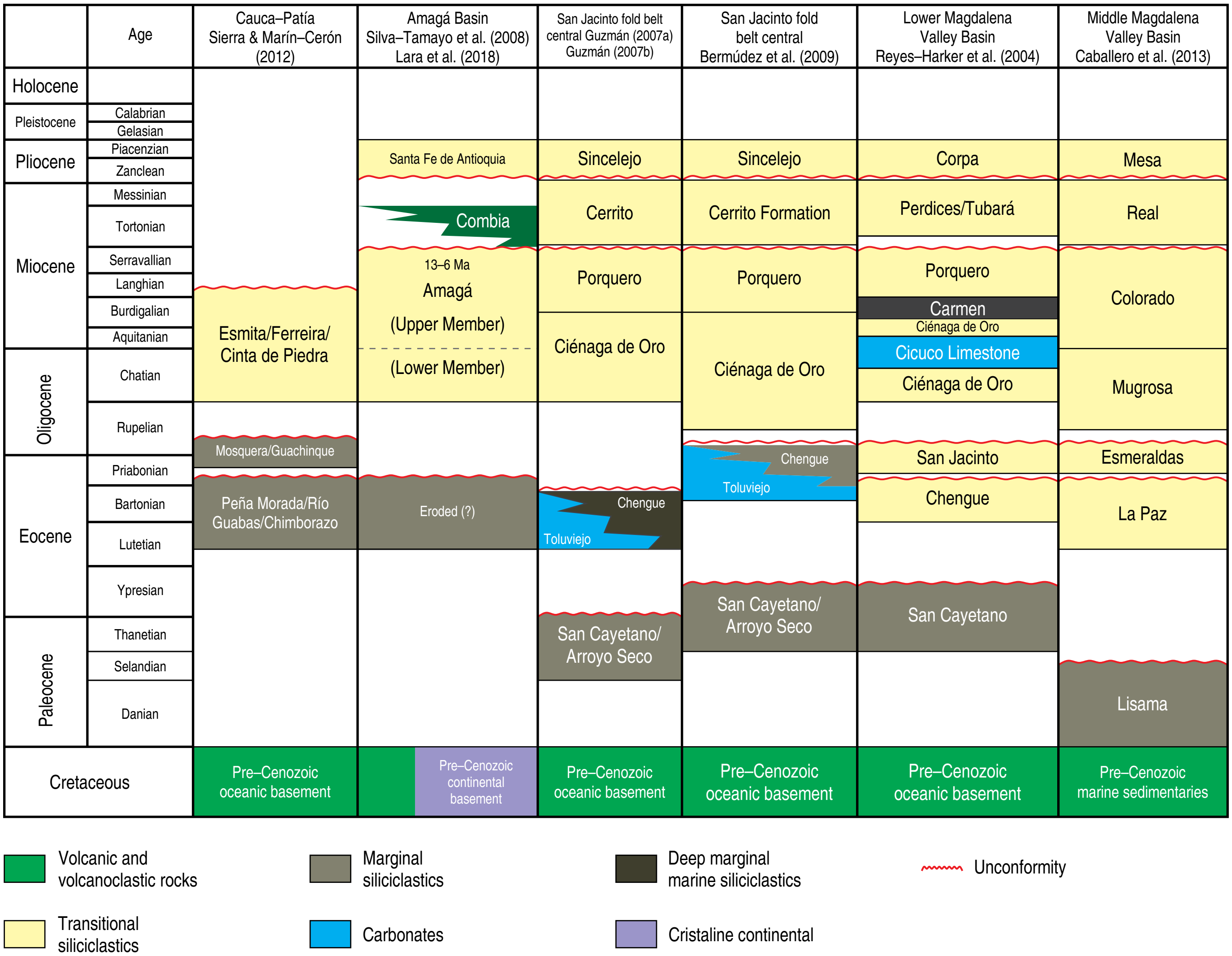


Figure 3. General Cenozoic litho–chronostratigraphic chart of western Colombia (references therein).

4. Results

4.1. Available and Published Lithostratigraphic Information

Sierra et al. (2003) and Silva–Tamayo et al. (2008) reported sedimentologic information for the Amagá Formation in the AV Sub–basin (Figures 1b, 2b, 4). The thickness of the Amagá Formation in this sub–basin is ca. 570 m. The Lower Member of the Amagá Formation unconformably overlies pre–Cenozoic rocks from the basement of the Central Cordillera of Colombia. The lowermost part of the Lower Member displays a series of aggradational conglomerates and conglomeratic sandstones overlain by fining–upward coarse– to medium–grained sandstones interbedded with slightly bioturbated (plant roots) siltstones and coals. Higher in the stratigraphy, the sandstones become medium to fine–grained and display both fining– and coarsening–upward characteristics. These sandstones, which also display a fining–upward trend, are interbedded with bioturbated siltstones and organic carbon–rich siltstones (coalbeds). The uppermost part of the Lower Member displays a decrease in the ratio of siltstone to sandstone, with the latter being coarser–grained and displaying mixed fining–upward and coarsening–upward trends. The lowermost part of the Upper Member of the Amagá Formation in the AV Sub–basin displays a basal series of thick, aggradational and coarsening–upward medium– to coarse–grained sandstones (Figure 4). Higher in the stratigraphy, the sandstone become thinner and interbedded with bioturbated (plant roots) siltstones. Unlike those in the Lower Member, the siltstones in the Upper Member are organic carbon–poor, which is reflected by the absence of coalbeds. The uppermost part of the Upper Member of the Amagá Formation in the AV Sub–basin displays a new increase in the proportion of sandstone to siltstone, with the former becoming more aggradational and thicker than those from the lowermost portion of the Upper Member.

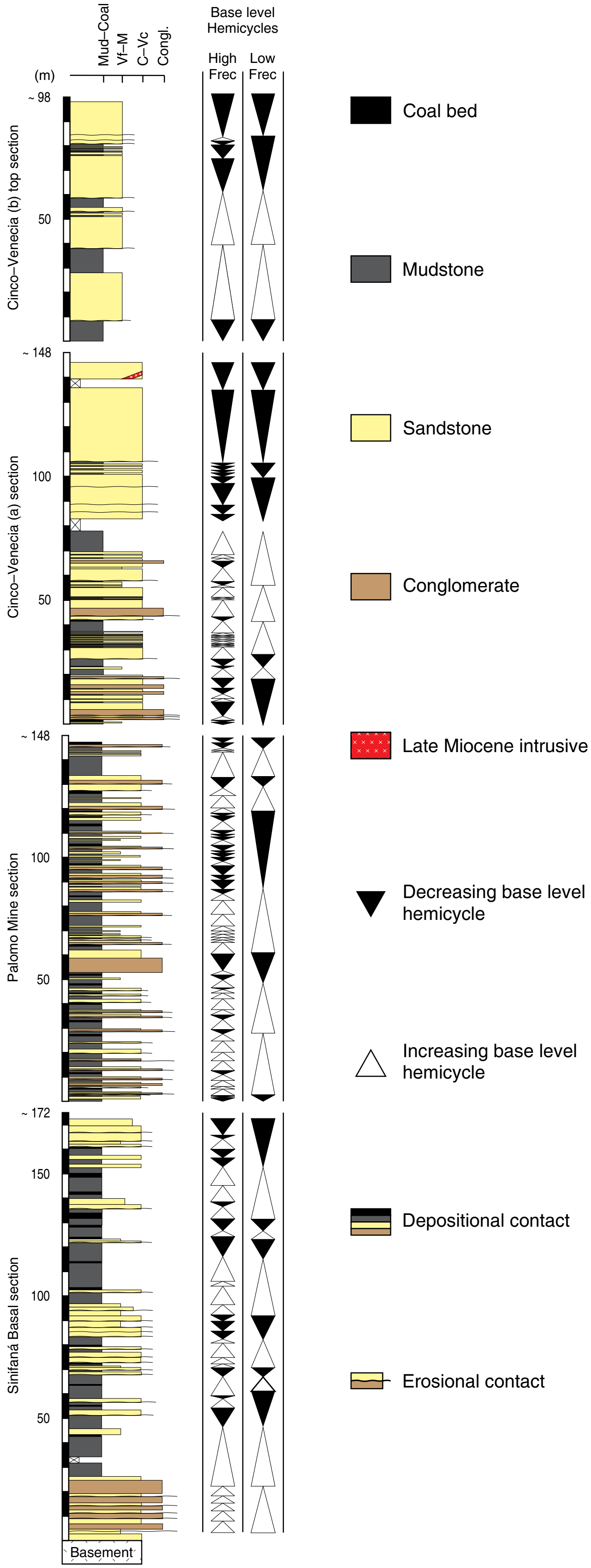


Figure 4. Lithostratigraphy of the Amagá Formation in the Amagá–Venecia Sub–basin (Silva–Tamayo et al., 2008).

