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Paleozoic of Colombian Andes: New Paleontological Data and Regional Stratigraphic Review

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Abstract The continental basement, east of the Otú–Pericos Fault, is made up of two sectors with different geological histories. The western sector, comprised of Payandé, and Payandé San Lucas blocks, are considered here as a part of the autochthonous basement of South America. The autochthonous basement is composed of high–grade metamorphic rocks with Grenvillian and Amazonian ages. The basal sedimentary cover includes marine deposits that span from Ediacaran to Ordovician in the Llanos Basin, and from the Ordovician, in the La Macarena and Magdalena Valley. The Eastern Cordillera consists of an allochthonous tectonic block (Quetame–Mérida Terrane) where several phases of metamorphism are identified. The Bucaramanga Gneiss and Silgará Schists (sensu stricto) were formed during the Precambrian. The Chicamocha Schists originated from a sedimentary protolith of Cambrian age. The identification of bioturbation in metamorphic rocks of the Quetame Massif confirms the existence of Phanerozoic rocks in the area. In the Eastern Cordillera, an Ordovician magmatic phase associated with the Famatinian Orogeny (Taconic) is recognized. Orogenic metamorphism and its termination are associated with the collision of the Quetame–Mérida Terrane against the pericratonic margin of South America. An erosive phase at the end of the Ordovician and the beginning of the Silurian separated a brief marine incursion during the Ludlow. In northern South America, Devonian sedimentation spans from the Emsian to the ends of the Famennian. The Devonian marine fauna is similar to the marine fauna of eastern North America. The flora tends to be cosmopolitan (several species of *Archaeopteris*) with elements common to Laurussia. However, fossil fish show elements of both Gondwana and Laurussia. The Carboniferous series is extended from the Sierra Nevada of Santa Marta to the south of Colombia. The fossils indicate that the sedimentation, limestones and mudstones of the shallow marine platform, spans from the Bashkirian to the Moscovian. The Permian sedimentation starts with basal conglomerates and continues with platform limestone deposits. The fossils indicate a range of sedimentation that spans from the Cisuralian to the Guadalupian. A tectonic phase (the assemblage of the Pangea) creates the hiatus between the late Permian (Lopingian) and the Middle Triassic. This phase results in magmatic activity and metasomatism in the Magdalena Valley (Payandé and Payandé–San Lucas).

Keywords: *fossils, tectonic provinces, Payandé and Payandé San Lucas Terranes, Quetame–Mérida Terrane.*

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Resumen El zócalo continental, al este de la Falla de Otú–Pericos, se compone de dos sectores con diferentes historias geológicas. El sector occidental, conformado por los bloques Payandé y Payandé–San Lucas, se considera aquí como parte del basamento autóctono de Suramérica. El zócalo autóctono se compone de rocas metamórficas de alto grado con edades grenvillianas y amazónicas. La cubierta sedimentaria basal incluye depósitos marinos que abarcan desde el Ediacariano hasta el Ordovícico en la Cuenca de los Llanos y desde el Ordovícico en La Macarena y el valle del Magdalena. La cordillera Oriental está constituida por un bloque tectónico alóctono (Terreno Quetame–Mérida) en el cual se identifican varias fases de metamorfismo. El Gneis de Bucaramanga y los Esquistos del Silgará (*sensu stricto*) se formaron durante el Precámbrico. Los Esquistos del Chicamocha se originaron a partir de un protolito sedimentario de edad cámbrica. La identificación de bioturbación en rocas metamórficas del Macizo de Quetame confirma la existencia de rocas fanerozoicas en el área. En la cordillera Oriental se reconoce una fase magmática ordovícica asociada con la Orogenia Famatiniana (Tacónica). El metamorfismo orogénico y su terminación se asocian con la colisión del Terreno Quetame–Mérida contra el margen pericratónico de Suramérica. Una fase erosiva al final del Ordovícico y el comienzo del Silúrico creó una breve incursión marina durante el Ludloviano. La sedimentación del Devónico en el norte de Suramérica abarca desde el Emsiano hasta el final del Famenniano. La fauna marina del Devónico es similar a la del este de Norteamérica. La flora tiende a ser cosmopolita (varias especies de *Archaeopteris*) con elementos en común con Laurusia. Sin embargo, los peces fósiles muestran elementos tanto de Gondwana como de Laurusia. La serie carbonífera se extiende desde la Sierra Nevada de Santa Marta hasta el sur de Colombia. Los fósiles indican que la sedimentación, calizas y lodolitas de plataforma marina somera, abarca desde el Bashkiriano al Moscoviano. La sedimentación del Pérmico comienza con conglomerados basales y continúa con depósitos de calizas de plataforma. Los fósiles indican un rango de sedimentación que abarca desde el Cisuraliano hasta el Guadalupiano. Una fase tectónica (el ensamblaje de Pangea) crea el hiato entre el Pérmico tardío (Lopingiano) y el Triásico Medio. Esta fase da como resultado actividad magmática y metasomatismo en el valle del Magdalena (Payandé y Payandé–San Lucas).

Palabras clave: *fósiles, provincias tectónicas, terrenos Payandé y Payandé–San Lucas, Terreno Quetame–Mérida.*

1. Introduction

A divergent evolution and structure characterize the mountain ranges that divide the Andes in Colombia. The Western Cordillera (western mountain range) on the Pacific Ocean and the Cauca Valley domain consist largely of Cretaceous oceanic crust (Figure 1). This tectonic block that includes Calima, Cuna, and Gorgona Terranes (Toussaint & Restrepo, 1993, 1994) will not be considered in this work nor will the Chocó Block (Duque–Caro, 1990), since during the Paleozoic, they were not yet formed. The Central Cordillera (central mountain range) is an assemblage of Mesozoic and Paleozoic metamorphic terranes (Figure 2). The central and northern part of this range belongs to the Tahamí Terrane (Toussaint & Restrepo, 1994), including the Cajamarca Complex (Maya & González, 1995), which is a tectonic assemblage of pre–Cretaceous metamorphic rocks. The Tahamí Terrane is composed of low grade metaigneous and metasedimentary rocks whose chronological ranges extend from Devonian (Anacona Terrane) to Jurassic (Blanco–Quintero et al., 2014; Restrepo et al., 2009; Spikings et al., 2015; Vinasco et al., 2006). To date, Precambrian rocks have not been found in this terrane (Ordoñez–Carmona et al., 2006). Both Western and Central Cordilleras were affected by Cretaceous and Paleogene magmatism (Maya, 1992). The oldest fossiliferous rocks in the Tahamí Terrane are those of the Early Cretaceous age of Valle Alto and Berlin areas (Barrero & Vesga, 1976; Etayo–Serna, 1985). Nelson (1957) discovered a rich fossil flora in the Valle Alto region that is attributed to the Early Cretaceous (Wealden facies). Nevertheless, Lemoigne (1984) proposes a Jurassic age based on the additional material. The above–mentioned age was controverted by Etayo–Serna (1985), who referred to a Lower Cretaceous mollusks fauna from the same deposits cited by Lemoigne (1984). Additionally, Vakhrameev (1991) subsequently checked the flora species studied by LEMOIGNE and concluded that the most convenient age for the fossil material is Early Cretaceous,

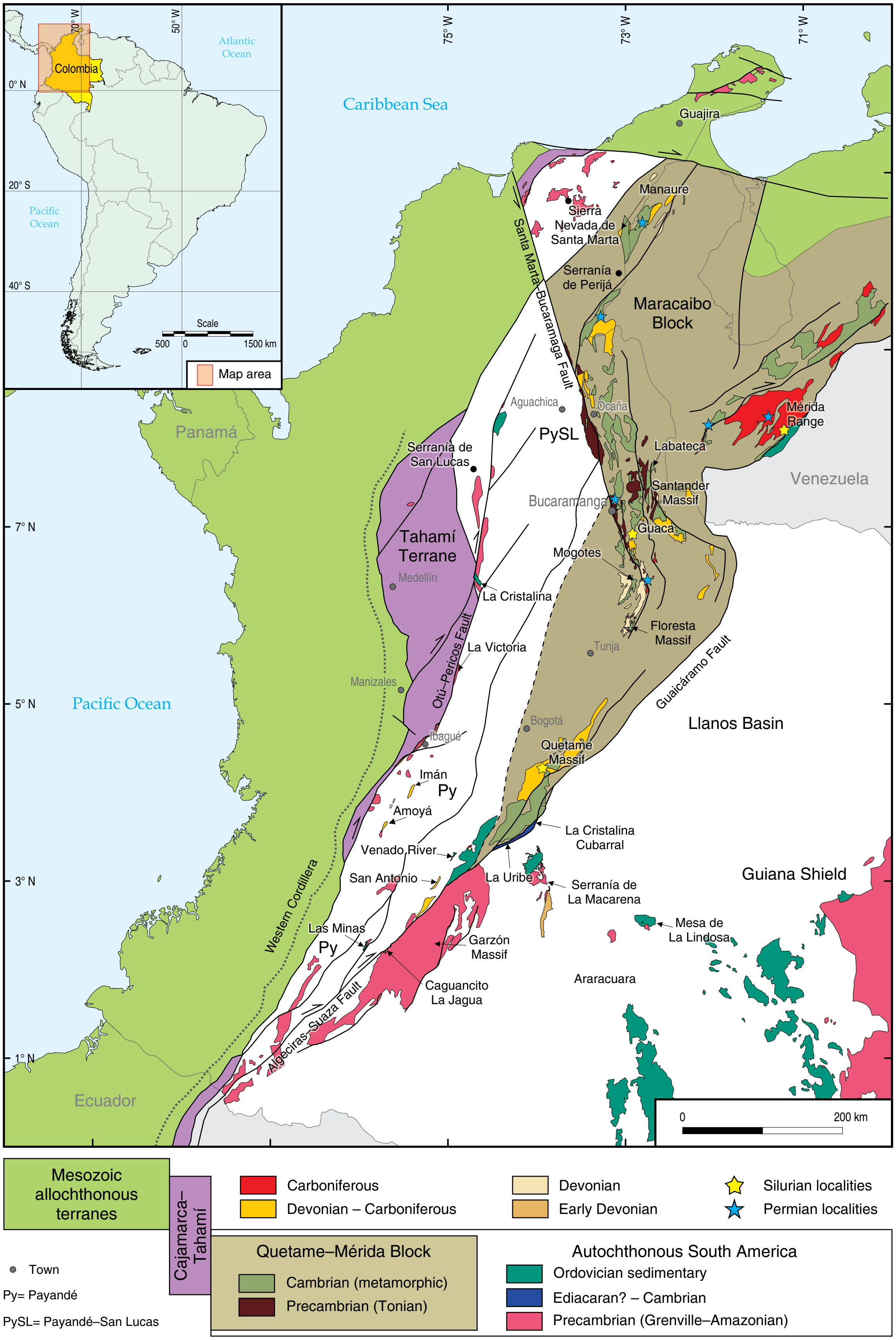

Figure 1. Geological sketch map of the northern Andes showing the main tectonic blocks.

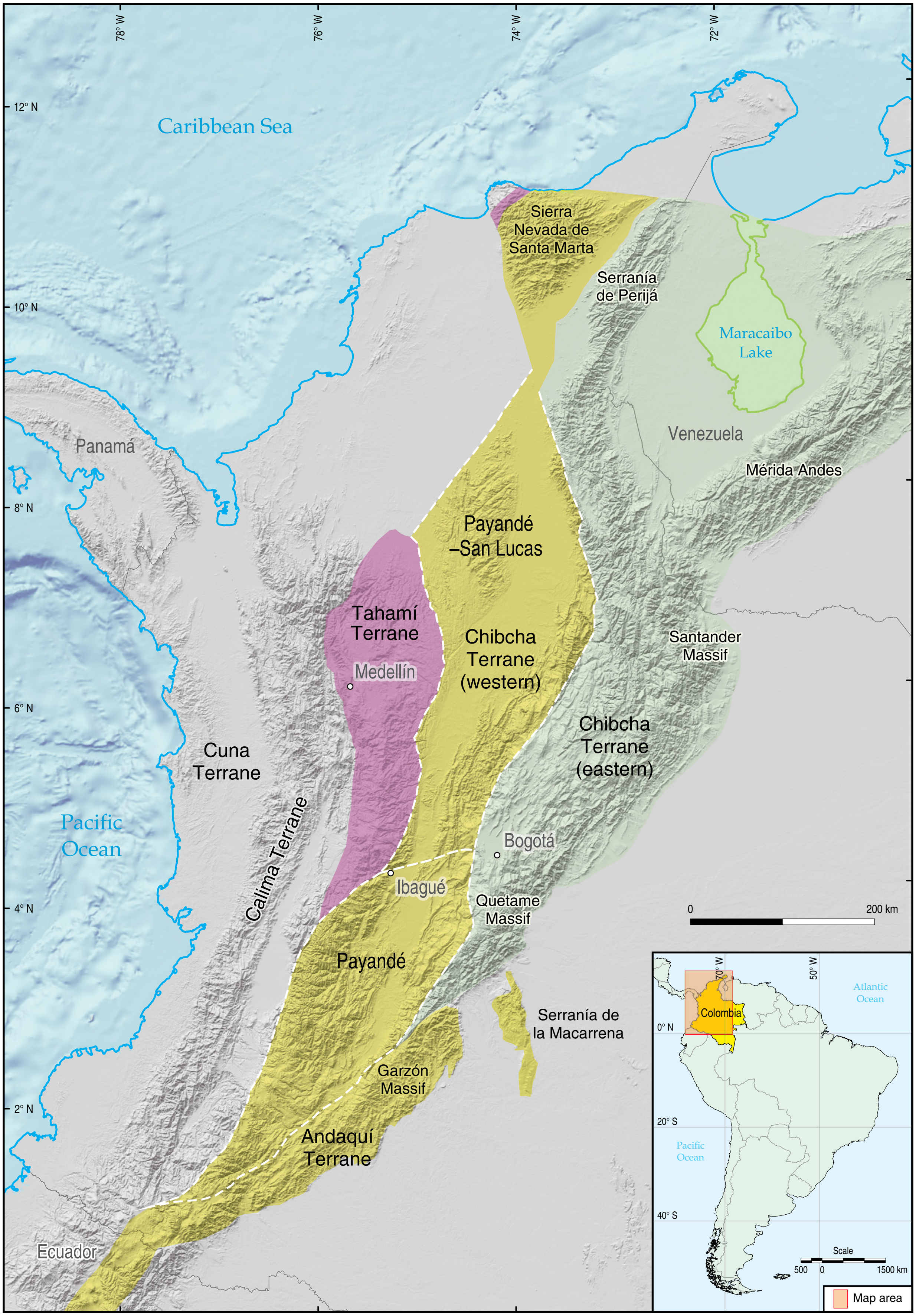

Figure 2. Geological terrane map and relief of Colombia and neighboring jurisdictions. Modified from Restrepo & Toussaint (1988).

which is in agreement with the Etayo–Serna's conclusions. To date, no pre–Cretaceous sedimentary rocks have been found in the Tahamí Terrane.

The Chibcha Terrane (Restrepo et al., 2009) is a geologic province located between the Otú–Pericos and Guaicáramo Faults (Borde Llanero Fault), which comprises the Sierra Nevada de Santa Marta, Magdalena Valley, the eastern slope of the Central Cordillera, Quetame and Santander Massifs, Mérida Andes, and the serranía de Perijá. The Magdalena Valley and the eastern slope of the Central Cordillera, included in the Payandé and Payandé–San Lucas Terranes sensu Etayo–Serna et al. (1983), has a Mesoproterozoic (Grenvillian) basement similar to the basement reported in the serranía de La Macarena, Sierra Nevada de Santa Marta, and Garzón Massifs (Kroonenberg, 1982; Ramos, 2010). Like serranía de La Macarena, the oldest sedimentary rocks from Magdalena Valley are lower and late Paleozoic age. Middle Ordovician graptolites are reported in the El Hígado (Borrero et al., 2007; Mojica et al., 1988) and La Cristalina Formations (Feininger et al., 1972) at the domain of the Payandé and Payandé–San Lucas Terranes.

In this work, the west part of the Chibcha Terrane of Restrepo et al. (2009), including the Payandé and Payandé–San Lucas Terranes of Etayo–Serna (1985), is provisionally called "Western Chibcha Terrane". We consider that the Western Chibcha Terrane has a geologic genesis distinct from the geologic genesis of the eastern Chibcha Terrane. Western Chibcha Terrane, with Grenvillian basement and covered with early Paleozoic sedimentary rocks, shares a tectonic history like the tectonic history of the serranía de La Macarena and Llanos Basin.

The eastern sector of the Chibcha Terrane ("Eastern Chibcha Terrane" in this work) is composed of a Proterozoic crystalline basement (Bucaramanga Gneiss) covered by Tonian–age schists (Silgará), Cambrian–age schists (Quetame, Perijá Series and Chicamocha Schists) and cut by Ordovician (Famatinian) granitoids. In addition, there is a cover of metasedimentites ("Filitas de San Pedro", Guaca Metasedimentites, and "Susumuco Silurian beds") of Silurian age (Forero, 1990; Grösser & Prössl, 1991; Mantilla–Figueroa et al., 2016).