Henao (2012) reported the sedimentologic and stratigraphic characteristics of the Amagá Formation along the FPV Sub–basin (Figures 1b, 2b, 5). In this sub–basin, the Amagá Formation is 345 m thick, but only the Lower Member of the Amagá Formation crops out. According to this author, the Amagá Formation unconformably overlies the pre–Cenozoic basement of the Central Cordillera of Colombia (Figures 1b, 2b, 5). The stratigraphic section reported by Henao (2012) displays a series of basal interbedded aggradational conglomeratic and coarse–grained sandstones. Higher in the stratigraphy, the conglomeratic sandstones become less frequent, and a series of fining–upward sandstones interbedded with bioturbated and organic carbon–rich siltstones (now coalbeds) occur. Even higher in the stratigraphy, these siltstones become more frequent and are interbedded with fining–upward medium to fine–grained sandstones. The uppermost part of the stratigraphic section reported by Henao (2012) is dominated by bioturbated and organic carbon–rich siltstones interbedded with limited fining–upward medium to coarse–grained sandstones (Figure 5).

Páez–Acuña (2013) reported sedimentologic and stratigraphic information for the two stratigraphic sections (Sabaletas and Sabaleticas sections) of the Amagá Formation from the FPV Sub–basin (Figures 1b, 2b, 6). The approximate composite thickness of the Amagá Formation is 257 m, but the base of the Amagá Formation does not crop out in either section. In the Sabaleticas stratigraphic section, the lowermost part of the Amagá Formation mostly displays aggradational, coarsening–upward medium–grained sandstones interbedded with bioturbated siltstones. These siltstones become more frequent higher in the stratigraphy, while the sandstones become thinner and fine upwards (Figures 2b, 6b). The lowermost part of the Sabaletas stratigraphic section displays a series of aggradational coarsening–upward medium– to coarse–grained sandstones with sporadic conglomeratic sandstones. Higher in the stratigraphy, the conglomeratic sandstones become less frequent, and the medium–grained sandstones become less aggradational and are interbedded with organic carbon–poor bioturbated siltstones (Figures 2b, 6a).

4.2. New Lithostratigraphic Information

The following paragraphs describe the six studied stratigraphic sections from the SS Sub–basin, which is the focus of this study. Figures 1b, 2a, and 7 show the generalized stratigraphic location and log of the Amagá Formation in the SS Sub–basin. The thickness of the Amagá Formation in this sub–basin is approximately 754 m. Figure 1 of the Supplementary Information shows the stratigraphic logs of the studied stratigraphic sec-

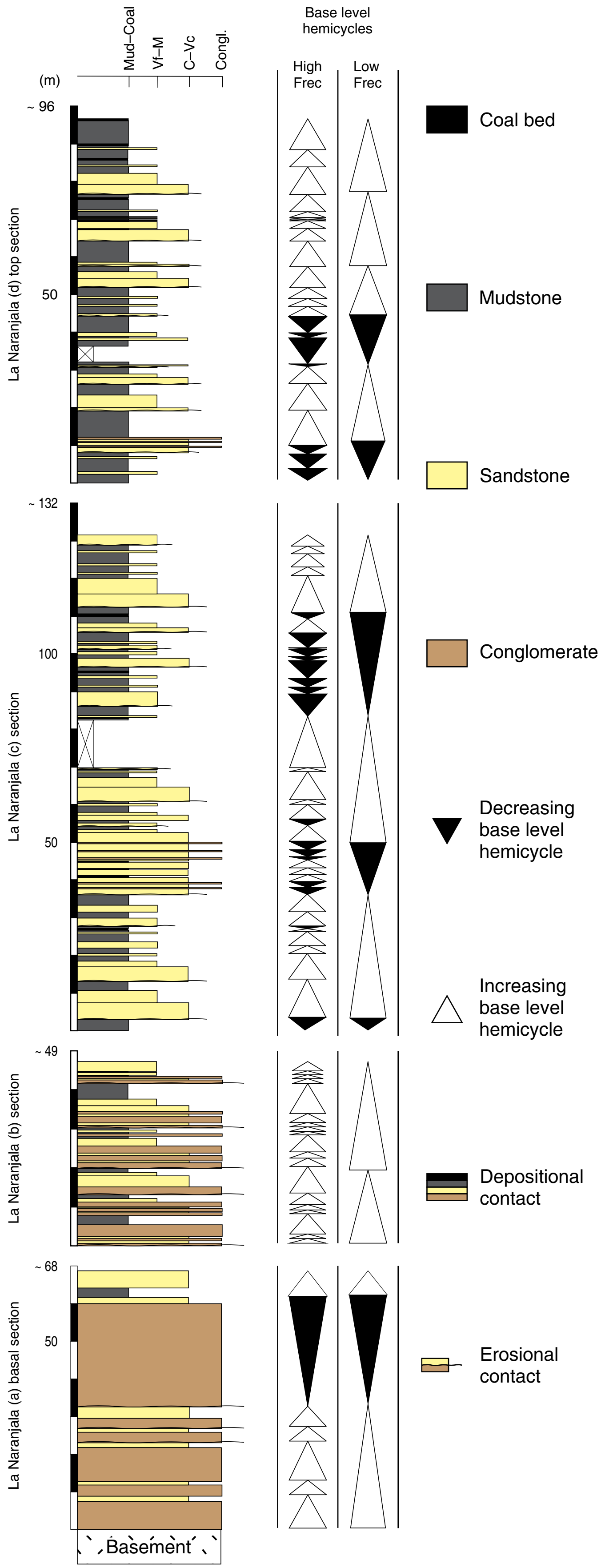


Figure 5. Lithostratigraphy of the Amagá Formation in the Fredonia area of the Fredonia–La Pintada–Valparaíso Sub–basin (Henao, 2012).

tions in detail. Figure 7 and the Figure 1 of the Supplementary Information also show the stratigraphic log of a consolidated uncemented sedimentary succession (54 m thick) that unconformably overlies the Amagá Formation. Table 1 presents the nomenclature of the principal sedimentary environments and related facies associations observed in the Amagá Formation (modified from Miall, 1985).

4.2.1. La Seca Stratigraphic Section

La Seca stratigraphic section corresponds to the lowermost part of the Amagá Formation (Figures 2a, 7). In this section, the Amagá Formation is 74 m thick and discordantly overlies the metamorphic basement of the Central Cordillera of Colombia, i.e., the Arquía Complex. The lower part of the stratigraphic section consists of sub–horizontal strata of coarse (St) to medium–grained (Sp) massive sandstones interbedded with polymictic conglomerates (Gt) and massive (Gms) and laminated (Gm) conglomeratic sandstones (Figure 8a). The stratigraphic succession displays a predominantly fining–upward character. The fining–upward Gt, Gm, and Gms facies are separated by erosional contacts and are often found amalgamated (Figure 7). The basal sandstones and conglomeratic facies are overlain by a 22 m thick interval of intercalated massive mudstones (Fsc) and laminated mudstones (Fl). This fine–grained interval is, in turn, overlain by a coarsening–upward package (14 m thick) of laminated fine to medium–grained massive (Sh) and laminated sandstones (Shl) and medium to coarse–grained massive sandstones (St, Sp). The uppermost part of this section is characterized by intercalations of mudstone (Fsc) with centimeter–scale layers of carbonaceous material (C) and laminated fine–grained sandstones (Shl).