Famatinian (Taconic) age arc granitoids, affecting low grade metamorphic rocks, are common along the Eastern Cordillera and Mérida Andes (Restrepo–Pace & Cediel, 2010). The oldest sedimentary rocks in the Eastern Cordillera are commonly cited as Devonian, suggesting that the metamorphic event of the Eastern Cordillera predates the Devonian (Renzoni, 1968; Stibane, 1968; Trumpy, 1943). However, in the Mogotes–Santa Bárbara area (Santander Massif), low grade metamorphic rocks with late Paleozoic fossils (Moreno–Sánchez et al., 2005; Ward et al., 1977) and Early Devonian zircons are reported (Mantilla–Figueroa & García–Ramírez, 2018). Additionally, Silurian (Ludlow) spores occur in weakly metamorphosed rocks of the Quetame Massif (Grösser & Prössl, 1991) and the Silurian brachiopod *Aenigmastrophia* sp. was recovered from low grade metamorphic rocks near Guaca town at the Santander Massif (Forero, 1990). Early Paleozoic igneous and metamorphic events are absent in the basement of Magdalena Valley (Payandé and Payandé–San Lucas Terranes sensu Etayo–Serna, 1985).

Based on the above, we consider that the pre–Devonian geological history of western and eastern Chibcha Terrane is not similar and, therefore, both crustal blocks could consider tectonic blocks that evolved independently from Precambrian to Ordovician times.

Minor occurrences of Devonian and Carboniferous sequences are known in the serranía de La Macarena and the Garzón Massif. To the west, from the Otú–Pericos System Fault to the Cauca Valley, Paleozoic sedimentary rocks are unknown. This area, integrated into the Tahamí Terrane by Restrepo et al. (2009), has undergone the effect of metamorphic events during the late Paleozoic and early Mesozoic, and all this region can be considered an allochthonous terrane.

The Quetame, Perijá, Santander, and Mérida Massifs are part of a tectonic block (abbreviated: Quetame–Mérida Terrane or Eastern Chibcha Terrane) affected by a mid–Ordovician orogenic greenschist event referred to as the Quetame–Caparonensis Orogeny by some authors (Mantilla–Figueroa et al., 2016; Restrepo–Pace, 1995). The Quetame–Caparonensis Orogeny is the northern extension of the Famatinian Orogeny that affected the western margin of South America during the Ordovician period (Mantilla–Figueroa et al., 2016; Ramos, 2015; van der Lelij, 2013; van der Lelij et al., 2016a). Late Paleozoic sedimentary sequences are known in the Llanos Basin but are not included in this study, as they are extensively studied in another chapter.

The first Paleozoic rocks of Colombia were recognized in the Floresta Massif (Figure 1). The discovery of Devonian strata in Colombia is a credit to Axel A. OLSSON and Parke A. DICKEY, geologists of the International Petroleum Company. The Devonian fossils, collected by OLSSON and DICKEY at the north of the Floresta town (Department of Boyacá), were studied by Caster (1939) and McNair (1940).

The Floresta Series (Olsson & Caster, 1937), then Floresta Formation (Botero, 1950), was divided into three units: The basal El Tíbet Formation, the Floresta Formation in the middle, and the Cuche Formation at the top (Mojica & Villarroel, 1984).

The oldest sedimentary unit of the Floresta Massif is the Emsian El Tíbet Formation. This formation covers unconformably Ordovician granites and early Paleozoic metamorphic rocks. The unit consists of a succession of conglomerates, sandstones, and gray–colored interbedded shales. The El Tíbet was initially included by Cediel (1969) as a member of the Floresta Formation but was later established as a separate formation by Mojica & Villarroel (1984). The Cuche Formation, previously considered a Carboniferous ensemble, is a clastic succession with Late Devonian fossils of a continental and transitional marine environment (Berry et al., 2000; Janvier & Villarroel, 2000; Moreno–Sánchez, 2004). The Devonian sequence extends from La Jagua, south of the Garzón village (Stibane & Forero, 1969), to the serranía de Perijá (Forero, 1970, 1991).

Scattered sedimentary Carboniferous rocks crop out from southern Colombia (Dickey, 1941; Mojica et al., 1987a) to the Sierra Nevada de Santa Marta (Gansser, 1955) and are also recognized in the subsoil of the Llanos Basin (Dueñas, 2001; Dueñas & Césari, 2003, 2006). The Carboniferous system in the Andean region is dominated by shallow carbonate marine deposits. At the Llanos Basin, Dueñas & Césari (2006) found a Late Devonian pollen assemblage (characterized by spores *Hystricosporites* spp., *Ancyrospora* spp., and *Teichertospora torquata*) in a sequence of siliciclastic nature that reaches the lower Carboniferous (Tournaisian – Visean).

The Permian record is limited to outcrops on the northern Andean region: the Santander Massif, serranía de Perijá, and Mérida Andes in Venezuela (Arnold, 1966; García–Jarpa, 1972; Hea & Whitman, 1960). The Permian sequences originate on a carbonate platform in shallow and warm marine waters. At the Mérida Andes, Permian Carache and Palmarito Formations preserve a floral assemblage characterized by the remains of *Delnorti*a, a gigantopterid fossil plant common in the Road Canyon Formation of Texas (Ricardi–Branco, 2008; Ricardi–Branco et al., 2005). At the serranía de Perijá, the Fusulinid *Paraschwagerina yabei* and presence of the ammonoids genus *Perrinites hilli*, *Medlicottia* sp., and *Titanoceras* sp. suggest an Artinskian – Kungurian age (Miller & Williams, 1945; Trumpy, 1943).

In recent years, new geochronological information has been presented, but this information has rarely been contrasted with the paleontological and stratigraphic data. The main purpose of this contribution is to present an integration of the paleontological and regional information to clarify the geological history of Colombia during the Paleozoic era. In this chapter, we included some of the most characteristic Paleozoic formations to the east of the Otú–Pericos Fault but not the Paleozoic formations in the Llanos Basin. Here, we present new paleontological data with geographic coordinates, along with a summarized stratigraphic framework and distribution of upper Paleozoic sedimentary sequences of the Andean region of Colombia. Additionally, the new geological data are used to discuss the ages of the metamorphic basement of the Chibcha Terrane (Restrepo, 1983; Restrepo & Toussaint, 1988).

2. Materials and Methods

Most of the original material cited in this work was collected during field campaigns conducted by the authors and students of the Universidad de Caldas. The samples and the geological sections were located by GPS (Garmin Map 64s). Fossils were prepared in the laboratory of paleontology. Some samples were cut and polished into thin sections. The petrographic thin sections were analyzed using a polarizing microscope (Nikon Eclipse E–200) with the camera adapter. A Nikon D610 camera assisted by the Helicon remote and Helicon focus 6 software was used to obtain net photographs of the macrofossils.

3. Serranía de Perijá

The serranía de Perijá, at the border between Colombia and Venezuela, includes the northernmost Paleozoic deposits of South America. The basement is constituted of weakly metamorphosed sedimentary rocks of the early Paleozoic age consisting of metapelites and quartzite of the Perijá Series (Forero, 1970). An angular unconformity separates metamorphic rocks from sedimentary sequences of the Devonian age. Gaps in the fossil succession suggest that separation surfaces, between Devonian, Carboniferous, and Permian strata, are disconformities (Forero, 1970) (Figure 3). Devonian strata, near 1300 m thick, are composed of a siliciclastic sequence of quartzite conglomerates, sandstones, and mudstones of shallow marine origin. The brachiopod fauna age of serranía de Perijá from Emsian?, Middle Devonian, and Frasnian is due to the presence of *Nervostrophia rockfordensis* (Forero, 1970).

The Carboniferous sequence, with a thickness close to 300 meters in the section of Manaure, is composed of conglomerates, red sandstones, and shallow platform limestones. The fossil fauna, containing brachiopods, mollusks, and bryozoans, indicates a Middle to Late Pennsylvanian age (Forero, 1970). The sedimentary rocks on the eastern side of the serranía de Perijá are correlated with the Lower and Middle Pennsylvanian Caño Indio and Río Palmar Formations of Venezuela (Benedetto, 1978).

Perijá Permian is made up of facies like those of the upper Carboniferous. The first mention of the presence of the Permian sequences in the serranía de Perijá is due to Trumpy (1943), who cites (from fossils collected to the east of Manaure by RENZ) Artinskian – Kungurian ammonites (*Perrinites hilli*, *Medlicottia* sp., and *Titanoceras* sp.), crinoids, brachiopods, and mollusks (*Bellerophon*). The Palmarito Formation, their stratigraphic equivalent on the Venezuelan flank of Perijá, has fauna in the range of Leonardian to Guadalupian (early to middle Permian).

From limestone material collected on the Colombian side of the serranía, east of the population of Manaure (10° 21’ 25.31’’ N, 73° 00’ 11.11’’ W), a fusulinid assemblage constituted of *Praeskinnerella hedbergi*, *Schwagerinoidea* sp., *Pseudoschwagerina dalmussi*, and *Climacammina* sp. (Figure 4) was recovered. The material, identified by Daniel VACHARD, is Sakmarian age (late Wolfcampian). At serranía de Perijá, the age of the Permian sequences lies between the lower Cisuralian (Sakmarian) and Guadalupian.

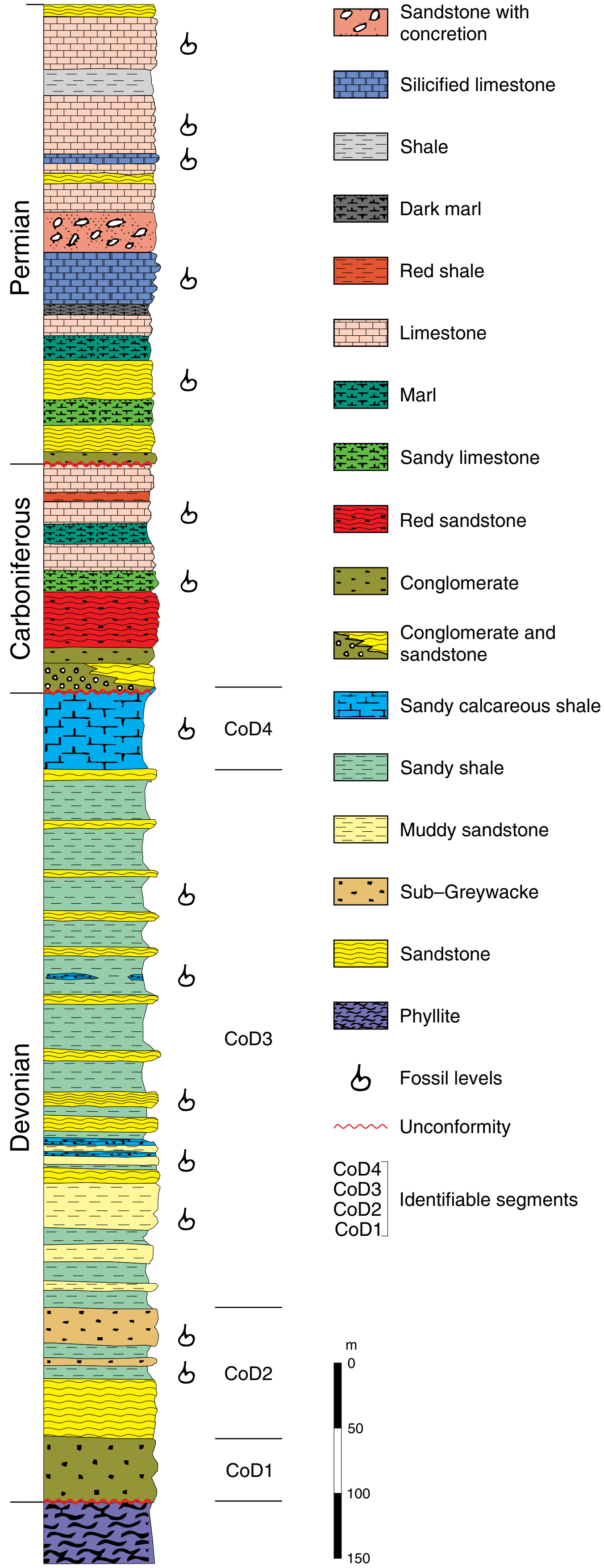

Figure 3. Geologic columns from serranía de Perijá (Forero 1970). Devonian sedimentary rocks cover unconformably early Paleozoic metamorphic basement (Perijá Series).

4. Santander Massif

The oldest rocks of the Santander Massif correspond to the Precambrian Bucaramanga Gneiss and the schists of the Silgará Formation (Ward et al., 1973, 1977). In the Chitagá River gorge (N 7° 16' 25.81'', W 72° 32' 52.48''), Devonian sandstones unconformable overlie low grade metamorphic basement constituted of quartzites and cordieritic metapelitic rocks of the Silgará Formation (sensu Royero & Zambrano, 1987). Metapelitic horizons still preserve traces of bioturbation (*Paleophycus* and *Teichichnus*), suggesting a post–Ediacaran age (Figure 5).

Along the Chitagá River, on the road that goes from Pamplona to Labateca, more than 700 meters of Devonian and Carboniferous sedimentary sequences are exposed. The Devonian deposits, unlike those of the Floresta Massif, are dominated by sandstones. Middle Devonian fossils occur at the base of the sequence, which includes *Eodevonaria imperialis*, *Mucrospirifer mucronatus*, "*Camarotoechia*"? cf., *C. sappho*, *Devonochonetes* sp., *D. coronatus*, and *D. mediolatus*, and *Leptaena* sp. (Boinet et al., 1986).

From loose material, Boinet et al. (1986) identify some fossil plants including *Platyphyllum* cf. *williamsonii*, *Taeniocrada decheniana*, cf. *Stockmansella* (*Taeniocrada*) *langii* in association with palinomorphs *Ancyrospora* sp., *Acanthotriletes* cf. *horridus*, *Auroraspora* sp., *Cirratriradites* sp., *Geminospora lemurata*, *Grandispora macrotuberculata, Hystrichosporites corystus*, *Leiotriletes ornatus*, *Raistrickia* sp., *Retusotriletes rugulatus*, *Rhabdosporites langii*, and *Spinizonotriletes* cf. *echinatus.* Additionally, BOINET report brachiopods *Devonochonetes* sp., *D. coronatus*, and *D. mediolatus*, *Eodevonaria imperialis*, *Leptaena* sp., *Mucrospirifer mucronatus*, and "*Camarotoechia*"? cf. C. *sappho*. The entire association points to a Middle to Late Devonian age. At the reddish sandstone and shales at the top of the Devonian sequence, the horizons contain flabellate leaves of genus form *Platyphyllum* (possibly detached leaves of *Archaeopteris obtusa*). These red beds, correlated with Cuche Formation of the Floresta Massif, are separated in this work from the Diamante Formation sensu Royero & Zambrano (1987). A disconformity surface separates the Carboniferous sandstone stratum from the underlying red beds of the Cuche Formation. We use Labateca Formation for the Carboniferous sedimentary succession composed of sandstones, limestones, and dark shales that crop out between the red beds of the Cuche Formation and the Girón Formation (Figure 6). At the Carboniferous occurs the rugose coral *Aulophyllum* sp. Permian fossils were not found in this formation.

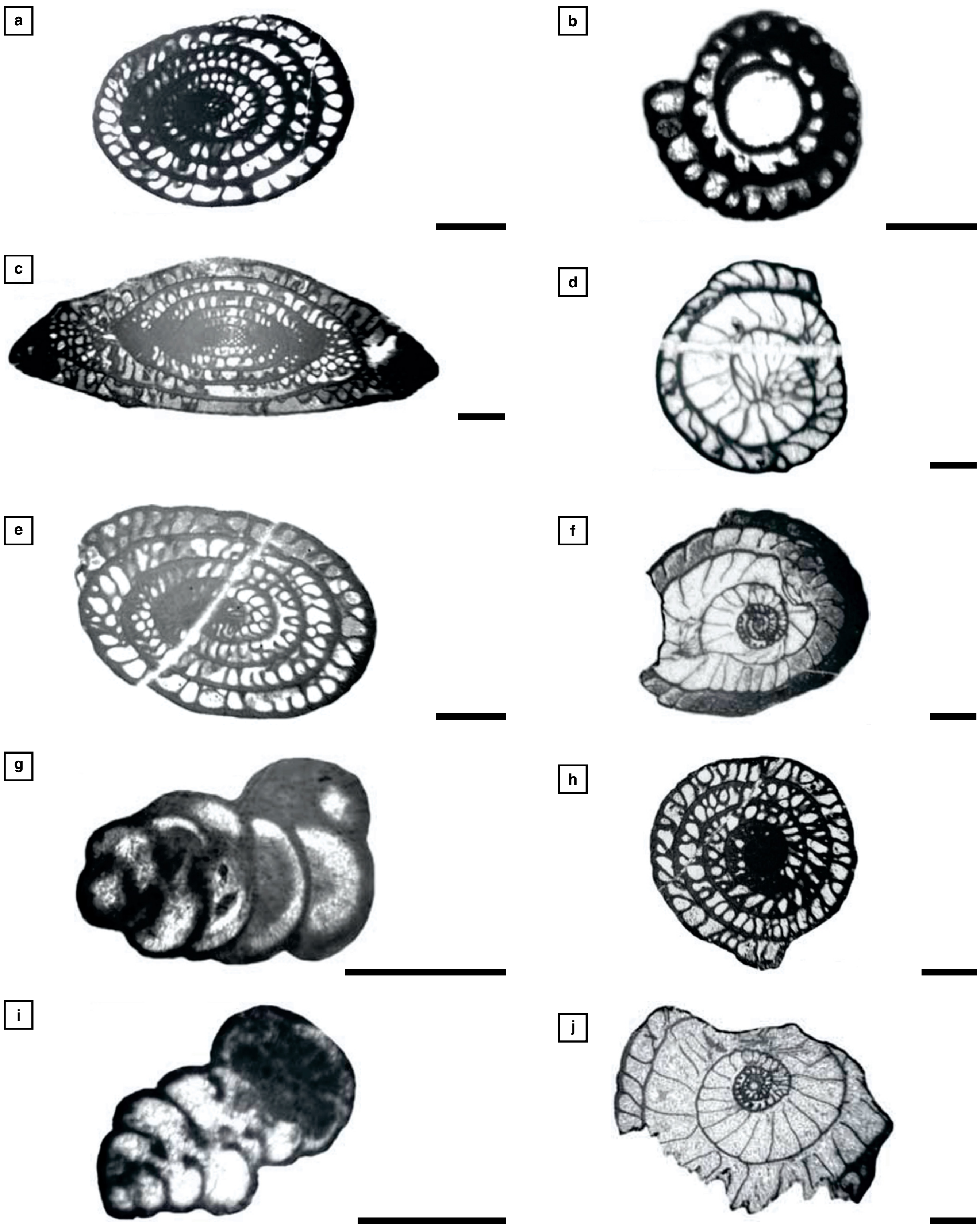

Figure 4. Fusulinids from Manaure (serranía de Perijá): **(a, c, e)** and **(h)** *Schwagerina? hedbergi* Thompson & Miller (1949); **(b)** *Schwagerinoidea* (indet.); **(d, f, j)** *Pseudoschwagerina dallmusi* Thompson & Miller (1949); **(g, i)** *Climacammina* sp. Sakmarian (late Wolfcampian) age. Scale bar is 1000 µm.

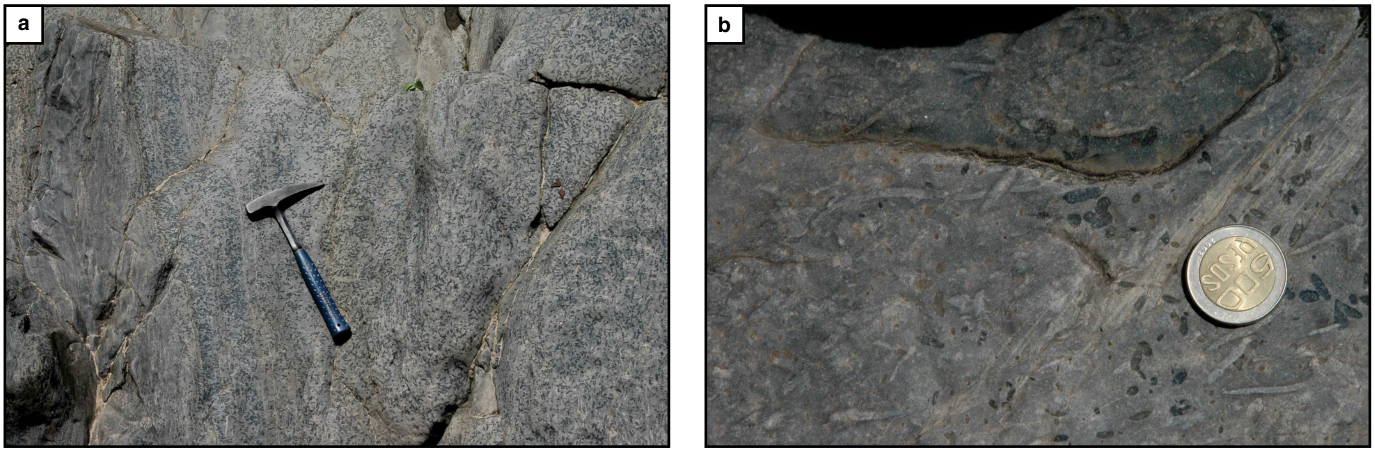

Figure 5. Metapelitic rocks at Chitagá River (Labateca). Floresta sedimentary rocks cover unconformably early Paleozoic metamorphic basement (Chicamocha Formation). **(a)** Cordieritic bands in stratified metapelite; **(b)** *Paleophycus* burrows preserved in metapelite. The dark patches are cordierite crystals.

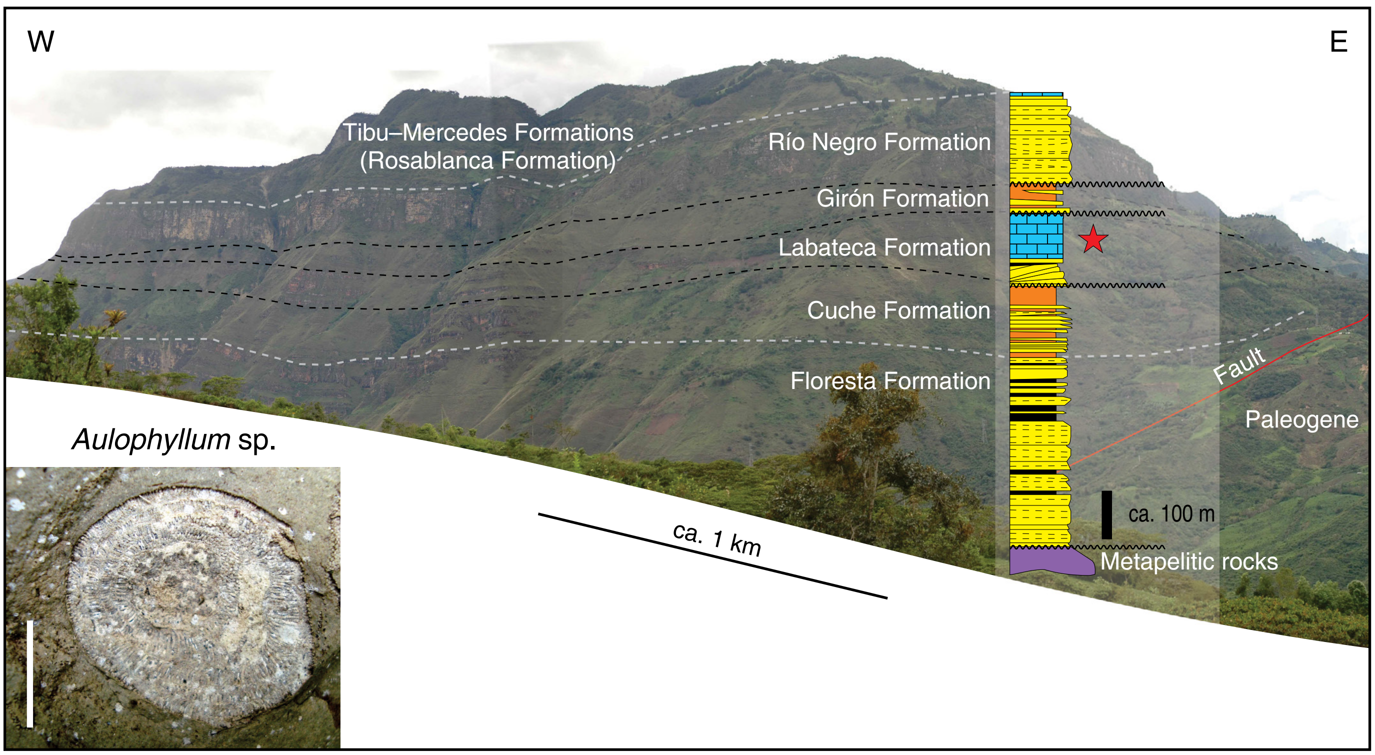

Figure 6. Paleozoic sedimentary succession at Chitagá River, near Labateca. Lower image, Carboniferous rugose coral *Aulophyllum* sp., the stratigraphic position is indicated by the red star. Scale represents 1 cm.

In the core of the Santander Massif, as in the sierra de Mérida, metamorphic rocks of Carboniferous age are exposed. The term "Metamorphosed Floresta Formation" is applied to a group of weakly metamorphosed rocks exposed between the towns of Santa Bárbara and Mogotes in the core of the Bucaramanga Massif (Ward et al., 1977). These rocks include Carboniferous low–grade metamorphic rocks of Mogotes, without relation to the true Floresta Formation (Moreno–Sánchez et al., 2005) and the "metasedimentary series of Guaca", where Forero (1990) identified *Aenigmastrophia* sp., a Silurian (Ludlowvian) brachiopod. The "Metamorphosed Floresta Formation" was dated Devonian based on bryozoans found in the metasedimentites. Diana GUTIÉRREZ (in Ward et al., 1977) identified Devonian Fenestellidae. Nevertheless, these fossils were not suitable for classification nor did they delimit a specific range of time since they are affected by metamorphism.

The "Metamorphosed Floresta Formation" is truly an association constituted of least by two lithological entities with a low degree of metamorphism:

- The youngest sequence, a succession of slates and weakly metamorphosed calcareous horizons (locally, marbles) that crop out near to Mogotes (6° 26' 02.29'' N, 72° 54' 46.77'' W) (Moreno–Sánchez et al., 2005), contains Carboniferous brachiopods (*Derbya* sp., and *Linoproductus*?) replaced partially by mica (Figure 7). At the Alto el Portachuelo hill (Molagavita, 6° 38' 26.80'' N, 72° 51' 18.90'' W and 6° 39' 55.30'' N, 72° 50' 44.50'' W), where Ward et al. (1977) found the fossils used to define the age of the unity, the metalimestone preserving the remains of brachiopods, trilobites (*Paladin* sp.), bryozoans, and crinoids. This upper calcareous segment, due to the paleontological and facial characteristics, can be correlated with the Carboniferous of Mogotes but not with the true Floresta Formation (Moreno–Sánchez et al., 2005).
- The oldest metasedimentary sequence, underlying the metalimestones, is composed of a succession of gray metamudstones and quartzites. The only fossiliferous locality in this unit is located north of Guaca and contains trilobites, crinoids, and brachiopods. The Silurian brachiopod *Aenigmastrophia* sp. occurs in distorted gray slates (Forero, 1990).

In the area between Tipacoque and Soatá (southern Santander Massif), Guaca and Mogotes metamorphic rocks are overlain in angular unconformity by the sedimentary sequence of the Río Nevado Formation, with the age between the Pennsylvanian and the Permian (Stibane & Forero, 1969). According to Stibane & Forero (1969), on the road that leads from the Chicamocha River to the Cocuy village near the Totumo bridge, the Río Nevado Formation composed of conglomerates, red and gray shales, sandstone and limestone of Pennsylvanian – lower Permian age (Figure 8).

To the east of the Bocas village (7° 13' 22.99'' N, 73° 08' 27.35'' W), in a calcareous section attributed to the base of the Bocas Formation, the foraminifers *Cuniculinella* ex gr. *fusiformis* that point to a lower Artinskian age (Figure 9) occur. In the same area, a calcareous bed also contains Wolfcampian conodonts (Rabe, 1974). Thus, adding the new material, the range of this segment would be Sakmarian to Artinskian. This segment, consisting of thick limestone packages, should be excluded from the Bocas Formation (sensu Remy et al., 1975) and included as an upper part of the Suratá Group of Dickey (1941; Navas, 1962). It is necessary to clarify that the siliciclastic segments of the Bocas Formation contain fossil flora that points to an early Mesozoic age (Remy et al., 1975; Ward et al., 1977).

Under the Carboniferous limestones (Suratá Group), between the Suratá River and Bocas village, a wedge of sandstone and mudstone with a fossil fauna consisting of brachiopods, trilobites, and crinoids that point to a late Middle Devonian age correlated to Floresta Formation (Rabe, 1974).

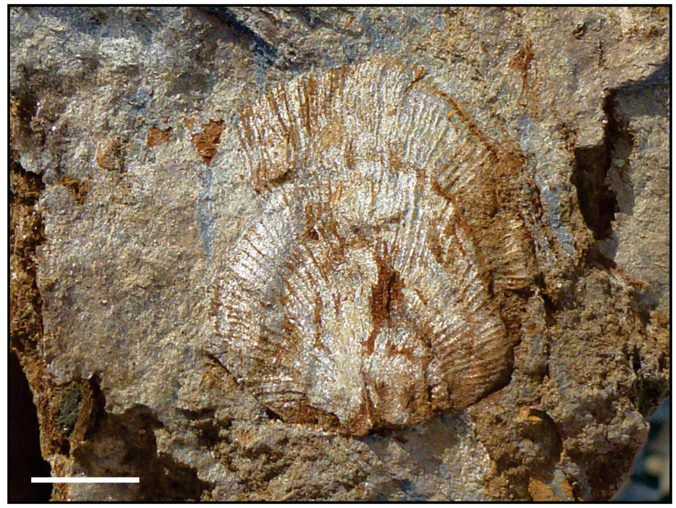

Figure 7. Pennsylvanian brachiopod *Derbyia* sp. From the Mogotes locality. The shell was partially replaced by muscovite. Scale represents 1 cm.

Figure 8. Carboniferous to Permian deposits of Río Nevado Formation at Totumo Bridge.

Pennsylvanian conodonts are found at the Suratá Group in northern Bucaramanga (Rabe, 1974). The assemblage contains *Adetognathus inflexus*, *Adetognathus lautus*, *Adetognathus spathus*, *Anchignathodus coloradoensis*, *Anchignathodus minutus*, *Gnathodus bassleri symmetricus*, *Gnathodus bassleri* n. subsp. *A., Gnathodus lateralis, Gnathodus noduliferus*, *Gnathodus roundyi, Gondolella clarki*, *Hindeodella* sp., *Idiognathodus delicatus*, *Idiognathoides sinuatus*, *Ligonodina* sp.*, Lonchodina* sp., *Metalonchodina* sp.*, Neoprioniodus*? *expandofundus*, *Ozarkodina delicatula*, *Ozarkodina* sp., *Streptognathodus expansus, Streptognathodus* sp. According to Rabe (1974), the assemblage suggests a Morrowan to Desmoinesian age (Bashkirian to Moscovian).

South of the same section (upper Suratá Group, Figure 10), at the Diamante Formation (lower part of the Suratá Group),

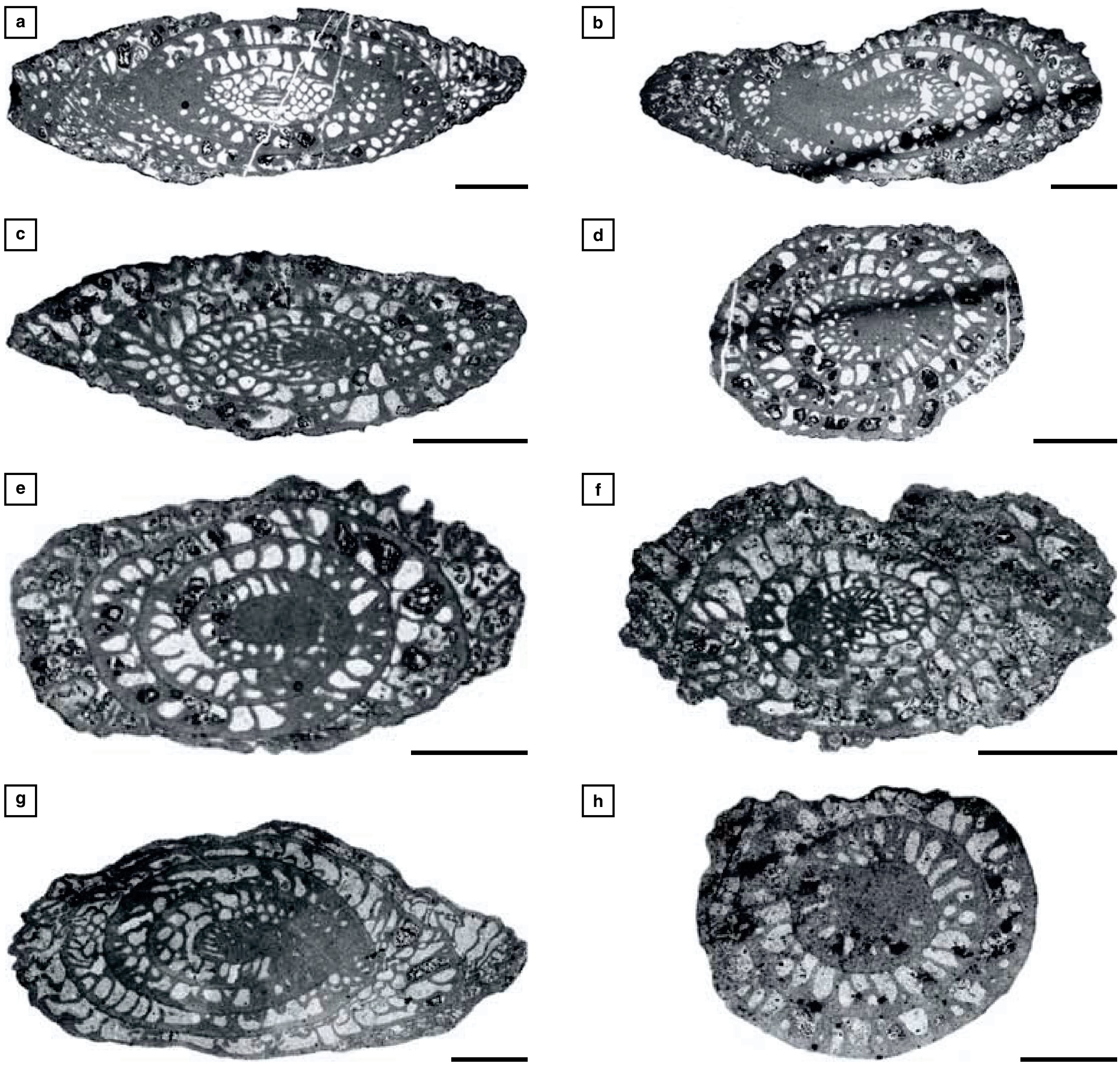

Figure 9. Permian Suratá Group foraminifer: **(a–h)** *Cuniculinella* ex gr. *fusiformis* Skinner & Wilde (1965). Early Artinskian age. Scale bar is 1000 µm.