4.2.2. El Puente Stratigraphic Section

El Puente stratigraphic section is ca. 331 m thick (Figures 2a, 7). The lowermost part (0–70 m thick) of this succession consists of fine–grained sandstones displaying planar and trough cross laminations (facies Sr and Srl) interbedded with strata of fine to medium–grained (Sh) and coarse to medium–grained sandstones (Sp, St), massive mottled mudstones (Fs), and organic matter–rich gray mudstones (Fsc) (Figure 8b). Some centimeter–scale coal layers (C) can also be found interbedded with the gray mudstones. An important increase in the grain size of the sandstones is observed between the heights of 34 and 70 m, where medium to coarse–grained sandstones with large scale high angle parallel laminations (Stl) and bimodal cross

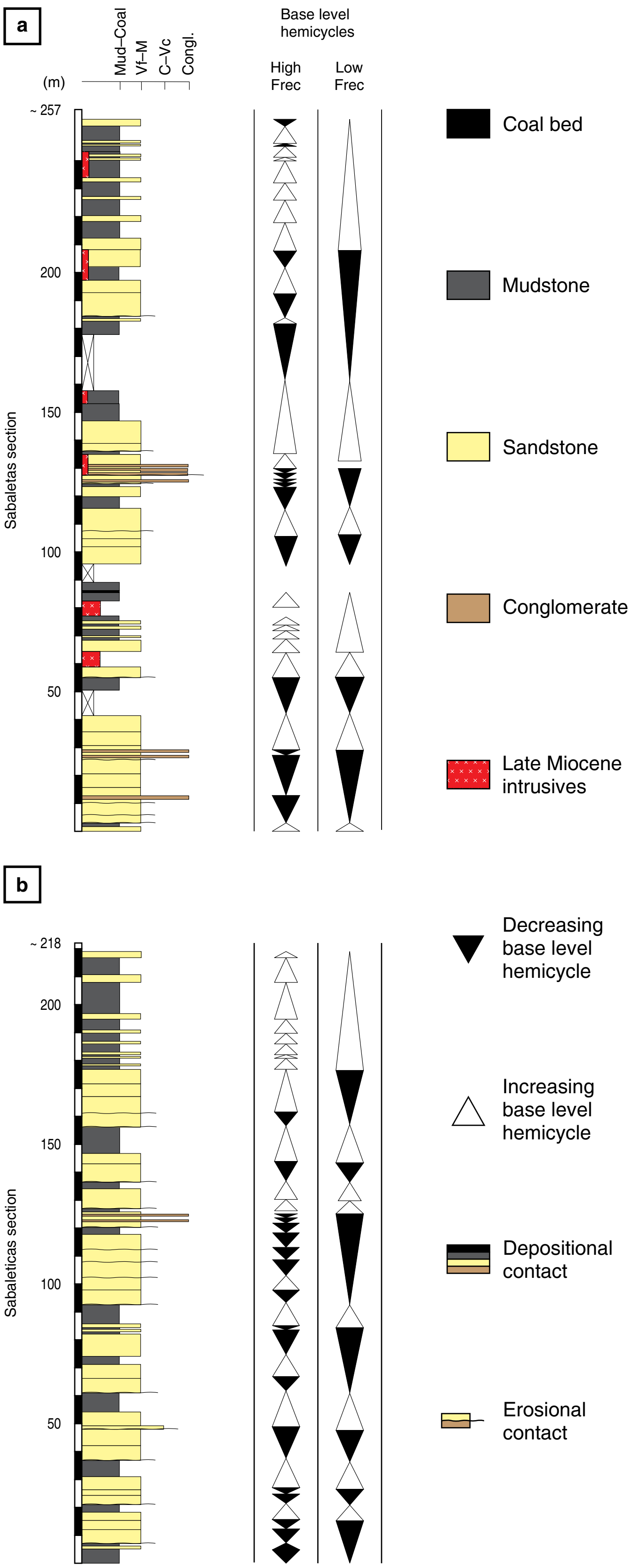


Figure 6. Lithostratigraphy of the Amagá Formation in the Valparaíso area of the Fredonia–La Pintada–Valparaíso Sub–basin (Páez–Acuña, 2013).

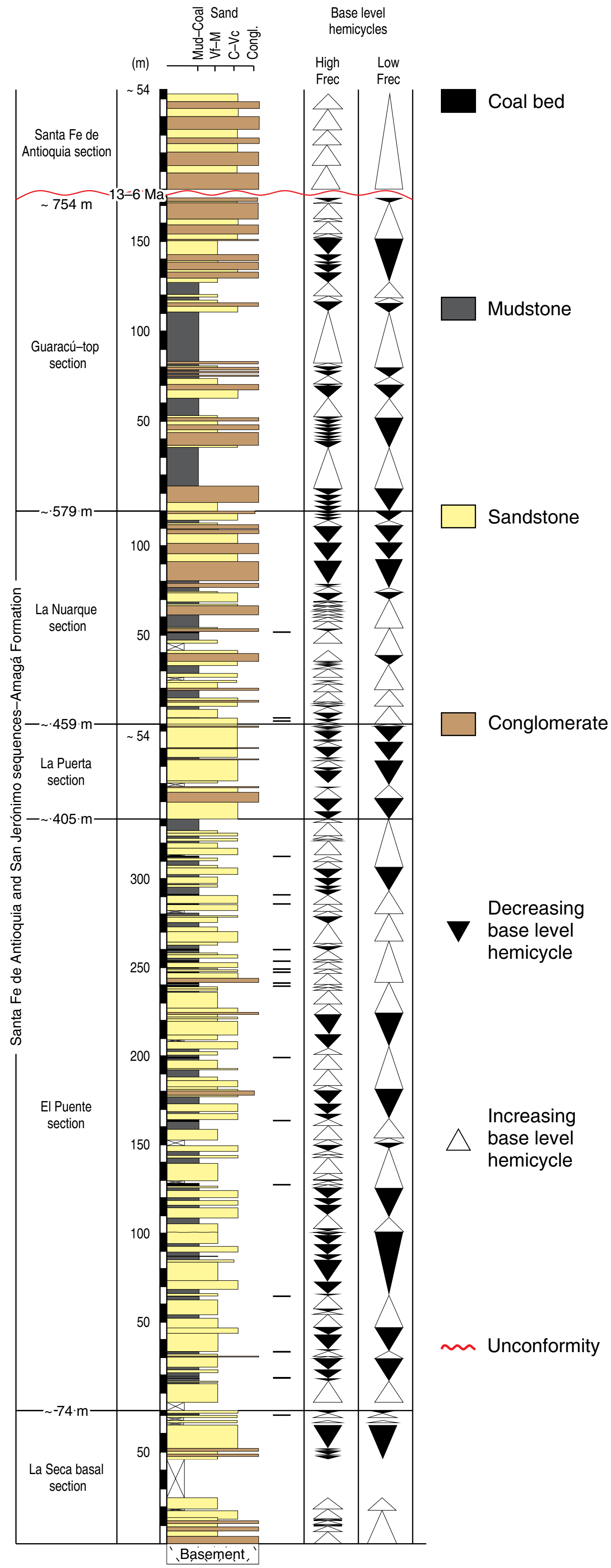


Figure 7. Lithostratigraphy of the Amagá and Santa Fe de Antioquia Formations in the Santa Fe de Antioquia–San Jerónimo Sub–basin.

Table 1. Principal sedimentary environments and related facies associations observed in the Amagá Formation.

Facies association	Facies	Facies code	Characteristics
Meandering channels	• Fine–grained sandstones with planar laminations.	Srl	• Fine–grained sandstone. It usually displays laminations. It is up to 1 m thick.
	• Fine–grained sandstone with trough laminations.	Sr	• Fine–grained sandstone. It can be found amalgamated and can be up to 2 m thick.
	• Fine– to medium–grained massive sandstone.	Sh	• Fine– to medium–grained sandstone up to 2 m thick.
	• Fine– to medium–grained laminated sandstone.	Shl	• Medium–grained sandstone up to 2 m thick.
	• Fine– to medium–grained sandstone with ripples.	Shcr	• Fine– to medium–grained sandstone. It can be amalgamated and is up to 2 m thick.
	• Fine– to medium–grained sandstone with high–angle parallel cross laminations.	Shlh	• Fine– to medium–grained sandstone up to 2 m thick.
	• Fine– to medium–grained sandstone with cross lamination.	Shc	• Fine– to medium–grained sandstone. It can be amalgamated and is up to 2 m thick.
	• Fine– to medium–grained sandstone with bimodal and trough cross stratification and laminations.	Shcb	• Amalgamated sandstone up to 3 m thick.
	• Fine– to medium–grained sandstone with large–scale cross stratification.	Shlc	• Amalgamated sandstone up to 5 m thick.
	• Fine– to medium–grained sandstone with climbing ripples.	Shcri	• Fine– to medium–grained sandstone with climbing ripples. Usually up to 2 m thick.
	• Fine– to medium–grained sandstone with undulated laminations.	Shu	• Fine– to medium–grained sandstone. It can be up to 2 m thick.
	• Coarse–grained sandstone with high–angle parallel cross laminations.	Stlh	• Coarse–grained sandstone up to 2 m thick.
	• Coarse–grained sandstone with bimodal cross stratification and laminations.	Stc	• Coarse–grained sandstone. It can be amalgamated and up to 3 m thick.
	• Coarse–grained sandstone with bimodal and trough cross stratification and laminations.	Stcb	• Coarse–grained sandstone. It can be amalgamated and up to 5 m thick.
	• Coarse–grained massive sandstone.	St	• Coarse–grained sandstone that is 0.5 to 5.0 m thick.
	• Medium–grained massive sandstone.	Sp	• Medium–grained massive sandstone that is 0.5 to 5.0 m thick.
Braided channels	• Massive mudstones.	Fsc	• Black, gray to green massive mudstones, up to 5 m thick.
	• Laminated mudstones.	Fl	• Black, gray to green laminated mudstones, up to 5 m thick.
	• Fine– to medium–grained massive sandstone.	Sh	• Fine– to medium–grained sandstone up to 2 m thick.
	• Fine– to medium–grained laminated sandstone.	Shl	• Fine– to medium–grained sandstone up to 2 m thick.
	• Coarse–grained massive sandstone.	St	• Coarse–grained sandstone that is 0.5 to 5.0 m thick.
	• Coarse–grained laminated sandstone.	Stl	• Coarse–grained laminated sandstone. Up to 5 m thick.
	• Coarse–grained sandstone with trough cross stratification.	Stt	• Coarse–grained sandstone. Up to 5 m thick and can be amalgamated.
	• Coarse–grained sandstone with planar cross stratification and laminations.	Stc	• Coarse–grained sandstone. Up to 5 m thick and can be amalgamated.
	• Medium–grained massive sandstone.	Sp	• Medium–grained massive sandstone 0.5 to 5.0 m thick.
	• Polymictic conglomerates.	Gt	• Clasts displaying several compositions. Generally very massive.
	• Conglomeratic sandstone with continuous parallel lamination.	Gm	• Coarse–grained sandstone 1 to 5 m thick.
	• Massive conglomeratic sandstone.	Gms	• Coarse–grained sandstone 1 to 5 m thick.
Crevasse	• Fine– to medium–grained sandstone with cross lamination.	Shc	• Sandstone up to 1 m thick.
	• Fine– to medium–grained sandstone with large–scale cross stratification.	Shlc	• Sandstone up to 1 m thick.
	• Fine– to medium–grained sandstone with climbing ripples.	Shcr	• Sandstone up to 1 m thick.
	• Fine– to medium–grained sandstone with undulating laminations.	Shu	• Sandstone up to 1 m thick.
Humid flood plain	• Laminated mudstones.	Fl	• Black, gray to green laminated mudstones, up to 5 m thick.
	• Massive mudstones.	Fs	• Black, gray to green massive mudstones, up to 5 m thick.
	• Coal/organic–rich mudstones.	C	• Coalbed organic matter.

Source: Data modified from Miall (1985).

laminations (Stc) occur. Coarse–grained and medium–grained sandstones displaying trough cross stratification (Stcb, Shcb), as well as coarse–grained and medium–grained sandstones displaying parallel high angle cross laminations (Shlh, Stlh), are also common. These sandstones are strongly amalgamated, display several erosional surfaces, and contain some levels of polymictic conglomerates. Sandstones with calcareous concretions are also common.

A slight decrease in the amount of amalgamated sandstones and an increase in the amount of mudstones (facies Fsc, Fl) occurs between 70 and 85 m in height (Figures 2a, 7). The sandstones become thinner, and some display undulating laminations and small–scale ripples (facies Shu and Shcr). An important increase in fine–grained facies, i.e., organic–rich muds, occurs between the heights of 85 and 109 m. The sandstones are thicker and display unidirectional cross stratification, parallel laminations, and undulating laminations (facies Shc, Shl, Shu). Between the heights of 109 and 204 m, the proportions of sandstones and mudstones are similar. The coarse–grained sandstones with trough and parallel cross stratification (facies Stcb, Stlh) become abundant. The fine to medium–grained sandstones display undulating laminations, small and large–scale cross stratification, and climbing ripples (facies Shl, Shlc, Shcri). Between 204 and 238 m in height, there is an increase in the facies of St and Sp. Erosional surfaces separating amalgamated channels are also present. From 240 to 330 m in height, there is an increase in fine–grained facies, such as Fm, Fsc, and C. These sandstones usually belong to the Sp, Sr, and Sh facies.

4.2.3. La Puerta Stratigraphic Section

La Puerta stratigraphic section (ca. 54 m thick; Figures 2a, 7) consists of coarse–grained sandstones displaying parallel lamination and trough and planar cross stratification (facies Stl, Stt, Stc) (Figure 8c). The sandstone packages display erosional surfaces separating amalgamated channels. Some conglomerate levels with trough and planar cross stratification (facies Gt, Gm) are also present. The sandstones display calcareous concretions. A few interbedded green–gray mudstones, which are both massive and laminated and contain plant remains (facies Fsc and Fm), are also present.

4.2.4. La Nuarque Stratigraphic Section

This stratigraphic section crops out along the La Nuarque Creek in the northeastern part of the SS Sub–basin and is ca. 120 m thick (Figures 2a, 7, 8d). The lowermost part of the section (0 to 40 m in height) displays basal fine to coarse–grained sandstones displaying planar laminations and trough cross stratification (facies Stl, Stt). The sandstone packages display erosional surfaces and are interbedded with green mudstones, which contain poorly preserved organic matter (facies Fsc, Fl). Some conglomeratic horizons that are a few centimeters in thickness (facies Gms and Gt) are also present. The coarse–grained facies become less abundant between 40 and 62 m in height. In this interval, facies Fsc, Fl, and C become more abundant. A few medium to coarse–grained sandstones are interbedded between the fine–grained facies. Between 62 and 82 m in height, the conglomeratic facies become more common (Gt and Gms). The proportions of the fine–grained facies (Fsc, Fl, and C) are similar to those in the lowermost part of the section. Between the heights of 82 and 120 m, the amounts of fine–grained facies substantially decrease, and the coarse–grained sandstone and conglomeratic facies become abundant (facies Gt, Gm, St, Sp) (Figure 7).

4.2.5. Guaracú Stratigraphic Section

The Guaracú stratigraphic section is ca. 175 m thick (Figures 2a, 7). It consists of amalgamated coarse–grained sandstones, massive and polymictic conglomerates, and conglomeratic sandstone (facies Gm, Gms, St, Sp) (Figure 8e). The sandstones display mudstone intraclasts and calcareous concretions, as well as common erosional surfaces between amalgamated sandstones and conglomerates (Figure 7). This section also displays massive mudstones interbedded with the main sandstone packages.

4.2.6. Santa Fe de Antioquia Stratigraphic Section

The Santa Fe de Antioquia stratigraphic section is ca. 54 m thick (Figures 2a, 7, 8f). It consists of consolidated but uncemented sandstones and conglomerates. This stratigraphic section starts with para–conglomerates displaying fining–upward gradations and clast imbrications (facies Gm). These para–conglomerates unconformably overlie the Santa Fe de Antioquia Batholith and overlie the Amagá Formation along an angular unconformity. Higher in the stratigraphic section, both ortho– and para–conglomerates (facies Gm and Gms), as well as coarse–grained sandstones displaying both trough cross stratification and planar cross stratification (Stt, Stc), occur. Based on its unconformable position on top of the Amagá Formation and the U–Pb detrital zircon ages reported by Lara et al. (2018), we consider this sedimentary succession to be part of an additional stratigraphic unit, which is herein named the Santa Fe de Antioquia Formation.

5. Discussion

5.1. Sedimentary Environments

The lowermost part of the Amagá Formation in the SS Sub–basin crops out along La Seca stratigraphic section. In this section, it displays aggradational and fining–upward thick–bedded coarse–grained sandstones and conglomerates with