Permian conodonts have been recovered (Rabe, 1974): *Anchignathodus* aff. *typicalis*, *Gnathodus bucaramangus* n. sp., *Gnathodus whitei*, *Gondolella* sp., *Hindeodella* sp., *Lonchodina* sp., *Ozarkodina* sp., *Streptognathodus elongatus*, *Streptognathodus sulcoplicatus*. According to (Rabe, 1974), this assemblage points to Wolfcampian to Guadalupian age (nearly Cisuralian to Guadalupian). The Diamante Formation (Dickey, 1941) is made up of 440 meters of sandstones, mudstones, and slightly recrystallized limestones. The unit outcrops along the old Rionegro–Bucaramanga road to the north of Bucaramanga city, particularly in the "Cementos Diamante" quarry where it takes its name. Fossils of Permian age including brachiopods (*Meekella* sp., cf. *Orthotichia* sp.) and fusulinids (Ward et al., 1973) occur at the formations.

5. Floresta Massif

A complete section of the Devonian in the Floresta Massif is found in the Potrero Rincón locality (Figure 11). The core of the Floresta Massif is formed by granitoids, phyllites, and slates of Cambrian – Ordovician age. The El Tíbet Formation (Cediel,

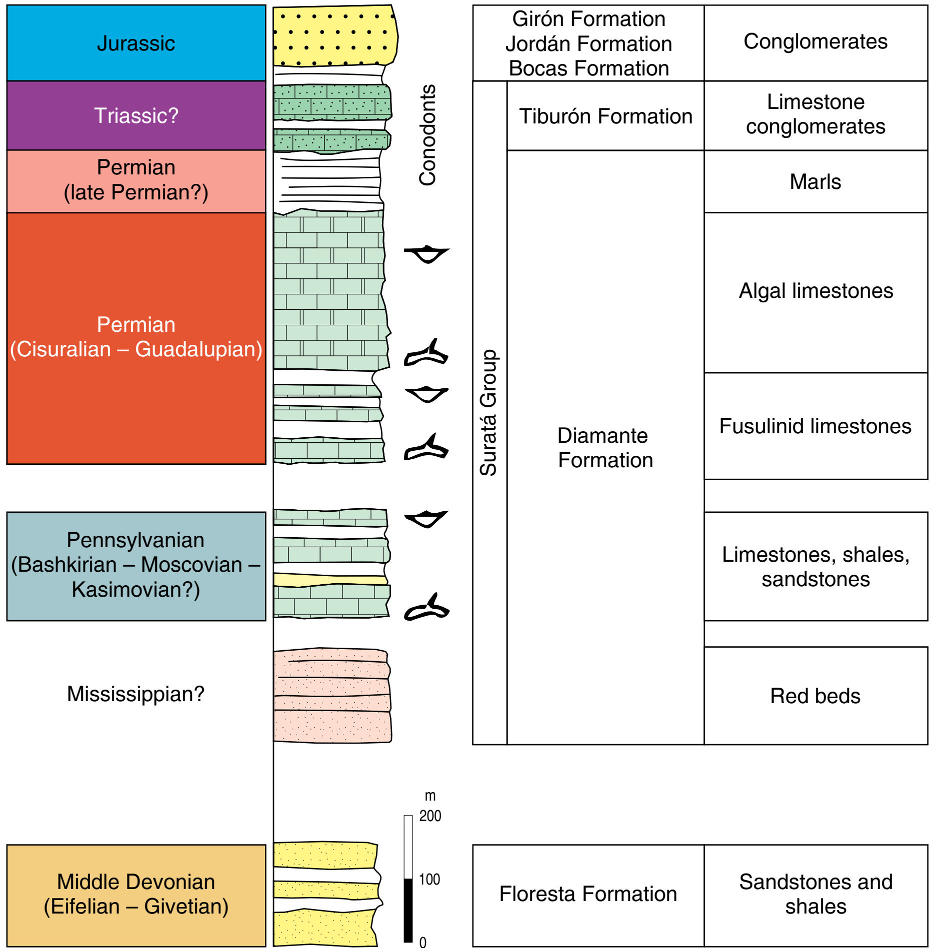

Figure 10. Stratigraphic chart of Suratá Group at the Santander Massif (Rabe, 1974).

1969; Mojica & Villarroel, 1984), separated from the metamorphic and igneous rocks by an unconformity, is a sedimentary succession composed of micaceous sandstones, conglomerates and thin layers of gray mudstones. At the Potrero Rincón, the thickness of this formation varies between 40 and 60 meters.

Fossils are rare, although towards the base, at a 4–meter clay level, brachiopods and plant remains have been found. The most common fossils of invertebrates in the El Tíbet Formation correspond to inarticulate brachiopods of the family Discinidae (*Schizobolus?* sp.) (Figure 12) and spiriferida brachiopods. Fossil plants (at 5° 49' 25.92'' N, 72° 55' 14.47'' W) correspond to fragmentary remains, something carbonized, where it is possible to identify the parenchymatous land plant *Spongiophyton* sp. (Moreno–Sánchez, 2004). U–Pb detrital zircon, recovered from the El Tíbet Formation, points to a maximum Early Devonian depositional age (414 Ma age peak) (Cardona et al., 2016). However, spores recovered from this formation indicate an Emsian age (Grösser & Prössl, 1994).

At the Floresta Massif, the El Tíbet Formation has a thickness that varies between 30 and 600 meters (Cediel, 1969), suggesting that during Early Devonian times in the region, there was a rugged paleotopography. The El Tíbet Formation was deposited in a coastal siliciclastic transgressive environment during the Emsian age.

The Floresta Formation mudstones, near 500 meters thick, conformably overlie the sandstones of the El Tíbet Formation. Floresta lithology consists mainly of mudstones and dark shales with some sandstone intercalations, to the base where thin ferruginous ooid strata occur. In all the studied sections, the richest fossil interval is very close to the base of the sedimentary sequence (e.g., Potrero Rincón A, Figure 11). The fossils, originally of carbonates, correspond now to molds, consisting of bryozoans, trilobites, tabulata (*Favosites* sp., *Pleurodictyum* sp.) rugose corals, brachiopods, crinoids, and mollusks (gastropods and bivalves). From the lower Floresta Formation, Trapp (1968) quotes *Hoareicardia cunea* ("*Conocardium cuneus*"), the first Rostroconchia from Colombia. Some dacryoconarid remains (Figure 13), semi–infaunal shelly fossils of unknown affinities, are found in the transition from the gray to the dark shales. On the argillaceous part, black shales with a few interbedded limestones predominate to the top of the formation.

At the Potrero Rincón B (5° 49' 41.48'' N, 72° 55' 35.71'' W; Figure 11), thin limestone layers, always weathered, con-

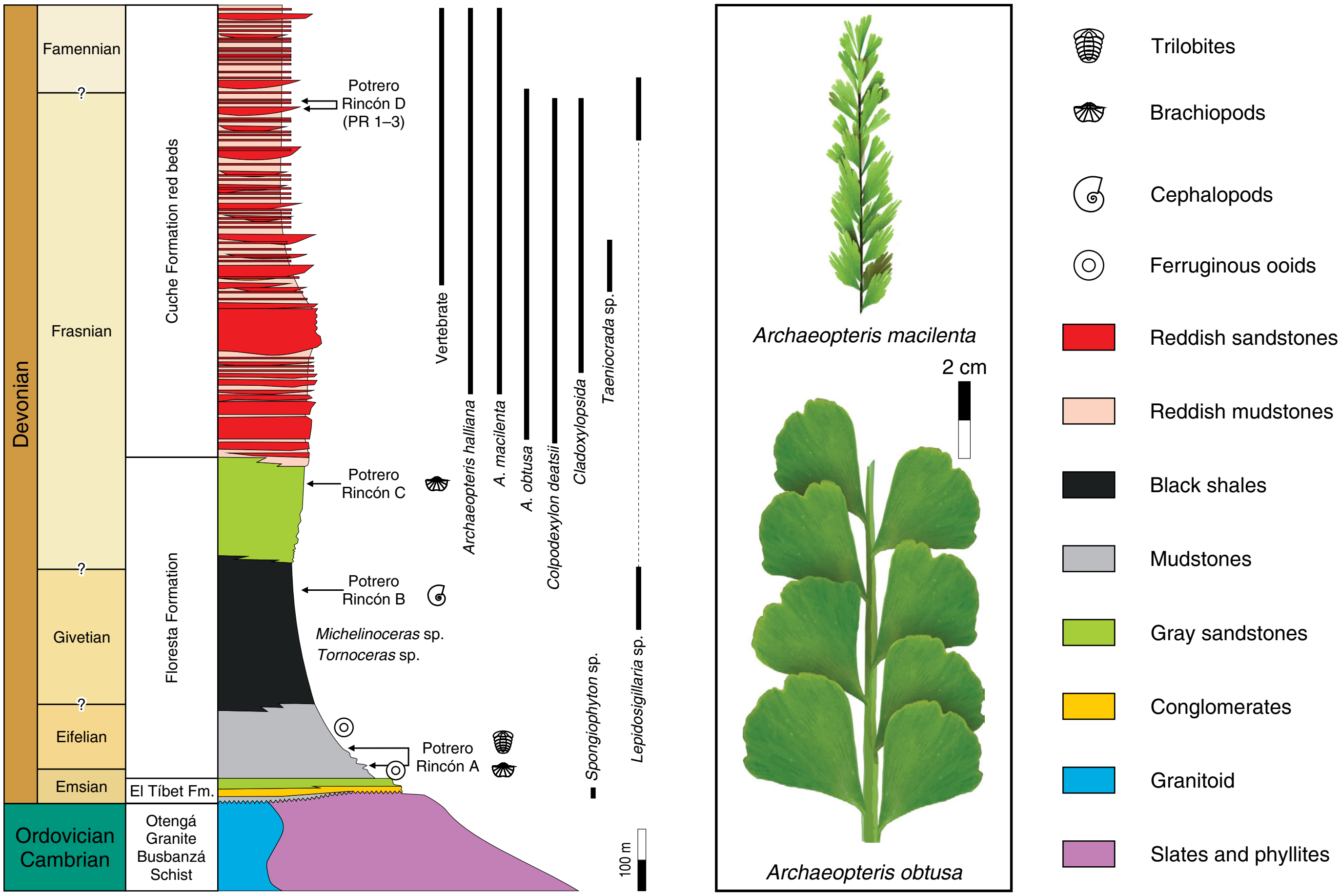

Figure 11. A geologic column of Devonian formations at Potrero Rincón locality (Floresta Massif).

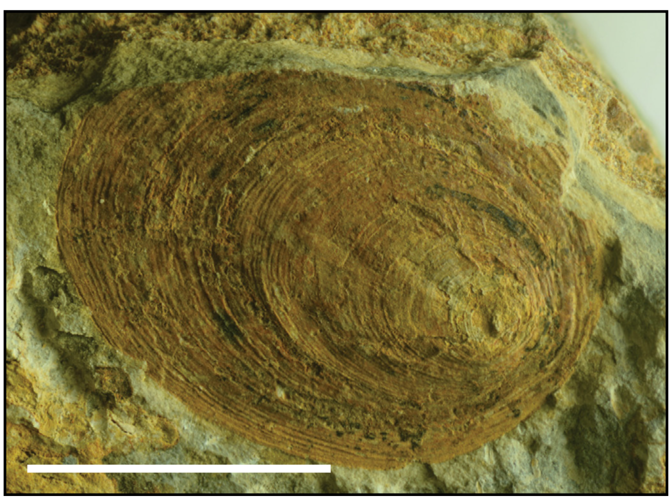

Figure 12. Inarticulate brachiopod (*Schizobolus?* sp.) recovered from the base of El Tíbet Formation. Scale bar represents 1 cm.

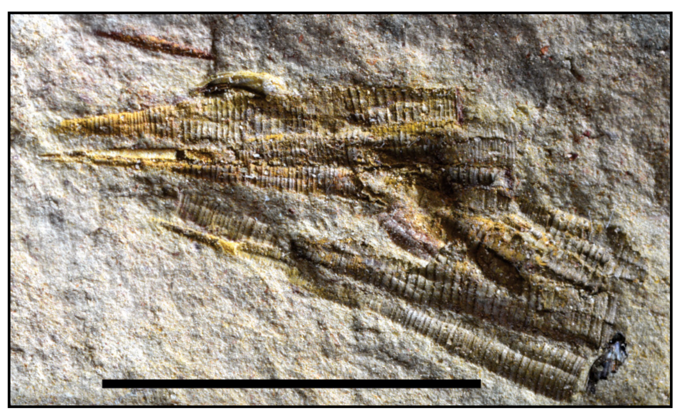

Figure 13. Dacryoconarids remains from the middle part of Floresta Formation. Scale bar represents 1 cm.

tain cephalopods of the genus *Michelinoceras* and *Tornoceras*) mixed with remains of Phyllocarida crustaceans (Figure 14). At the top of Floresta Formation, the silty sandstone beds contain the brachiopod *Composita* sp., that indicates a Frasnian age for this segment (Potrero Rincón C; Figure 11).

The fauna of Floresta Formation, quoted by Caster (1939), McNair (1940), Morales (1965), and Barrett (1988), shows similarities to the Onondaga Formation and Hamilton Group of eastern North America, suggesting an Eifelian to Givetian age. Based on trilobites and brachiopods, Morzadec et al. (2015)

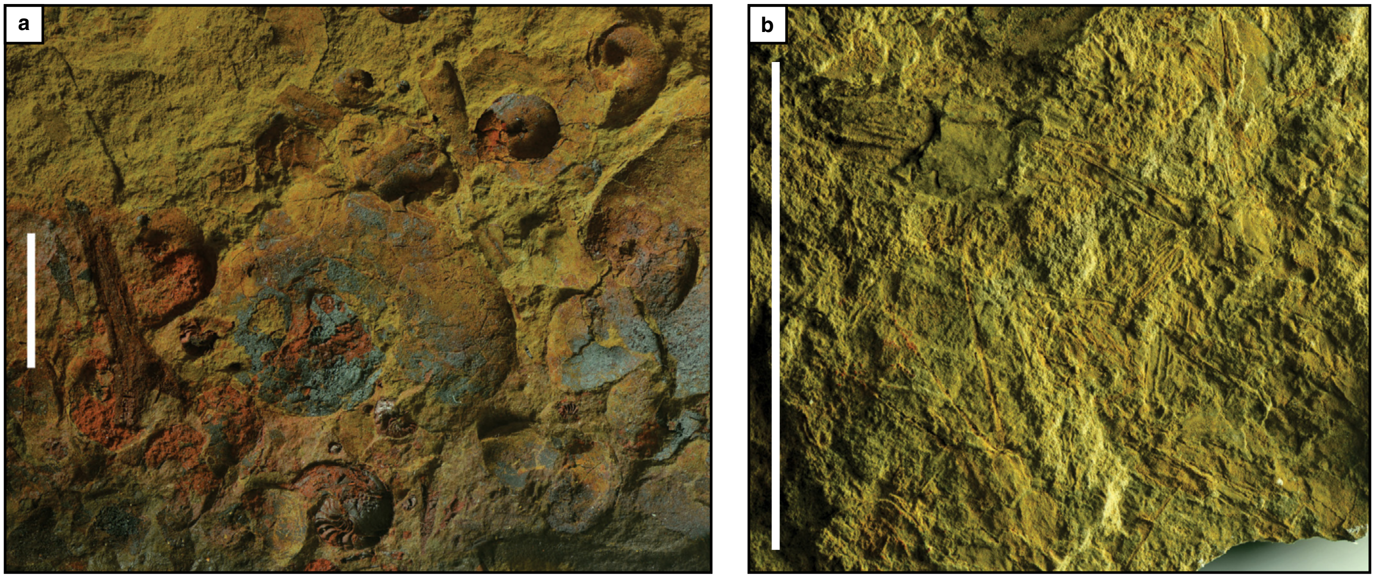

Figure 14. (a) Cephalopods *Tornoceras* sp. from the Floresta Formation; **(b)** phyllocarid remains. Scale bar represents 1 cm.

propose a late Emsian age for the lower part and a Givetian age for the upper part of the formation. Fragments of the plates of placoderm fishes (order Rhenanida) have been found in the lower part of the Floresta Formation (Janvier & Villarroel, 1998, 2000). The Floresta Formation was deposited in an epicontinental marine environment. Rich fossil assemblages in the Potrero Rincón A locality (Figure 11) indicate a shallow marine environment. Cephalopods in the black shales (Potrero Rincón B) suggest a maximum flooding surface at the middle part of the Floresta Formation. Ferruginous ooid beds are interpreted as non–deposition conditions in a low–energy marine environment (Burkhalter, 1995).