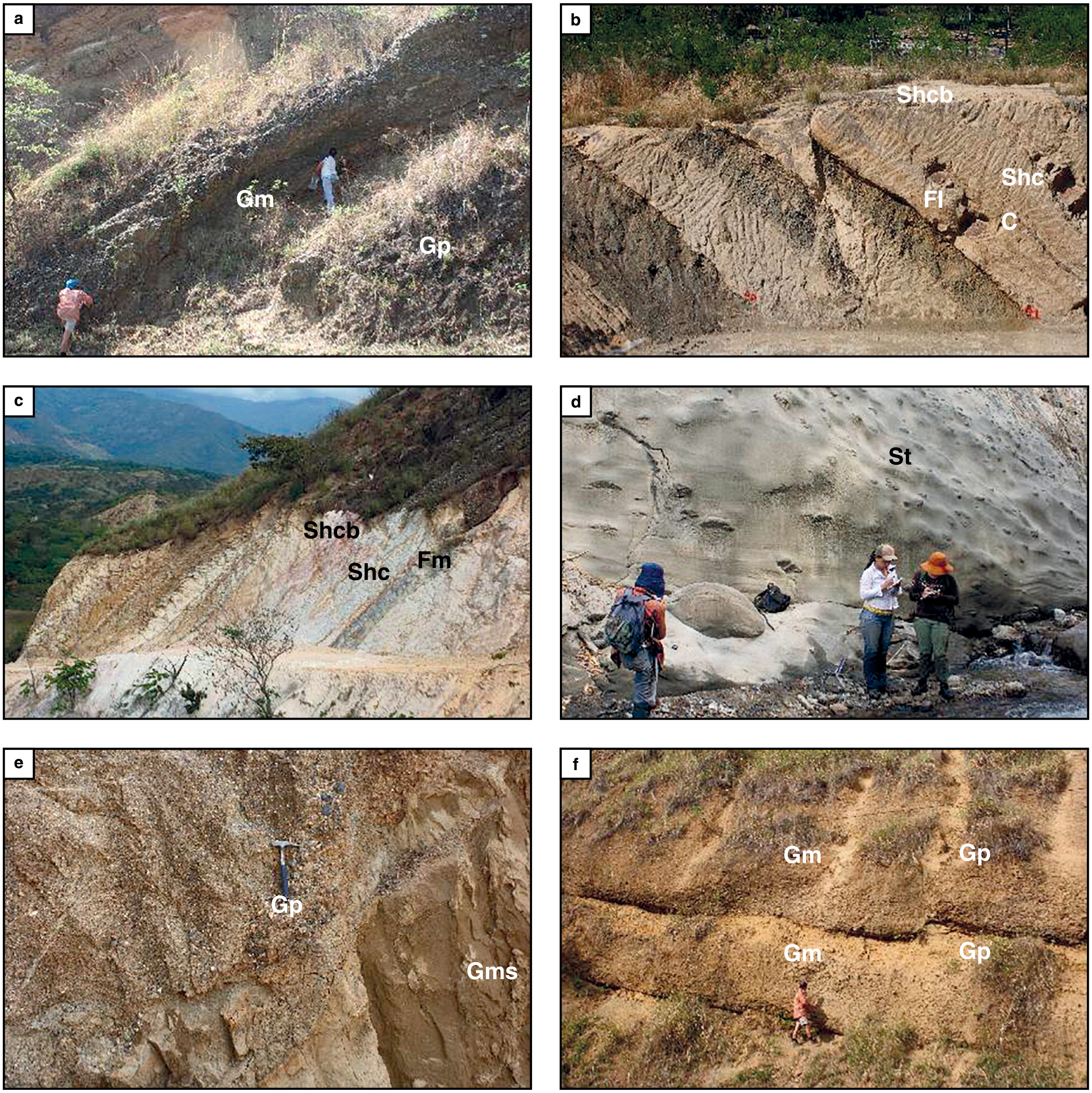
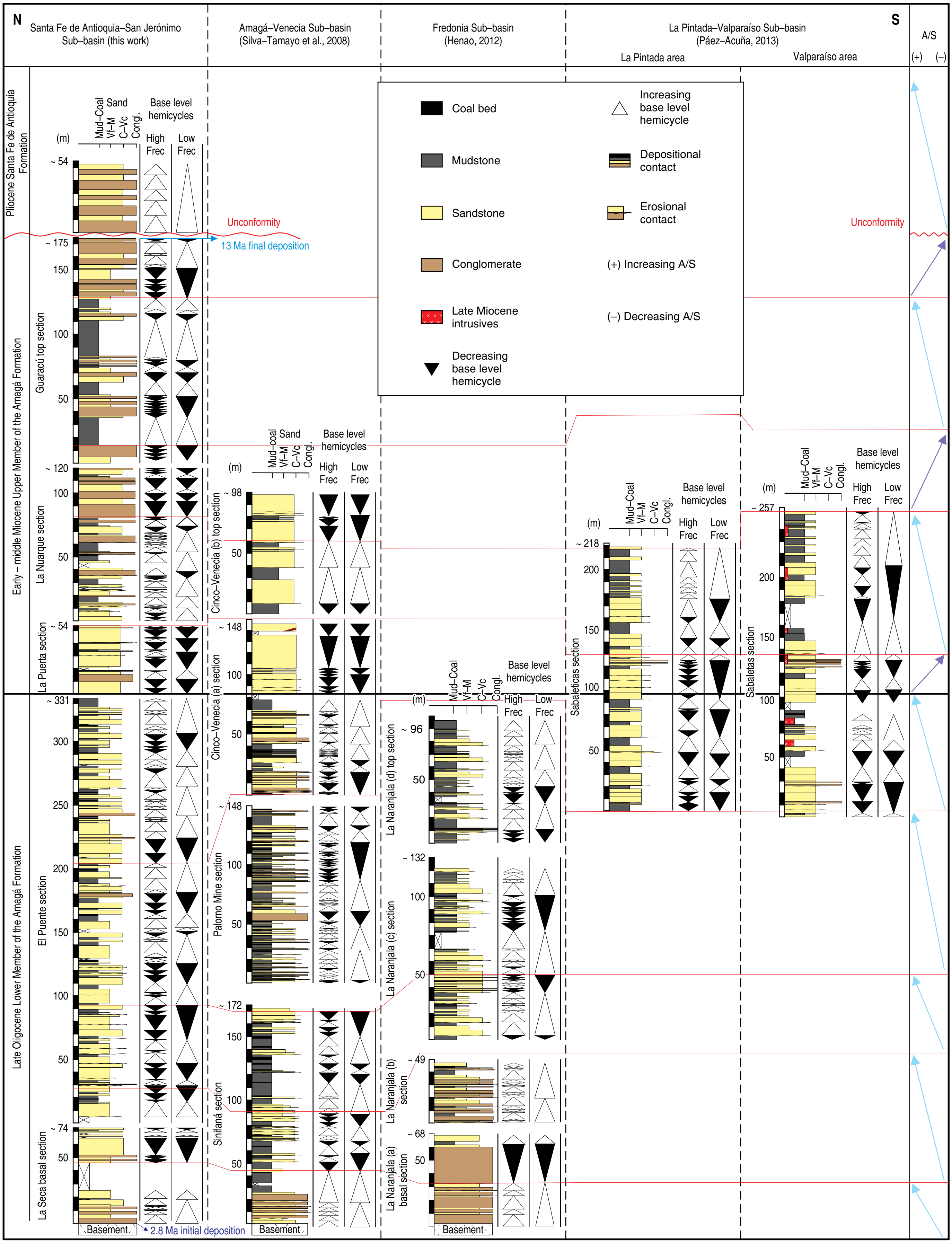


Figure 8. Images of outcrops of the Santa Fe de Antioquia and San Jerónimo sequences from the Amagá Formation. **(a)** Conglomerates and conglomeratic sandstones from the La Seca stratigraphic section. **(b)** Interbedded fining–upward sandstones and organic–rich mudstones from El Puente stratigraphic section. **(c)** Aggradational sandstones from La Puerta stratigraphic section. **(d)** Aggradational sandstones from La Nuarque stratigraphic section. **(e)** Conglomerates and conglomeratic sandstones from the Guaracú stratigraphic section. **(f)** Conglomerates and conglomeratic sandstones from the Santa Fe de Antioquia Formation. See Table 1 for facies descriptions.

poorly preserved fine–grained sedimentary facies. These facies, along with the poor preservation of fine–grained facies and geomorphic elements (i.e., flood plains), suggest that their deposition was associated with a braided river system (Figure 7; Table 1; Figure 1 of the Supplementary Information). The presence of highly amalgamated channels and the asymmetry of the stratigraphic cycles are consistent with this interpretation and suggest that they were deposited under the condition of low accommodation space. Following Silva–Tamayo et al. (2008), we suggest that the sedimentary record from La Seca stratigraphic section corresponds to the Lower Member of the Amagá Formation.


N
Santa Fe de Antioquia–San Jerónimo Sub–basin (this work)
Amagá–Venecia Sub–basin (Silva–Tamayo et al., 2008)
Fredonia Sub–basin (Henao, 2012)
La Pintada–Valparaíso Sub–basin (Páez–Acuña, 2013)
La Pintada area
Valparaíso area
S
A/S
(+) (–)
Pliocene Santa Fe de Antioquia Formation
Early – middle Miocene Upper Member of the Amagá Formation
Late Oligocene Lower Member of the Amagá Formation
Guaracú top section
La Nuarque section
La Puerta section
El Puente section
La Seca basal section
Cinco–Venecia (b) top section
Cinco–Venecia (a) section
Palomo Mine section
Sinifaná section
La Naranjala (d) top section
La Naranjala (c) section
La Naranjala (b) section
La Naranjala (a) basal section
Sabaletas section
Unconformity
13 Ma final deposition
2.8 Ma initial deposition
Basement
Mud–Coal
Vf–M
C–Vc
Congl.
Sand
Base level hemicycles
High Frec
Low Frec
(m)
Coal bed
Mudstone
Sandstone
Conglomerate
Late Miocene intrusives
Decreasing base level hemicycle
Increasing base level hemicycle
Depositional contact
Erosional contact
(+) Increasing A/S
(–) Decreasing A/S

←

Figure 9. Sequence stratigraphic correlation of the sedimentary records of the Amagá Formation in the Santa Fe de Antioquia–San Jerónimo, Amagá–Venecia, and Fredonia–La Pintada–Valparaíso Sub–basins. A/S = accommodation space/sediment supply ratio.