The Cuche Formation, approximately 750 meters thick, is composed of red and gray sandstones interbedded with reddish mudstones originating in a deltaic and fluvial environment (Moreno–Sánchez, 2004). Petrographically, the sandstones are classified as litharenites whose source, according to Dickinson (1985), is the one of a recycled orogen (Cardona et al., 2016). The formation covers conformably the epeiric marine layers of the Floresta Formation. The Cuche Formation red beds contain vertebrates and plant remains often found in the muddy intervals of the unit. At the Potrero Rincón D beds (at 5° 49' 08.30'' N, 72° 56' 29.71'' W; Figure 11), Janvier & Villarroel (2000) found fish remains that include *Cheiracanthoides*? sp., *Antarctilamna*? sp., placoderms (*Bothriolepis* sp., *Asterolepis*? sp.), and sarcopterygians (*Holoptychius*, *Strepsodus*? sp.). The fish assemblage shows Laurussian affinities, but *Antarctilamna* is a Gondwanan chondrichthyan; Burrow et al. (2003) also quote other species such as *Nostolepis gaujensis* and *Florestacanthus morenoi* (Figure 15). The age of the fish assemblage of Potrero Rincón D (PR 1–3) is late Frasnian (Janvier & Villarroel, 2000).

The most common fossil plant in the red beds of the Cuche Formation is *Archaeopteris* (Figure 16), a sporangiate tree with pycnoxylic wood similar to that of some conifers. *A. obtusa*, a species with the largest leaves, and *A. notosaria* are the most common plants in the lower part of the formation. *Archaeopteris halliana* and *A. macilenta* are the dominant plants towards the upper part of the Cuche Formation, originating possibly in a drained portion of a floodplain. Almost every *Archaeopteris* species has a global distribution, although *A. notosaria* is known only from the Upper Devonian from South Africa (Anderson et al., 1995). All recognized *Archaeopteris* species are constrained to the Frasnian – Famennian (Fairon–Demaret, 1986). Impressions of detached fan–shaped leaves with parallel bifurcating veins of *Ginkgophytopsis* (*Ginkgophyton*) and *Platyphyllum* genus are common throughout the unit. Fossil assemblages of Cuche Formation include highly dissected isolate leaves, often confused with *Baiera*, which are ascribable to the Paleozoic genus *Ginkgophyllum*. Remains of Cladoxylopsida–like plants, *Colpodexylon deatsii*, and arborescent lycopsida (*Lepidosigillaria* sp.) are found in association with channel margin and lacustrine deposits (Moreno–Sánchez, 2004). Sandstones of the El Tíbet, Floresta, and Cuche Formations are composed of arkosic and lithic siliciclastic components (Cardona et al., 2016), but there are no primary volcanic deposits attributable to proximal volcanism. The abundance of muscovite flakes in the sandstones (especially in the El Tíbet Formation) suggests that a large part of the detrital components of these units comes from the erosion of a metamorphic massif.

In South America, the Cuche Formation is the equivalent of the Catskill Formation of the eastern North America. The Cuche Formation correlates with the Frasnian age Campo Chico Formation (Harvey, 1999) at the serranía de Perijá (Colombia–Venezuela border). The Campo Chico Formation yields a Phyllolepid fish fauna composed of Gondwanan and Laurussian elements (Young & Moody, 2002a, 2002b).

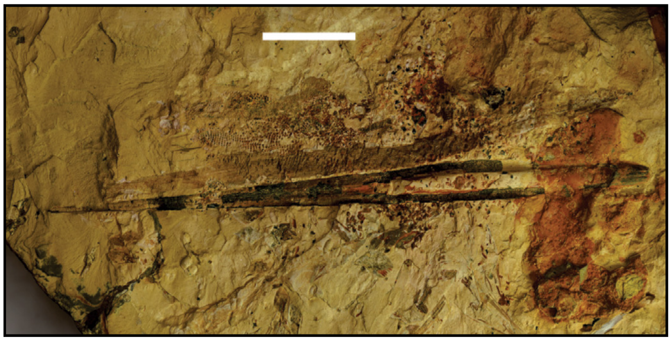

Figure 15. *Florestacanthus morenoi* from the fish assemblage of Potrero Rincón D (PR 1–3). Scale bar represents 1 cm.

6. Quetame Massif

The oldest rocks reported in the Quetame Massif that crop out on the Bogotá–Villavicencio highway, correspond to quartzitic conglomerates, phyllites, and schists originally described by Hettner (1892). Trumpy (1943, 1945), based on lithological comparisons, suggests that the metamorphic rocks of the Quetame Massif are the time equivalent to the sedimentary succession of the Güejar River canyon in the serranía de La Macarena. Therefore, after the publication of the work of Trumpy (1943), a Cambrian – Ordovician age has been assumed for the sedimentation of similar rocks on the Eastern Cordillera (Campbell & Bürgl, 1965; Renzoni, 1968; Stibane, 1968). Trapp (1968) brings together the different metamorphic units of the massif (conglomerates, quartzites, and gray and greenish phyllites) in the so–called "Quetame Group", which includes rocks characterized by penetrative planar fabric.

At the Casa de Teja Creek site (Bogotá–Villavicencio road, 4° 11' 55.87'' N, 73° 46' 24.98'' W), despite the penetrative foliation (S_1 average: 310°/70°) that affects the Quetame Group rocks, the bedding is still visible. The phyllites expose sectors with a high degree of bioturbation (Figure 17). Thus, the presence of ichnofossil burrows such as ichnogenus *Teichichnus*, in agreement with the invertebrate evolution, discards a Precambrian age (Gradstein et al., 2012) for the phyllites and quartzites of Guayabetal Formation (part of the Quetame Group). The finding of Silurian palynomorphs in a sequence of clastic rocks (conglomerates, sandstones, and mudstones), slightly metamorphosed and lithologically different from those of the underlying Quetame Group, indicates that the main phase of the Quetame metamorphism is older than the Silurian (Grösser & Prössl, 1991).

All the Paleozoic sedimentary formations of the Quetame Massif (from the Devonian to the Carboniferous) were gathered by Braun (1979) within the Farallones Group. The Areniscas de Gutiérrez and Pipiral Formations (Middle Devonian), composed of sandstones, siltstones and black mudstones, correlate with the El Tíbet and Floresta Formations in the Macizo de Floresta. Towards the upper part of the group is the Capas Rojas de Guatiquía Formation, of Pennsylvanian age, composed of siltstones, red and green pale beds, and limestones (Braun, 1979; Pulido & Gómez, 2001; Pulido et al., 1998). Trapp (1968) mentions Mississippian deposits; however, this has not been confirmed by biostratigraphic data.

The Farallones Group, at Guateque–Santa María road, includes a sequence of conglomerates, sandstones, and mudstones of middle Devonian age (Segovia & Renzoni, 1965). The most common fossils are brachiopods, tentaculites, and bivalves. *Orthonata undulata* (4° 53' 33.72'' N, 73° 17' 11.94'' W, Figure 18), a Givetian razor clam, is reported in the mudstones.

Limestones collected by Fernando ETAYO–SERNA from the Farallones Group, to the north of Quetame Massif (4° 43' 16.20'' N, 73° 21' 37.79'' W), contain foraminifers identified by Daniel VACHARD as an assemblage of Middle Pennsylvanian age (Moscovian: late Atokan or Kashirian – Podolskian): *Fusulinella* ex gr. *thompsoni*, *Schubertellina* sp., *Fusulinella* sp., *Pseudoacutella* cf. *grozdilovae*, *Planoendothyra* sp., *Palaeotextularia* sp., *Millerella* sp., *Climacammina* sp., and *Plectomillerella* sp. (Figure 19).

7. Late Paleozoic Sedimentary Rocks on the Eastern Flank of the Central Cordillera

To the west of Ibagué city (Chapetón neighborhood), a strip of limestone and marble crops out, cited by Nelson (1957) as part of the Cajamarca Series. These late Paleozoic marbles, cropping out to the east of the Otú–Pericos Fault, are constituted of thick layers of crinoidal limestones (Gómez & Bocanegra, 1999; Moreno–Sánchez et al., 2008a). The Carboniferous limestones at Ibagué are correlated with other marmorized limestones cropping out along the eastern flank of the Central Cordillera. The marbles, some of them included in the Aleluya Complex (Ferreira et al., 2002), are thermally affected by Mesozoic intrusives. Hernández–González & Urueña–Suárez (2017) dated the biotite of the marbles and obtain a $^{40}Ar/^{39}Ar$ age of 211.2 ± 1.18 Ma (Triassic) attributed to a metasomatic event.

In the El Imán Creek, near Rovira in the eastern foothills of the Central Cordillera, there is a sedimentary sequence consisting of conglomerates, sandstones, and fossiliferous shales (Núñez & Murillo, 1982). Fossil (bryozoans and brachiopods) age ranges from the Middle Devonian to Carboniferous (Tournaisian), the latter suggested by the presence of the brachiopod *Ericiatia* (Forero, 1986). The fossil fauna of Rovira contains elements common to New Mexico, which, according to Forero (1986), suggest that the northern South America platform was in a latitudinal position similar to that of the Old–World Province (sensu Johnson & Boucot, 1973). The fossil assemblage includes *Adolfia* cf. *A. deflexa, Cariniferella alleni*, *Cryptothyrella* cf. *C. cylindrica*, *Devonoproductus intermedius*, *Eleuterocoma* cf. *E. beardi*, *Laminatia*

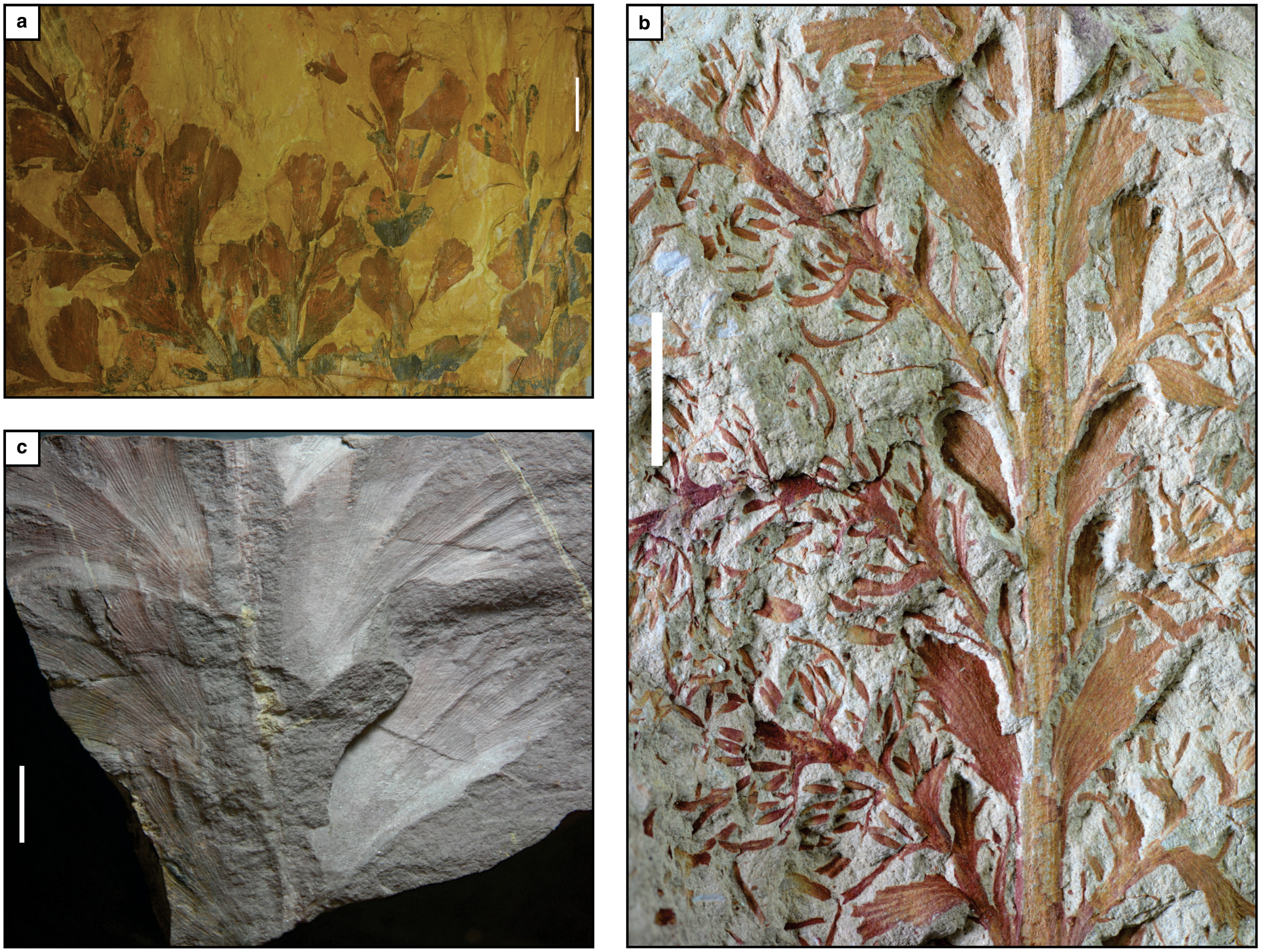

Figure 16. Plant remains from the Cuche Formation. **(a)** *Archaeopteris obtusa*; **(b)** A. *macilenta*; **(c)** *A.* cf. *notosaria*. Scale bar represents 1 cm.

laminata, Schizophoria amanuensis, *Strophopleura notabilis*, besides the genera *Cyrtina*, *Eostrophalosia, Schelwienella,* and *Tylothyris*.

At the Amoyá Formation (Núñez et al., 1984), constituted of a failed sequence of black shales with intercalations of sandstones exposed on the eastern flank of Central Cordillera, *Cymbosporites catillus*, *Stenozonotriletes inequaemarginalis*, *Dibolisporites abitibiensis*, and *Apiculiretusispora pygmaea* were recovered. The aforementioned pollen assemblage indicates, at the place of sampling (near to 3° 46' 54.41'' N, 75° 33' 33.16'' W), an Eifelian age (Prössl & Grösser, 1995). Sedimentary facies at Amoyá and Rovira (Forero, 1986) indicate near shore marine environments during the Middle and Late Devonian.

To the east of San Antonio on the border of Garzón Massif, a Pennsylvanian sequence composed of siliceous mudstones, quartzites, and oolitic limestones crops out. The rocks are thermally affected by Jurassic intrusives that locally generate marbles. The limestones contain crinoids and brachiopods. A limestone was sampled (2° 54' 51.00'' N, 75° 05' 12.96'' W) and contained *Seminovella* sp., an early Bashkirian (Morrowan) Millerellinae foraminifer (Figure 20). The carboniferous Formation of San Antonio is correlated with the nearby Cerro Neiva Formation (Mojica et al., 1987a).

8. La Jagua (Huila)

Stibane & Forero (1969) use the term "Paleozoic of the La Jagua" to refer to a sedimentary section exposed near La Yunga farm. However, detailed field geological work has determined that, in the vicinity of the farm outcrops mentioned above, the Gualanday Group is of Paleogene age. Carboniferous deposits of the La Jagua (Stibane & Forero, 1969) crop out along the Caguancito Creek, southwest of the municipality of Garzón, Huila. The occurrence of the brachiopod *Acrospirifer olssoni* (Stibane & Forero, 1969) and tentaculitids in the shales exposed to the west of the section of Caguancito indicates the presence of Devonian in this area.

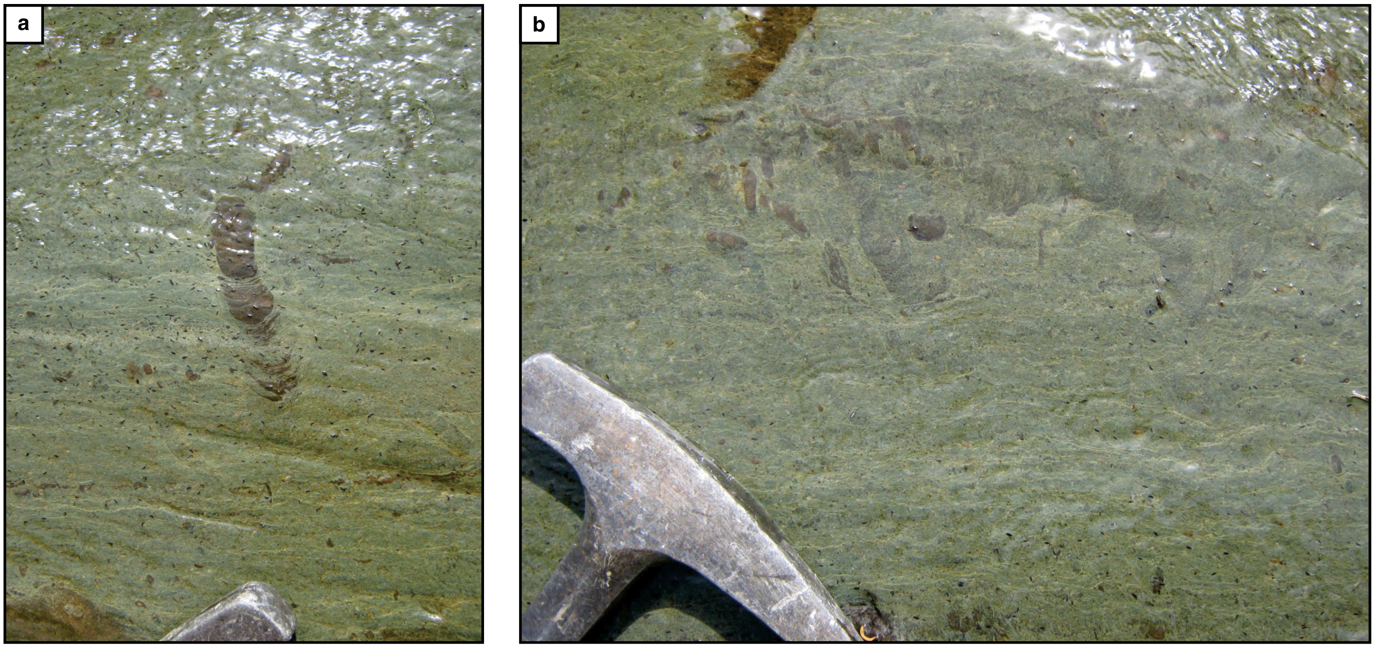

Figure 17. Fossil traces at the Quetame Massif. **(a)** *Teichichnus* isp.; **(b)** pervasive bioturbation at the Quetame phyllites.

Figure 18. Bivalve *Orthonata undulata* from the Farallones Group. Scale bar represents 1 cm.

At the Caguancito Creek, a tributary of Aguas Calientes River (5 km to the southeast of the La Yunga farm), the most continuous outcrops of the Carboniferous on the Garzón Massif occur. The section, according to Velandia et al. (1996), is 660 m thick, measured at the junction with the Aguas Calientes Creek (2° 06' 13.94" N, 75° 39' 14.77" W).

In the Caguancito Creek, it is possible to recognize repetitive sequences in which layers of continental origin alternate with marine deposits (Figure 21) indicating cyclic sea level changes characteristic of Carboniferous global glaciations (Heckel, 2008). The segments of marine origin are characterized by calcareous levels, sometimes oolitic, and gray to black shales, with a fauna consisting mainly of brachiopods, crinoids, conulariids, bryozoans, and mollusks. Goniatitid ammonoidea (*Gastrioceras* sp.) are present at the dark shale segments (e.g., 2° 06' 27.00" N, 75° 38' 56.30" W). The continental deposits are characterized by desiccation cracks, rain drop marks, eurytopic leaioid conchostracan (*Hemicycloleaia* sp.) and fossil plants such as *Calamites* sp., *Odontopteris* sp., and seed impressions (*Samariopsis* sp.) (Figure 22). The presence of dolomites with pseudomorphs of anhydrite suggests sedimentation under dry climatic conditions and high temperatures (Gómez–Cruz & Chevalier, 2003).

Several samples of limestone were studied in this section by Daniel VACHARD, providing an association of foraminifera composed of *Millerella* sp., *Asteroarchaediscus*? sp., *Calcivertella* sp., *Planoendothyra* sp., *Glovivalvulina* sp., *Millerella* sp. 1., *Millerella* sp. 2., *Tetrataxis* sp., *Tubispirodiscus*? sp., *Planoendothyra aljutovica* (Figure 23). The assemblage age is Lower Pennsylvanian (Bashkirian). The Pennsylvanian deposits of La Jagua are correlated with the "Calizas y Arenitas de La Batalla" at Las Minas.

9. The Problem of Crystalline Basements of Eastern Cordillera and Magdalena Valley

During the Precambrian and early Paleozoic, the stratigraphic and tectonic history of the Eastern Cordillera (Quetame–Mérida Terrane) differs clearly from the stratigraphic and tectonic history of the Magdalena Valley (Payandé and Payandé–San Lucas Terranes sensu Etayo–Serna et al., 1983).

Bucaramanga Gneiss is the oldest metamorphic rock at the Santander Massif. Cordani et al. (2005) report U–Pb zircon ages between 1558 and 864 Ma, Ward et al. (1973) quote a 945 ± 40 Ma K/Ar age, and Restrepo–Pace (1995) give $^{40}Ar/^{39}Ar$

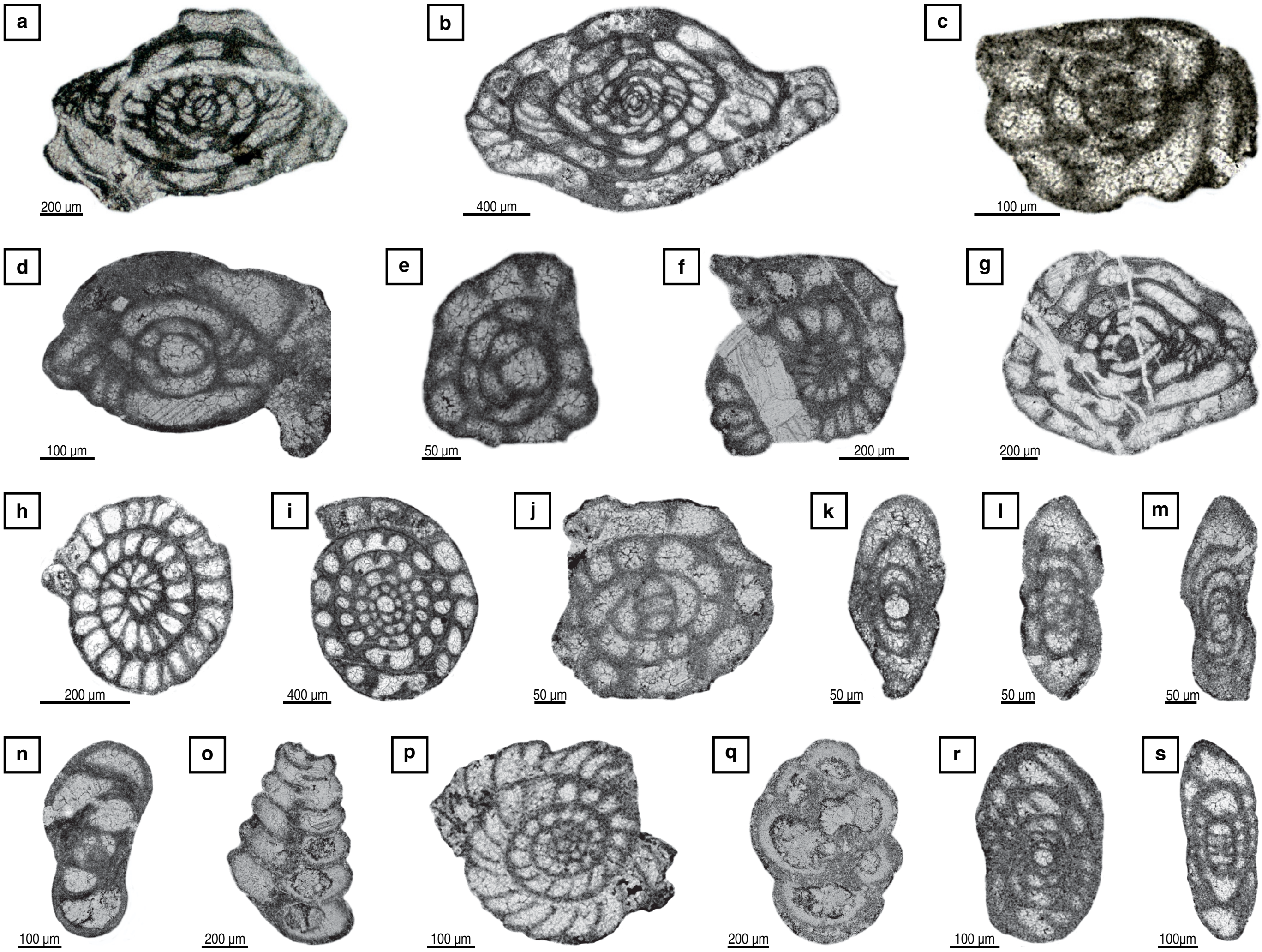

Figure 19. Pennsylvanian foraminifers from Mámbita (Quetame Massif): **(a, b)** *Fusulinella* ex gr. Thompsoni Skinner & Wilde (1954); **(c, d, e)** *Schubertellina* sp.; **(f, g, h, i, j)** *Fusulinella* sp.; **(k, l, m)** *Pseudoacutella* cf. *grozdilovae* Maslo & Vachard (1997); **(n)** *Planoendothyra* sp. Skinner & Wilde (1954); **(o)** *Palaeotextularia* sp.; **(p)** *Millerella* sp.; **(q)** *Climacammina* sp.; **(r, s)** *Plectomillerella* sp. Early Moscovian (Kashirian and /or Podolskian) age.

ages between 850–800 Ma. At the same locality where Ward et al. (1973) report the K/Ar samples, Ordóñez–Carmona et al. (2006) obtained a 1.71 Ga for the protolith sedimentation based on Sr and Nd isotopic analyses. However, due to the sample location on a tectonic wedge placed along the Bucaramanga Fault between Aguachica and Ocaña, it is not reliable that gneisses can be included safely either in the Santander Massif or in the Payandé–San Lucas Block (Figure 1).

The Silgará Formation includes sequences of metamorphosed clastic rocks consisting of schists, slates, phyllites, siltstones, sandstones, and calcareous phyllites. Based on petrographic features and detrital zircons, Mantilla–Figueroa et al. (2016) split off the older Silgará Formation (sensu Ward et al., 1973) into three different units.

- The Silgará Formation sensu stricto is restricted to the type section of the Silgará Formation (Santander Massif, Matanza–Cachirí area), which contains detrital zircons with peaks of Precambrian U–Pb ages approximately 940, 1010 and 1248 Ma (Mantilla–Figueroa et al., 2016).
- The Chicamocha Schists, with a maximum depositional age of 506.7 ± 9.3 Ma (middle Cambrian), is constituted of the schists and quartzites that crop out at the Chicamocha canyon on the Piedecuesta–Aratoca section. Chicamocha Schists are intruded by Ordovician foliated granitoids (orthogneisses) (Mantilla–Figueroa et al., 2016).
- The San Pedro Phyllites, cropping out at the Piedecuesta–Aratoca sector, contain the youngest zircons of 451.6 ± 7.7 Ma (Mantilla–Figueroa et al., 2016), suggesting a maximum depositional age near the Ordovician – Silurian boundary.

The Chicamocha Schists can be correlated with the Quetame Group and with the metasedimentary rocks with fossil traces of Labateca (Silgará Schists sensu Royero & Zambrano, 1987). Quetame and Chicamocha units, with *Teichichnus* that suggest

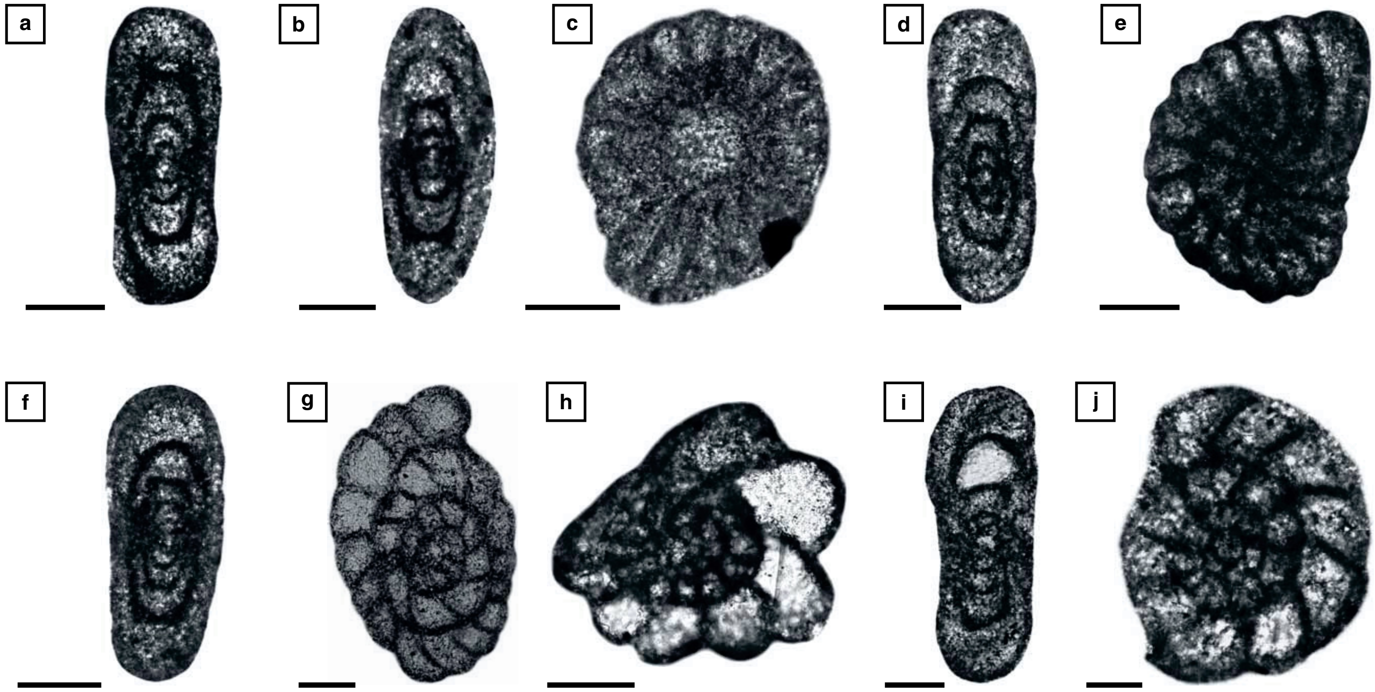

Figure 20. Early Bashkirian (Morrowan) Millerellinae foraminifer from San Antonio: **(a–i)** Seminovella sp. Maslo & Vachard (1997). Scale bar is 20 µm.

a post–Ediacaran age, are intruded by Early to Middle Ordovician granitoids (Horton et al., 2010; Mantilla–Figueroa et al., 2016). The San Pedro phyllites can be correlated with the lower part of "metamorphosed Floresta Formation" and could be equivalent to the Silurian metasedimentary rocks of Guaca.

At the Quetame, Floresta, Santander, and Perijá areas, the late Paleozoic sedimentary sequences were deposited over a basement constituted of Precambrian to early Paleozoic metamorphic rocks intruded by Ordovician granitoids (e.g., Boinet et al., 1985; Cardona et al., 2016; Goldsmith et al., 1971; Horton et al., 2010).

The upper Paleozoic sedimentary sequences in the Eastern Cordillera unconformably cover lower Paleozoic metamorphic rocks. The highest degree of burial is presumed to occur where the Carboniferous metasedimentary rocks (Mogotes–Mucuchachí) were latter exhumed were exhumed. Late Pennsylvanian low–grade metamorphism was developed in the core of the Santander Massif and the Mérida Andes. At the Mérida Andes, the Mucuchachí Formation is composed of green to black slates, metavolcanic rocks, and phyllites, which yield fossil plants of the Pennsylvanian age (Odreman & Wagner, 1979; Pfefferkorn, 1977). Volcanic rocks of the Mucuchachí Formation could be correlated with magmatism present in the Pennsylvanian series on the Maya Block (e.g., Bateson, 1972). At Santander Massif and Mérida Andes, metamorphic rocks of the Carboniferous age precede deposition of Sabaneta and Río Nevado sequences. The Mucuchachí Formation is covered unconformably by Permian conglomerates of the Sabaneta Formation. Additionally, compared with the Santander Massif, a lower exhumation degree in the Quetame Massif is suggested by the absence of Precambrian gneisses and the presence of Ordovician unfoliated granitoids.

The analysis of detrital zircons on early Paleozoic rocks from the Santander Massif and Mérida Andes suggests that they come from sources within the Amazonian Craton (Horton et al., 2010; Mantilla–Figueroa et al., 2016; van der Lelij et al., 2016b).