The middle and upper parts of the Lower Member of the Amagá Formation crop out along El Puente stratigraphic section (Figures 7, 9; Table 1; Figure 1 of the Supplementary Information). This section displays predominantly symmetric and fining–upward stratigraphic cycles, as well as a significant increase in the diversity of low–energy sedimentary facies (i.e., Fm, Fl, Fsc, and C) compared to La Seca stratigraphic section. It also displays the high preservation of geomorphic elements such as flood plains, point bars, and crevasse splay deposits. These characteristics suggest that their deposition was associated with a meandering river system under the condition of high accommodation space along the basin (Figure 7; Table 1; Figure 1 of the Supplementary Information).

The Upper Member of the Amagá Formation crops out in La Puerta, La Nuarque, and Guaracú stratigraphic sections. The lowermost part of the Upper Member (in the La Puerta section) mostly consists of aggradational and coarsening–upward amalgamated sandstones and conglomerates and displays poorly preserved fine–grained geomorphologic features such as flood plains. These characteristics suggest that it was deposited along a braided river system under the condition of low sediment accommodation (Figures 7, 9; Table 1; Figure 1 of the Supplementary Information). The change from a braided river to a meandering river environment is not the only main feature that allows us to divide the Amagá Formation into two members. As highlighted by Lara et al. (2018), the change in the composition of the sandstone from chemically mature to chemically immature is another characteristic that differentiates the Lower Member of the Amagá Formation from the Upper Member.

Higher in the stratigraphy, in La Nuarque stratigraphic section, the Upper Member of the Amagá Formation displays a subtle increase in the diversity of fine–grained sedimentary facies. Here, the sandstones become finer and the sandstone packages become thinner. They also display a lower degree of amalgamation compared to the sandstones from La Puerta section. These sedimentary packages from La Nuarque stratigraphic section also display predominantly fining–upward stacking patterns. These characteristics indicate that their deposition involved a different energy level than the sedimentary units from La Puerta stratigraphic section. These characteristics, along with the increase in the presence of greenish fine–grained sediments (mudstones and siltstones) and the presence of organic–rich mudstones, also suggest that they were deposited along a meandering river system during a period of humid climate. The uppermost part of La Nuarque stratigraphic section displays a significant increase in medium– to coarse–grained sandstones and conglomerates. It is almost devoid of fine–grained facies. These characteristics suggest a return to a braided river system (Figure 7; Table 1; Figure 1 of the Supplementary Information).

The uppermost part of the Upper Member of the Amagá Formation crops out in the Guaracú stratigraphic section. This section mainly consists of coarsening–upward conglomerates and medium to coarse–grained sandstones interbedded with thick massive mudstones separating the sandstone packages. These facies suggest that they were deposited along a braided river system. The uppermost part of this stratigraphic succession displays conglomerates and sandstones with predominantly aggradational stacking patterns. These patterns suggest a significant decrease in accommodation space and an increase in the sediment supply. The coarse–grained nature of this succession, together with the presence of aggradational packages, suggests that it was deposited along a braided river system (Figure 7; Table 1; Supplementary Figure 1).

Finally, the Santa Fe de Antioquia Formation displays thick tabular aggradational conglomerates and fining–upward sandstones interbedded with limited and thin siltstones. The amalgamated nature of these coarse–grained sedimentary facies, as well as the presence of several erosional surfaces, suggest that they were deposited along a braided river system (Figure 7; Table 1; Figure 1 of the Supplementary Information).

5.2. Sequence Stratigraphic Framework

To date, several sedimentologic studies have focused on the Amagá Formation (i.e., Grosse, 1926; Guzmán & Sierra, 1984; Delsant & Tejada, 1987; Guzmán, 1991, 2003, 2007a; Murillo, 1998; Hernández, 1999; Correa & Silva–Tamayo, 1999; González, 2001; Sierra et al., 2003; Silva–Tamayo et al., 2008; Henao, 2012; Sierra & Marín–Cerón, 2012; Páez–Acuña; 2013; etc.). However, few studies have integrated the sedimentologic and sequence stratigraphic analyses of this unit (Guzmán, 2007b; Silva–Tamayo et al., 2008).

Silva–Tamayo et al. (2008) used high–resolution lithostratigraphic analyses to investigate the depositional style of the Amagá Formation and proposed a sequence stratigraphic framework for it (Figure 9). These authors used changes in sedimentary stacking patterns, facies diversity, and the preservation of geomorphic elements to constrain changes in the accommodation space (A) – sediment supply (S) ratio (A/S) during the deposition of the Amagá Formation along the AV Sub–basin. According to these authors, the lower part of the Lower Member of the Amagá Formation displays facies associations and stratigraphic stacking patterns implying that its deposition was associated with a braided river system and low A/S conditions. Silva–Tamayo et al. (2008) also suggested that the upper part of the Lower Member of the Amagá Formation displays facies associations typical of a meandering river system, thus implying an increase in A/S conditions. Silva–Tamayo et al. (2008) also proposed that the Upper Member of the Amagá Formation in the AV Sub–basin displays a change towards a braided river depositional system, thus indicating a decrease in A/S conditions.

In this contribution, we use the changes in sedimentary stacking patterns, facies diversity, and the preservation of geomorphic elements reported for the Amagá Formation in the SS Sub–basin and those identified in other sub–basins (i.e., the AV and FPV Sub–basins, Silva–Tamayo et al. 2008; Henao, 2012; Páez–Acuña, 2013) to propose a sequence stratigraphic framework for the Amagá Formation (Figure 9).

Important sedimentologic and stratigraphic changes are observed in the Amagá Formation in the SS Sub–basin (Figures 7, 9). The lowermost part of the Amagá Formation in the SS Sub–basin (La Seca stratigraphic section) displays thick conglomerates and sandstones with the poor preservation of sedimentary structures and geomorphic elements. It also displays very asymmetrical stratigraphic cycles, which preferentially fine upwards at the base and coarsen upwards at the top. The facies associations and stratigraphic stacking patterns are typical of braided rivers and suggest deposition under low A/S conditions. Similar facies associations and stratigraphic cycles have been reported by Silva–Tamayo et al. (2008) for the Lower Member of the Amagá Formation in the AV Sub–basin (Sinifaná section) and by Henao (2012) and Páez–Acuña (2013) in the FPV Sub–basin (Fredonia area, sections a and b of La Naranjala stratigraphic section) (Figures 4, 5, 6, 9).

Higher in the stratigraphy, the Amagá Formation displays facies associations typical of meandering rivers (El Puente stratigraphic section). The lower and middle parts of this stratigraphic section display a high diversity of sedimentary facies, as well as the high preservation of fine–grained facies (Figures 7, 9). It also displays the high preservation of geomorphic elements such as channels, flood plains, and crevasse splays. The high diversity of facies results in predominantly symmetrical fining–upward – coarsening–upward cycles. These characteristics suggest an important increase in A/S conditions compared to the record from La Seca stratigraphic section (Figure 9). The upper part of the sedimentary succession from El Puente stratigraphic section displays an increase in coarse–grained sediments. The presence of thicker channel sandstones, together with the moderate preservation of geomorphic elements such as flood plains and point bars, suggest a moderate decrease in A/S conditions (Figure 9). Silva–Tamayo et al. (2008) also reported high and moderate A/S conditions in the middle and upper parts of the Lower Member of the Amagá Formation in the AV Sub–basin (Unit II and lower part of Unit III, Palomos Mine, and lower El Cinco–Venecia stratigraphic sections). Henao (2012) reported similar facies associations and stratigraphic cycles for the La Naranjala stratigraphic sections c and d in the Fredonia areas of the FPV Sub–basin (Figure 9).

The sedimentary record from the La Puerta stratigraphic section, which constitutes the lowermost part of the Amagá Formation, consists of very aggradational and amalgamated, medium– to coarse–grained sandstones and conglomerates (Figures 7, 9; Figure 1 of the Supplementary Information). These units also display poorly preserved fine–grained sedimentary facies and geomorphic elements. These characteristics reflect a significant decrease in A/S conditions. These decreased A/S conditions would have occurred regionally and resulted in the deposition of sedimentary successions along braided river systems, as suggested by the occurrence of similar sedimentologic and stratigraphic features in the lowermost part of the Upper Member of the Amagá Formation in the AV (Silva–Tamayo et al., 2008) and FPV (middle part of the Sabaletas and Sabaleticas sections – Henao, 2012; Páez–Acuña, 2013) Sub–basins (Figure 9). As discussed by Silva–Tamayo et al. (2008), the strong decrease in A/S conditions regionally marks the limit between the Lower and Upper Members of the Amagá Formation. As discussed below, this decrease occurred between 23 and 15 Ma and resulted from major changes in the tectonic regime occurring along the northern Andes.