Contrasting with the data mentioned above, there are no early Paleozoic events recorded in the rocks of the Magdalena Valley (Payandé and Payandé–San Lucas), as well as in the Llanos Basin and the La Macarena mountain range. The basement at serranía de La Macarena is composed of Precambrian gneisses (Calymmian?) and Ediacaran syenites. Buchely et al. (2015a) quote a 1528 Ma U–Pb age from a quartzofeldspathic gneiss outcropping at Caño Rojo (serranía de La Macarena). Gneisses of the serranía de La Macarena are intruded by syenites with a 600 Ma U–Pb peak age (Buchely et al., 2015a). To the south of the La Macarena (San José del Guaviare), U–Pb dating on nepheline syenite indicates a crystallization age 577.8 +6.3/–9 Ma (Arango et al., 2012). Both dates on syenites suggest an event of crustal stretching during the Ediacaran.

Geochronological data from high–grade metamorphic rocks at the Garzón Massif range between 1200 to 900 Ma (Cordani et al., 2005); similar data have been obtained in the Sierra Nevada de Santa Marta and the La Guajira Peninsula. The high–grade metamorphic rocks of the Garzón Massif, as well as part of the Sierra Nevada de Santa Marta, were included in the same Grenvillian belt by Kroonenberg (1982).

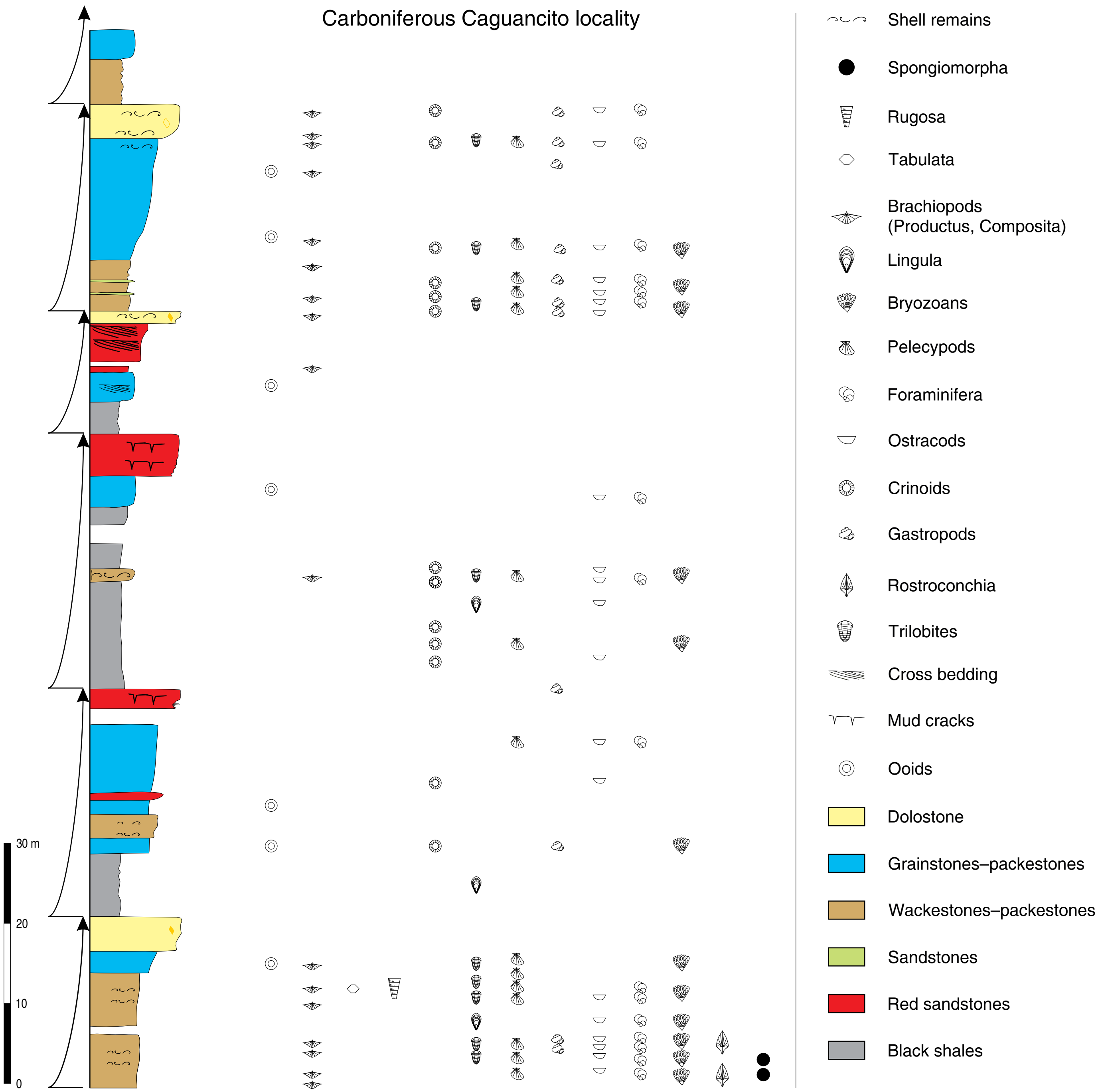

Figure 21. Repetitive sequences at Caguancito Creek in which layers of continental origin alternate with marine deposits indicating cyclic eustatic changes of sea level.

The El Vapor Mylonitic Gneisses under the La Cristalina Formation (Figure 1), indicates an age Rb/Sr isochron of 894 ± 36 Ma (Ordóñez–Carmona et al., 1999). La Cristalina Formation is a sequence of sandstones and mudstones with graptolites of Middle Ordovician age (Gutiérrez–Marco et al., 2006). At La Victoria (Figure 1), on the eastern flank of the Central Cordillera, a metamorphic complex cited as Tierradentro Gneisses and Amphibolites with 1360 ± 270 Ma K/Ar age is exposed (Barrero & Vesga, 1976; Marquínez & Núñez, 1998; Vesga & Barrero, 1978). Santa Marta and La Victoria (Caldas) include the only two known reports of anorthosites in Colombia (Figure 24).

At Las Minas area (Figure 1), Restrepo–Pace et al. (1997) quote a $^{40}Ar/^{39}Ar$ hornblende age of 911 ± 2 Ma for amphibolites that underlie the Ordovician El Hígado Formation (Mojica et al., 1987b, 1988). The preceding information suggests that the basement of the Magdalena Valley (Payandé, and Payandé–San Lucas Terranes) is typically Grenvillian with strong affinities with the autochthonous block (serranía de La Macarena, Garzón,

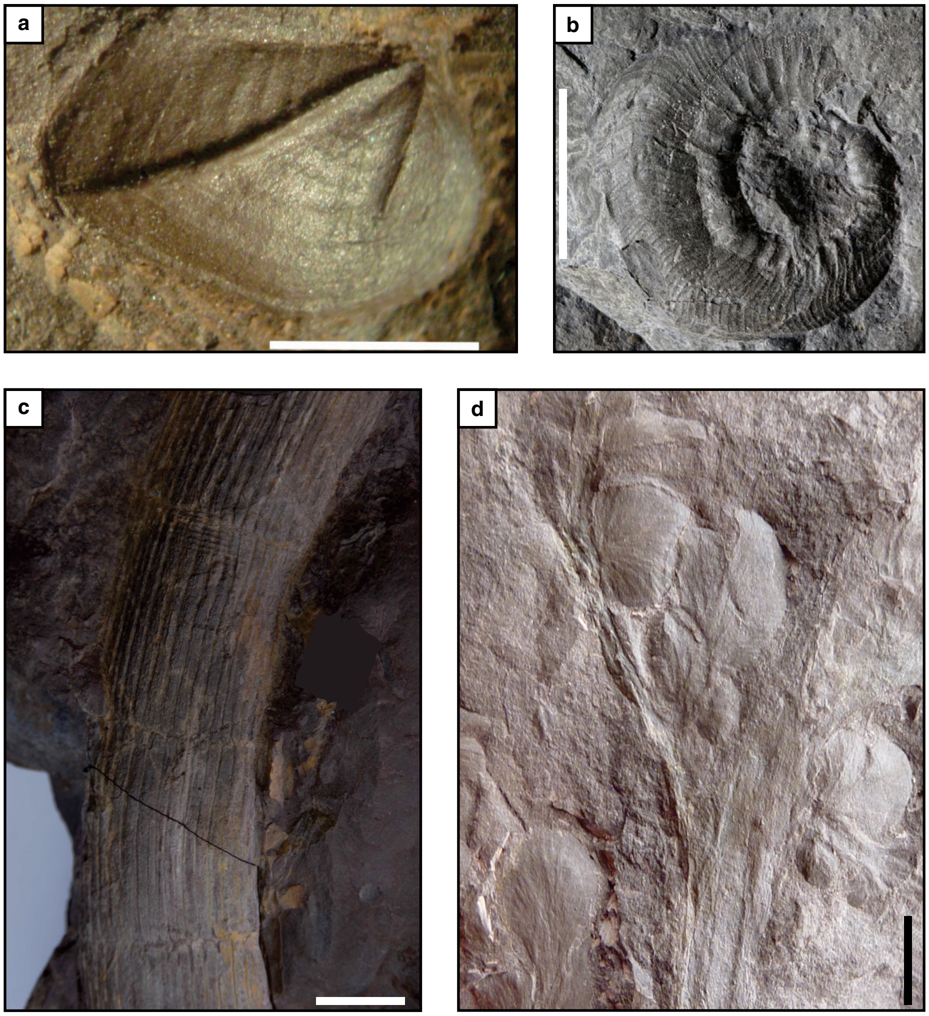

Figure 22. Caguancito Creek fossils: **(a)** *Hemicycloleaia* sp., a leaioid conchostracan; **(b)** *Gastrioceras* sp.; **(c)** *Calamites* sp.; **(d)** *Odontopteris* sp. Scale bar for a is 2 mm.; scale bar for b, c, and d is 1 cm.

Amazonian Terranes, and Llanos Basin basement) and Santa Marta. However, the oldest sedimentary rocks of the Magdalena Valley correspond to the Ordovician sequence that is exposed in La Cristalina, Río Venado, and serranía de las Minas.

At the serranía de las Minas, the fossil assemblage of the El Hígado Formation contains Tremadocian conodonts (probably winnowed) of the biozones of *Paltodus deltifer* and *Paroistodus proteus*. Graptolites and conodonts of *Lenodus variabilis* and *Eoplacognathus suecicus* biozones suggest that sedimentation reaches the lower Darriwilian (Borrero et al., 2007; Gutiérrez–Marco et al., 2007). At the Venado and Ambicá Rivers (Figure 1), a turbiditic sequence correlated with Zanza Formation (La Macarena) contains a Floian assemblage composed of *Acrograptus filiformis*, *Baltograptus kurcki*, *Phyllograptus* cf. *ilicifolius*, and *Expansograptus* cf. *extensus* (Buchely et al., 2015a; Moreno–Sánchez et al., 2008b, 2014).

Similarly, Ordovician sedimentary rocks are widespread in most of the subsoil of the Llanos Basin, although Ediacaran and Cambrian sequences are known in the north of the basin (Arauca Graben). Towards the Amazon region, in the Araracuara area, Ordovician sandstones (Théry et al., 1984) emerge, forming table–top mountains (tepuis).

The sedimentary cycle of the Llanos Basin begins with the Ediacaran marine deposits reported in the Chigüiro–1 and Strat–11a oil wells. At the Chigüiro–1 oil well (to the north of the Llanos Basin), an Ediacaran microfossil assemblage occurs, composed of *Chuaria circularis*, *Synsphaeridium conglutinatum*, *Stichtosphaeridium* spp., *Kildinella* sp., *Pterospermopsimorpha* sp., *Synsphaeridium* sp., and *Trematosphaeridium* sp. (Dueñas, 2001).

The early to middle Cambrian fossil assemblage at Chigüiro–1 oil well contains microfossils, including *Acanthodiacrodium constrictum*, Acritarch *Acrum* cf. *cylindricum*, *Archaediscina* cf. *umbonulata, Baltisphaeridinium pellicidum*, *Comasphaeridium stigosum*, *Dasydiacrodium bicuspidata, Granomarginata squamacea*, *Dictyotidium birvetense*, *Leio-*

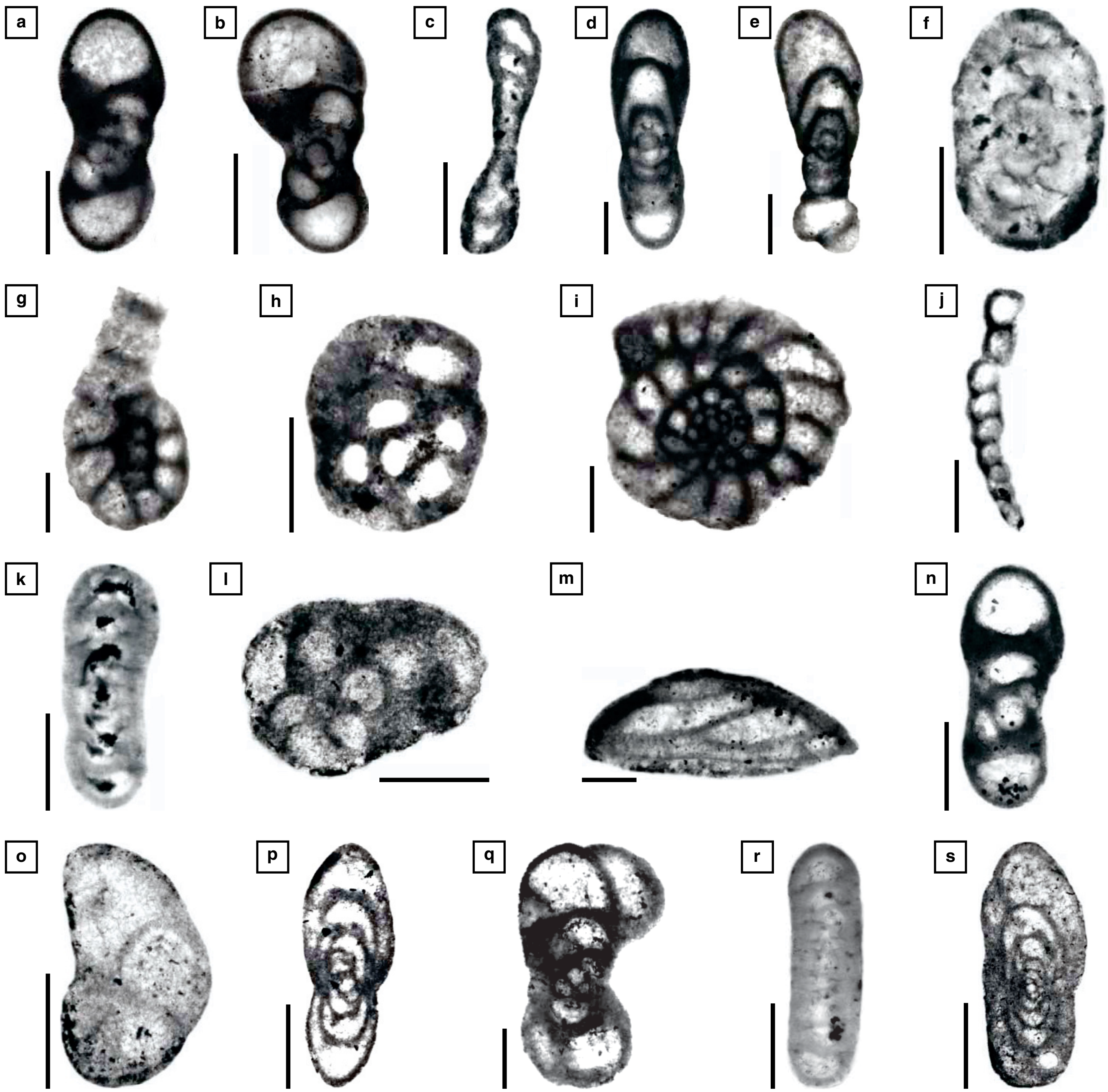

Figure 23. Pennsilvanian foraminifers from Caguancito: **(a, b, n)** *Planoendothyra* sp.; **(c)** *Cornuspira* sp.; **(d, e)** *Millerella marblensis*. Thompson (1942); **(f)** *Asteroarchaediscus* ex gr. *Rugosus* Rauzer–Chernousova (1948); **(g)** *Endothyranella* sp.; **(h, l)** undeterminate calcivertelid; **(i)** *Millerella* sp.; **(j)** *Calcivertella* sp.; **(k)** *Asteroarchaediscus?* sp.; **(m)** *Tetrataxis* sp.; **(o)** *Globivalvulina* sp.; **(p)** *Millerella* sp. 1; **(q)** *Planoendothyra aljutovica* Reitlinger (1950); **(r)** *Tubispirodiscus?* sp.; **(s)** *Millerella* sp. 2. Bashkirian (Morrowan) age. Scale bar represents 50 µm for c and f, scale bar for s is 200 µm and 100 µm for the others.

sphaeridia sp., *Micrhystridium lubomlense*, *Micrhystridium notatum*, *Micrhystridium multipliciflagellata*, *Protosphaeridinium* cf. *densum, Tasmanites* cf. *bobrowskii, Synsphaeridinium conglutinatum,* and *Tectitheca additionalis* (Dueñas, 2001). Upper Cambrian samples yielded palynological assemblages composed of *Timofeevia brevibifurcata* and *Timofeevia lancarae,* and including *Acanthodiacrodium costata*, *A. latizonale*, *Archaeotrichion* sp., *Cristallinium ovillense*, *Leiofusa* sp., *Leiosphaeridia* sp., *Lophodiacrodium* sp., *Pterospermopsimorpha* sp., *Protosphaeridium* sp., *Retisphaeridium dichamerum*, *Synsphaeridium conglutinatum*, and *Trachysphaeridium laminarum* (Dueñas, 2001). The Negritos Formation, distributed through the subsurface of the Llanos Basin (e.g., Negritos–1 and Heliera–1 wells), consists of calcareous sandstones with intercalations of fossiliferous dark and gray shales of Early to Middle Ordovician age. The Heliera Member contains

Figure 24. Anorthosites (An) in the Tierradentro Gneisses and Amphibolites Metamorphic Complex near La Victoria (Payandé Terrane).