La Nuarque stratigraphic section in the SS Sub–basin displays a basal increase in fine–grained facies and a subsequent increase in the predominance of amalgamated conglomerate–sandstone packages with a low diversity of sedimentary structures (Figure 9). The presence of asymmetrical stratigraphic cycles and facies associated with braided river systems suggests their deposition under very low A/S conditions. Similar stratigraphic and sedimentological characteristics have been reported in the upper part of the Upper Member of the Amagá Formation along the AV and FPV Sub–basins (Figure 9; Silva–Tamayo et al., 2008; Páez–Acuña, 2013).

The uppermost part of the Upper Member of the Amagá Formation in the SS Sub–basin crops out at the Guaracú Creek. It displays facies associations typical of braided river systems. The presence of abundant fine–grained sedimentary facies and geomorphic elements (i.e., flood plains) suggests an increase in A/S conditions compared to the middle part of the Upper Member (La Nuarque stratigraphic section). These moderate A/S conditions are supported by the presence of several erosional surfaces within the thick amalgamated conglomerate packages and the very low diversity of fine–grained sedimentary facies and geomorphic elements. This increase in A/S conditions cannot be inferred for the AV and FPV Sub–basins due to the lack of sedimentary records cropping out along those sub–basins (Figure 9; Silva–Tamayo et al., 2008; Páez–Acuña, 2013).

The sequence stratigraphic characteristics of the Amagá Formation in the SS Sub–basin are very similar to those reported by Silva–Tamayo et al. (2008) for this formation in the AV Sub–basin and those reported by Henao (2012) and Páez–

Acuña (2013) for the Amagá Formation in the FPV and SS Sub–basins. Although important variations in sedimentary environments can be observed, the temporal variations in stratigraphic cycles are very similar within sub–basins and can be used to differentiate the Lower and Upper Members (following Silva–Tamayo et al., 2008). These differences in sedimentary environments, which result in lateral variations in sedimentary facies, can be attributed to autogenetic processes typical of continental environments (Cross, 1988).

Finally, in the SS Sub–basin, the sedimentary record from the Amagá Formation is discordantly overlain by a series of thick massive sandstones and ortho–conglomerates (Figure 9). The absence of fine–grained sedimentary facies and the presence of very asymmetrical stratigraphic cycles suggest very low A/S conditions. These low A/S conditions are consistent with the presence of facies associations reflecting braided river systems. This unit has not been reported in the AV and FPV Sub–basins, where the Amagá Formation is discordantly overlain by Serravallian – Tortonian (late Miocene) volcanoclastic successions from the Combia Formation.

5.3. Regional Implications

This work presents new sedimentologic and stratigraphic information for the Amagá Formation along the SS Sub–basin. It also presents the first systematic sequence stratigraphic correlation of the sedimentary records of the Amagá Formation cropping out along three different interconnected sub–basins, i.e., the SS, AV, and FPV Sub–basins (Figure 9; Figure 1 of the Supplementary Information). These sedimentological and sequence stratigraphic data allow us to identify major changes in the accommodation space/sediment supply ratio (A/S) of the Amagá Formation, which can in turn be correlated to major geologic events affecting the northern Andes.

Recent provenance studies in the SS Sub–basin of the Amagá Formation (Montes et al., 2015; Lara et al., 2018) have shown important variations in the source areas of the sediments from the Amagá Formation. Montes et al. (2015) and Lara et al. (2018) reported U–Pb detrital zircon ages for the Lower Member of the Amagá Formation that suggest that the Western and Central Cordilleras of Colombia were already exhumed during its deposition and constituted the main sediment source areas of the Lower Member of the Amagá Formation. This interpretation is in line with that of Silva–Tamayo et al. (2008), who suggested a north–trending paleocurrent direction for the river system of the Amagá Formation. Montes et al. (2015) and Lara et al. (2018) also suggested that the Upper Member of the Amagá Formation had two very distinctive sediment source areas, i.e., the South America Block and the PC Block. While Montes et al. (2015) suggested that the input of sediments from the PC Block to the Romeral paleo–suture started in the middle Miocene (15 Ma), Lara et al. (2018) suggested that such sediment input started as early as the early Miocene (23 Ma). The differences in sediment provenance between the Lower and Upper Members of the Amagá Formation parallel our proposed major regional changes in A/S conditions, which controlled the deposition of this formation. This implies that the sedimentologic evolution of the Amagá Formation was mainly controlled by a major change in tectonic setting along northern South America, specifically, the Oligocene – Miocene interaction between the PC and South American Blocks.

The initial interaction of the PC Block with northwestern South America has been proposed to have begun as early as the late Eocene (Müller et al., 1999; Farris et al., 2011; Montes et al., 2012a, 2012b, 2015). The interactions between these two blocks seem to have increased during the late Eocene – early Oligocene, coinciding with the break–up of the Farallon Plate into the Nazca and Cocos Plates (Pilger, 1984; Lonsdale, 2005), as well as during the late Oligocene, coinciding with the change from oblique convergence to orthogonal convergence between the Nazca and South American Plates between 28 and 25 Ma (Pilger, 1984; Müller et al., 1999; Lonsdale, 2005). The late Eocene – early Oligocene interaction between these tectonic blocks caused pervasive erosion along both the PC Block and the Central Cordillera of Colombia (Restrepo–Moreno et al., 2009; Farris et al., 2011; Barbosa–Espitía et al., 2013); this erosion resulted in a regional late Eocene – early Oligocene sedimentary hiatus along the westernmost part of the Middle Magdalena Valley Basin (Reyes–Harker et al., 2015), the Cauca–Patía Basin, and the southern part of the San Jacinto Basin (Alfaro & Holz, 2014; Rosero et al., 2014). This sedimentary hiatus cannot be identified along the different sub–basins where the Amagá Formation was deposited, as no pre–late Oligocene sedimentary records occur along these sub–basins.

Several marginal continental and transitional Eocene sedimentary records have been identified along diverse basins located along the trace of the Romeral paleo–suture, e.g., the Cauca–Patía and San Jacinto Basins. The presence of those Eocene sedimentary records may suggest the potential occurrence of already eroded marginal continental–transitional Eocene sediment along the sub–basins where the Amagá Formation was deposited. The existence of those pre–existing Eocene sediments, which would have potentially served as a source area for the Amagá Formation, is supported by the presence of reworked Eocene palynomorphs in the Lower Member of the Amagá Formation (Lara et al., 2018). The erosion and lack of preservation of those Eocene sediments along the sub–basins where the Amagá Formation crops out imply that a major tectonic event differentially affected the Cenozoic sedimentary basins located along the Romeral paleo–suture between the late Eocene – early Oligocene. This potential major tectonic event could have been related to uplift resulting from the change from a fore–arc to a hinterland/intramontane tectonic setting along the northern Andes. A similar change has been already proposed for the Tumaco Basin, which is located to the south of the study area (Echeverri et al., 2015).

This late Eocene – early Oligocene change in tectonic setting would have led to the opening of the different pull–apart basins where the Amagá Formation was deposited. Piedrahita et al. (2017) interpreted the occurrence of late Eocene and late Oligocene zircon fission–track cooling ages to propose an Oligocene depositional age for the Lower Member of the Amagá Formation. These ages are in line with the presence of Oligocene palynomorphs in the Lower Member (Pons, 1984). Lara et al. (2018) used these chronologic constraints to suggest that the lag time between sediment erosion and the deposition of the Lower Member was short and occurred soon after the opening of the different pull–apart basins where the Amagá Formation was deposited in the early Oligocene.

Piedrahita et al. (2017) also reported an early Miocene (22 Ma) zircon fission–track cooling age for the Upper Member of the Amagá Formation. This age can be interpreted as the maximum depositional age of the Upper Member of the Amagá Formation. The six–million–year gap between the late Oligocene – early Miocene cooling events reported by Piedrahita et al. (2017) suggests that the Lower Member of the Amagá Formation was deposited during a period of increasing accommodation space and rapid landscape development. These conditions explain the sedimentologic/stratigraphic characteristics of the Lower Member of the Amagá Formation, which records an evolution from braided river to meandering river sedimentary deposits during a period of increasing A/S conditions (Figure 9).

Piedrahita et al. (2017) related the occurrence of early Miocene zircon fission–track cooling ages in the Upper Member of the Amagá Formation to a major uplift event and the related basement exhumation of the Central Cordillera of Colombia during the accretion of the PC Block to northern South America. The early Miocene zircon fission–track cooling ages reported by Piedrahita et al. (2017), along with the early Miocene palynological ages reported by Ramírez et al. (2015), suggest that the lag time between the early Miocene exhumation and erosion of the Central Cordillera and the deposition of the Upper Member of the Amagá Formation was short. The implied rapid early Miocene exhumation of the Central Cordillera of Colombia coincides with the proposed major change in the depositional style from a meandering river system to a braided river system, which indicates that a decrease in A/S conditions occurred along the track of the Romeral Fault System. It also coincides with the major change in the compositional modes of the sandstones of the Amagá Formation (Silva–Tamayo et al., 2008; Lara et al., 2018).

Farris et al. (2011) and Lara et al. (2018) suggested that the major peak of the interaction and collision between the PC Block and the South American margin occurred between 25–23 Ma, when the break–up of the Farallon Plate also occurred (Pilger, 1984; Pardo–Casas & Molnar, 1987; Lonsdale, 2005; Barckhausen et al., 2008). During this time, more precisely, at the Oligocene – Miocene boundary, faster and accelerated tectonic convergence between the Americas also occurred (Müller et al., 1999). According to Müller et al. (1999), an increase in the rate of motion of the Caribbean Plate from 3.6 mm/y (early Eocene) to 9.9 mm/y (late Oligocene – early Miocene) at 85° W dramatically changed the tectonic regime of the Caribbean Plate and increased the deformation occurring along the circum Caribbean. The enhanced convergence between the Caribbean Plate and northern South America explains the faster deformation and exhumation that occurred in the northern Andes during the Oligocene – Miocene interval (Reyes–Harker et al., 2015 and references therein). These data are in line with our interpretation and provide a further explanation of the regional processes that would have controlled the changes in depositional style displayed by the Amagá Formation.

Montes et al. (2015) used detrital zircon ages to suggest that the final docking of the PC Block to northern South America occurred by 13 Ma. However, such docking could have occurred as early as the early Miocene, with more convergence occurring between the PC Block and northern South America in the middle Miocene (Lara et al., 2018). The increased interaction between the PC and South American Blocks, as well as the resulting higher degree of exhumation along the Romeral paleo–suture, explain the predominance of sedimentary facies typical of braided river systems in the uppermost part of the Amagá Formation. Regionally, this middle Miocene increase in tectonic exhumation corresponds to the change in the deformation front towards the Eastern Cordillera (Alfaro & Holz, 2014; Reyes–Harker et al., 2015 and references therein).

The 13 Ma detrital zircons reported by Montes et al. (2015) from the Upper Member of the Amagá Formation and the late Miocene (11–6 Ma) magmatic arc rocks that intruded the Amagá Formation (Restrepo et al. 1981; Aspden et al., 1987; Silva–Tamayo et al., 2008; Leal–Mejía, 2011; Rodríguez & Zapata, 2014) allow us to suggest a middle Miocene age (13–11 Ma) as the maximum depositional age for this unit. During the late Miocene, the rate of motion of the Caribbean Plate decreased to 5.2 mm/y, and the exhumation of the northern Andes was not as significant (Müller et al., 1999; Mora et al., 2013; Reyes–Harker et al., 2015). However, this apparent tectonic quiescence conflicts with the occurrence of volcanism of adakitic affinity along the track of the Romeral paleo–suture, which affected the Amagá Formation. This adakitic–affinity volcanism resulted in the deposition of volcano–sedimentary successions from the Combia Formation above the Amagá Formation. This change in sedimentation implies that a new change in tectonic setting from a hinterland/intramontane to an intra–arc tectonic setting occurred along the Romeral Fault System.

The change in tectonic setting would have promoted the strong deformation of the Amagá Formation along some of the studied sub–basins, which would have occurred between 13 and 4.8 Ma, as suggested by the 4.8 Ma detrital zircon ages obtained from the Santa Fe de Antioquia Formation, which overlies the Amagá Formation in the SS Sub–basin. These 4.8 Ma detrital zircon ages could be associated with source areas such as the volcanic products of the Pliocene Combia Formation or some currently undiscovered hypabyssal bodies cropping out along the northern Andes (Lara et al., 2018). These detrital zircon ages, which suggest a minimum hiatus of ca. 8 Ma between the depositions of the Amagá and Santa Fe de Antioquia Formations, coincide with the shift of the deformation front eastward towards its current position along the Guaicáramo Fault System (Reyes–Harker et al., 2015 and references therein). This shift, as well as the deposition of the Santa Fe de Antioquia Formation, would have finally coincided with the final and complete closure of the Central America Seaway, as proposed by Lara et al. (2018).

5.4. Implications for Coal Exploration in the Amagá Formation

The Amagá Formation displays commercially exploitable coal deposits. Most of them have been found in the middle and upper parts of the Lower Member along the AV and FPV Sub–basins (Figure 9). These coal deposits are associated with the flood plains of meandering river system deposits (Silva–Tamayo et al., 2008). However, no coalbeds have been reported in the SS Sub–basin. Our records suggest that the middle and upper parts of the Lower Member of the Amagá Formation in the SS Sub–basin display predominantly coarser facies associations than their correlatives in the AV and FPV Sub–basins. Based on the sedimentologic and stratigraphic characteristics of the Amagá Formation along the AV and FPV Sub–basins, we suggest that these sub–basins were affected by higher subsidence rates than the SS Sub–basin. Although these differences in subsidence, which likely resulted from autogenic processes within different sub–basins, can explain the higher occurrence of organic–rich siltstones and thus coalbeds in the AV and FPV Sub–basins, they do not explain their differences in organic carbon maturity and thus the absence of coalbeds in the SS Sub–basin. The sandstones from the Amagá Formation in the SS Sub–basin (Rojas–Galvis & Salazar–Franco, 2013) display similar diagenetic features as those in the AV and FPV Sub–basins (Correa & Silva–Tamayo, 1999; Guzmán, 2007b; Henao, 2012; Páez–Acuña, 2013). However, the presence of silica cements and diagenetic sericite in the sedimentary records from the AV and FPV Sub–basins suggests that these units were submitted to higher temperatures under a high diagenetic fluid to rock ratio. Miocene intrusive rocks affecting the sedimentary records from the AV and FPV Sub–basins have been reported and are associated with the volcanism of the Combia Formation. We suggest that the low thermal maturity of organic matter–rich deposits, and therefore the absence of coalbeds, in the SS Sub–basin is probably best explained by the absence of intrusive beds affecting the sedimentary record of the Amagá Formation in that sub–basin.

6. Conclusions

We performed sedimentologic and sequence stratigraphic analyses of the Amagá Formation in three pull–apart basins occurring along the trace of the Romeral paleo–suture in the northernmost part of the Andes. Important variations in the depositional style and sequence stratigraphic patterns of the Amagá Formation have been identified. These changes allowed us to divide the Amagá Formation into two members (i.e., the Lower and Upper Members). These changes also paralleled the major changes in regional tectonics occurring along the Northern Andean Orogenic Belt. The deposition of the Amagá Formation occurred along a series of intramontane/hinterland basins that formed after the break–up of the Farallon Plate into the Nazca and Cocos Plates and the change from oblique convergence to orthogonal convergence between the Nazca and South American Plates. The Lower Member, which documents the change from a regional fore–arc to a hinterland tectonic setting, records a change from braided to meandering river systems during a period of increasing sediment accommodation space. The Upper Member of the Amagá Formation, which displays facies associations typical of braided river systems, was deposited during a period of decreasing sediment accommodation space. The decrease in sediment accommodation space that was dominant during the deposition of the Upper Member of the Amagá Formation likely resulted from a major regional uplift event associated with the early Miocene docking of the PC Block to northern South America. The cessation of the deposition of the Amagá Formation occurred during the late Miocene and paralleled the change from a hinterland/intramontane to an intra–arc tectonic setting along the Romeral Fault System. This work finally allowed us to identify the occurrence of Pliocene consolidated but uncemented fluvial sedimentary units deposited by braided rivers along one of the studied sub–basins. These sediments constitute a new stratigraphic unit (the Santa Fe de Antioquia Formation) along the SS Sub–basin, which discordantly overlies the Amagá Formation. The Pliocene age of the Santa Fe de Antioquia Formation suggests the occurrence of a sedimentary hiatus in the SS Sub–basin. This hiatus paralleled the occurrence of adakitic volcanism along the other two studied sub–basins, which in turn promoted the thermal maturation of the sedimentary record and thus the occurrence of economically exploitable coalbeds.

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Explanation of Acronyms, Abbreviations, and Symbols:

ASM	Anisotropy of magnetic susceptibility
AV	Amagá–Venecia
FPV	Fredonia–La Pintada–Valparaíso
PC	Panamá–Chocó
RFS	Romeral Fault System
SS	Santa Fe de Antioquia–San Jerónimo
ZFT	Zircon fission–track

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