Janograptus sp. and Didymograptus sp., Triarthus sp. and Acrotreta sp., these fossils are restricted to an Early Ordovician age (Ulloa et al., 1982).

At the serranía de La Macarena, Ordovician platform deposits cover unconformably Precambrian metamorphic rocks (syenites and amphibolites). In silty shales sequence, in the central and northern of serranía de La Macarena, an Early Ordovician fossils assemblage is reported, including Dichograptus octobrachiatus (Hall), *Didymograptus* sp., *Tetragraptus* sp., aff. *T. bigsbyi* (Hall), *"Obulus"* sp. cf. *Elkania ambigua* (Walcott), *"Lingula"* sp. cf. *Obolus elongatus* (Harrington), *Caryocaris* sp. (Trumpy,1943). Near the locality mentioned above, an association of Tremadocian brachiopods is reported. This includes *Acrotreta aequatorialis n.* sp., *Lingulella* cf. *desiderata*, *Nanorthis?* sp., and the trilobites *Geragnostus tilcuyensis*, *Kainella colombiana*, *Parabolinopsis* sp., and cf. *Pseudokainella* sp. (Harrington & Kay 1951). The fossil assemblage, contained in quartz silty sequence of upper Tremadocian age, includes, *Apheoorthis?* sp., *Basiliella trumpyi n.* sp., *Megalaspis* sp. cf. *M. planilimbata Angelin, Raphiophorus? pyrus* n. sp., *Tropidopyge stenorhachis* n. gen., n. sp., Cytid plate, Bellerophontid gastropod. This fossil assemblage were reported by Trumpy, (1943) and Harrington & Kay (1951). At the north of the La Macarena, at the Zanza Creek (3° 16' 24.14'' N, 73° 55' 16.48'' W) and La Recebera locality (3° 20' 28.98'' N, 73° 56' 28.89'' W), a turbiditic sequence with the Floian graptolite Baltograptus cf. turgidus is exposed (Buchely et al., 2015a; Gutiérrez–Marco et al., 2006).

Therefore, the remnants of the Ordovician sedimentary sequence of the Magdalena Valley are stratigraphically correlated with the remnants of the Ordovician sedimentary sequence of the serranía de La Macarena. The sedimentary rocks of the Ordovician age of the Magdalena Valley (El Hígado Formation, Río Venado, Ambicá, and La Cristalina), Llanos Basin, and La Macarena were deposited on a continental platform in a shallow marine environment without volcanic influence.

Mid–Cambrian trilobites were recovered from a locality near the Uribe, on the Duda Formation (Bridger, 1981). The material, studied by Rushton (1963), contained *Paradoxides* sp., *Peronopsis* sp., *Ehmania akanthophora*, a genus of common occurrence in the Avalonian Terranes. Duda Formation, at the Cristalina Creek (Cubarral), is a sedimentary succession composed of diamictites, feldspathic conglomerates, and sandstones originated by submarine mass flows due to tectonic activity (Buchely et al., 2015a). Underlying the Duda Formation, the Ariari and Guape Formations (Ediacaran? – Cambrian) are exposed. Guape is a sedimentary formation composed of sandstones, black shales, thin limestones beds, and volcanic deposits (Bridger, 1982; Buchely et al., 2015b; Toro et al., 2014).

10. Discussion

The metamorphic basement of the Magdalena Valley (Western Chibcha Terrane or Payandé and Payandé–San Lucas Blocks) was affected by the Grenvillian event in the same way that the Garzón Massif and the Sierra Nevada de Santa Marta (Álvarez, 1981; Kroonenberg, 1982; Ordóñez–Carmona et al., 1999; Priem et al., 1989; Ramos, 2010; Restrepo–Pace et al., 1997) were affected. A nonconformity surface separates the Grenvillian rocks from the Ordovician siliciclastic marine deposits. Shallow marine deposits at La Cristalina, El Hígado (Las Minas), Río Venado, and Ambicá contain Early to Middle Ordovician graptolites. Ordovician sequences of Magdalena Valley can be understood as an extension of platform deposits of serranía de La Macarena and Llanos. The Ordovician magmatic event (Famatinian–Caparonensis), common to Quetame–Mérida Terrane, is not recorded at Garzón Massif, serranía de La Macarena, Magdalena Valley (Western Chibcha Terrane or Payandé San Lucas and Payandé–San Lucas Blocks), and the Santa Marta area.

Traditionally, it has been accepted that the Chibcha Terrane was a single geologic block with an active margin to the east, with Cambrian to Silurian arc volcanism and metamorphism (Ramos, 2010; Restrepo & Toussaint, 1988). Thus, Payandé and Payandé–San Lucas (Western Chibcha) can be explained as the trailing age of the Quetame–Mérida Crustal Block (Eastern Chibcha). Although this model seems to be a simpler explanation, it does not explain the greater complexity that the eastern block (Eastern Chibcha) presents and that can be summarized as follows:

- The Chibcha Terrane has a Grenville basement. However, the Quetame–Mérida Crustal Block has a Tonian sedimentary cycle (Silgará Formation) not registered in the Payandé Block (Western Chibcha).

Permian

Carboniferous

Devonian

Silurian

Ordovician

Cambrian

- The Eastern Chibcha has a Cambrian sedimentary sequence with volcanic rocks (Chicamocha Formation and Quetame Group). This cycle is absent in the western block.
- The Silurian age sedimentary cycle is only registered in the Eastern Chibcha Terrane.
- Ordovician rocks are without signs of volcanism in the western block. The Ordovician conglomerates of the Venado Formation are composed of clasts of gneisses and granulites. No volcanic debris are reported.

On the eastern slope of the Central Cordillera, Tierradentro Gneisses and Amphibolites unity (Marquínez & Núñez, 1998), truly a geologic complex with a complex thermal history, have a wide range of lithologies including ortho– and paragneisses, amphibolites, minor granulites, metagabbros, anorthosites, migmatites, and mylonitic rocks. The Tierradentro Complex is located to the east of the Otú–Pericos Fault. Therefore, the Tierradentro Complex is incorporated as the Precambrian basement of the western part of the Chibcha Terrane (Payandé and Payandé–San Lucas Terranes). Bustamante et al. (2017) propose, based on U–Pb data of zircons (271 and 234 Ma), that the high–grade metamorphic rocks in this complex were formed during a Permian to Triassic event. However, the Bustamante et al. (2017) interpretation ignores the regional geologic data and field observations. Additional issues could be the result of bias in the sample collection or thermal episodes (including metasomatism), taking as orogenic metamorphic events or loss of radiogenic lead related to uplifting and eroding of the crystalline basement. The conclusions of Bustamante et al. (2017) are in conflict with the following facts:

- Occurrence, on the eastern slope of the Central Cordillera, of Ordovician sedimentary sequences such as La Cristalina and El Hígado Formations (Las Minas).
- Occurrence, near Ibagué city, of Devonian (Imán and Amoyá) and Triassic (Luisa and Payandé Formations) sedimentary sequences. Luisa Formation (Geyer, 1973), underlying Payandé Formation, is a continental sequence composed of red sandstones and matrix–supported conglomerates with clasts of granites.
- The occurrence of crinoidal Carboniferous metalimestones and marbles cropping out to the west of Ibagué city (Gómez & Bocanegra, 1999; Moreno–Sánchez et al., 2008a) in the area of Bustamante et al. (2017) sampling.
- Record of Triassic metasomatism on marbles and metalimestones (Aleluya Complex) on the eastern slope of Central Cordillera is dated as a Triassic intrusive event (Hernández–González & Urueña–Suárez, 2017).

However, the Quetame, Santander, Perijá, and the Mérida Cordillera have experienced complex metamorphic histories. On the Santander Massif, the oldest metamorphic rocks are of Tonian age, although it has been proposed that these are the result of rejuvenation of Grenvillian–age rocks (Ordóñez–Carmona et al., 2006). The low–grade metamorphic rocks, such as the Perijá Series, the Chicamocha and the Quetame Schists, originated in a terrane not too far from Gondwana, since they have detrital zircons derived from sources on the South American Craton (van der Lelij, 2013). Cambrian sedimentary rocks were later metamorphosed and thermally affected by Ordovician intrusives (Famatinian–Caparonensis or Taconian event).

The Ediacaran – Cambrian oceanic gabbros (Ariari Metagabbro) and basalts (Guape Formation) covering by submarine mass flow deposits (diamictites) of Duda Formation suggest an extended continental margin. The recognition of Ediacaran – Cambrian remnants of oceanic gabbros and basalts between the Eastern Cordillera (at the La Cristalina, Cubarral locality) and Llanos Basin let us infer that, during the Ediacaran – Cambrian, the early Palaeozoic proto–Andean margin of South America (Iapetus coast?) was near this modern tectonic limit (Bridger, 1982; Buchely et al., 2015b; Toro et al., 2014). Syenites of the Ediacaran age (Arango et al., 2012; Buchely et al., 2015a) intruding basement rocks at the serranía de La Macarena and western Llanos Basin record the extension of the proto–Andean margin during the aperture of the Iapetus Ocean.

During Cambrian to Ordovician times, the proto–Andean margin in northern South America was a subsiding passive platform in front of an ocean basin and not too far from a volcanic arc formed in a peri–Gondwana microcontinent (Quetame–Mérida Terrane). The Quetame–Mérida volcanic arc could have been the prolongation towards the north of the volcanic chain developed to the west of South America during the Ordovician (e.g., Benedetto et al., 2009). The basement of Eastern Cordillera and Mérida Andes, a continental fragment, was accreted to the pericratonic platform of Gondwana during the Late Ordovician or early Silurian times. The microcontinent and its volcanic arc (e.g., Forero, 1990) collided against the proto–Andean margin, leaving a remnant of transitional oceanic crust in the region of the Cristalina (Cubarral). During the closure of the basin (fore–arc to continental platform), oceanic crust sank into the mantle along a subduction zone with a westward–dipping orientation (Figure 25).

The modern position of Payandé, Payandé–San Lucas, Santa Marta, and portions of the La Guajira Peninsula can be interpreted as a geologic artifact result of strike–slip displacements (e.g., Bayona et al., 2010; Scott, 1978) produced by the oblique subduction during late Paleozoic or Mesozoic times. These lithospheric clasts are interpreted as Grenvillian fragments detached from the pericratonic margin of Gondwana and dragged to the north and then superimposed on the front of the Quetame–Mérida Terrain.

We proposed, as has been suggested in other works (Aleman & Ramos, 2000; Bellizzia & Pimentel, 1994; Forero, 1990; Restrepo et al., 2009; Restrepo & Toussaint, 1988), that a large part of the Eastern Chibcha Terrane were part of an allochthonous continental fragment that was accreted on the pericratonic South American margin during the Paleozoic period. However,

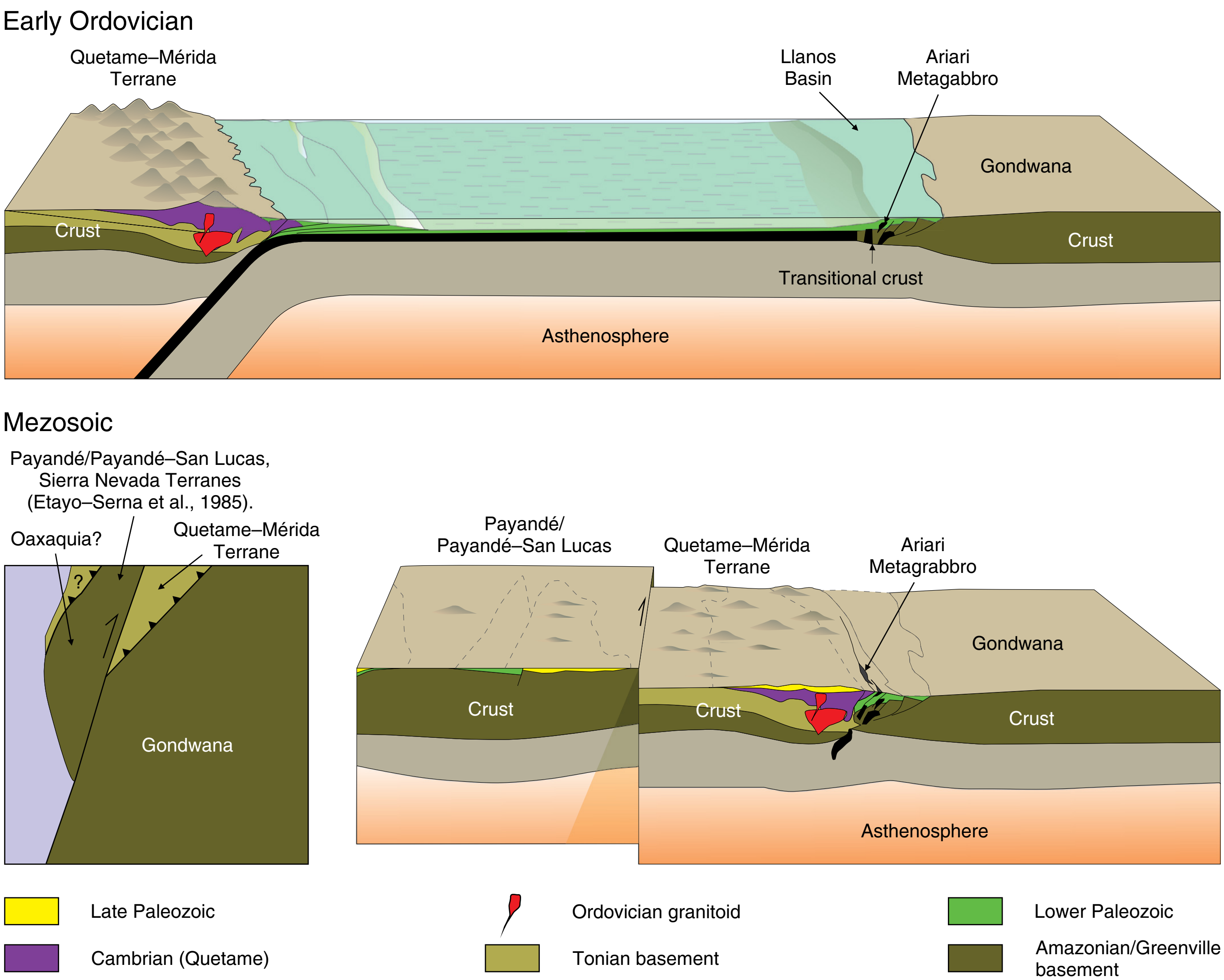

Figure 25. Geological evolution of the terranes east of the Otú–Pericos fault. Western Chibcha Terrane (Payandé) can be explained as being the trailing age of Eastern Chibcha Terrane (Quetame crustal block). However, based on the stratigraphic differences, we propose that this area is made up of at least two tectonic blocks with dissimilar geologic histories.

we suggest that Payandé and Payandé–San Lucas Blocks (Western Chibcha Terrane) should be included in the autochthonous basement and not as part of the Chibcha Terrane (sensu Restrepo & Toussaint, 1988).

The Trilobites (*Paradoxides* sp., *Peronopsis* sp., *Ehmania akanthophora*) of the Duda Formation (see Rushton, 1963) suggest the presence of tectonic blocks located in front of the prism of the Quetame–Caparo arc that may have had a platform connection with the Avalonia continent during the Cambrian. Metamorphism of the Quetame Group, Chicamocha Schists, and Perijá Series is constrained between the igneous activity (Caparo–Famatinian or Taconic event) and the erosive phase of the Late Ordovician and early Silurian during the closure of the marine basin located between the Quetame–Caparo Terrane and the pericratonic margin of Gondwana (Figure 25). Bordonaro (1992) attributes the fossils of cited by Rushton (1963) to the serranía de La Macarena and the Llanos Basin. However, the *Paradoxides* locality is actually found in the Eastern Cordillera at the Duda Formation (Figure 1). The Duda Formation is a very thick accumulation (more than a thousand meters) of diamictites, sandstones, and mudstones, with evidence of tectonic stacking, which may include sediments from both the continental margin of South America and the Quetame Block (Chibcha Terrane).

During Precambrian and Ordovician times, the geologic history of South America remains closely similar to the Oaxaquia Terrane in Mexico (Restrepo–Pace et al., 1997; Ruiz et al., 1999; Sedlock et al., 1993). The geological evidence indicates that some tectonic blocks, now belonging to Mexico and Central America (Maya and Chortis), during Precambrian and early Paleozoic times were part of the proto–Andean margin of South America.

The Silurian sequence of the north of South America was deposited after the collision of the Quetame–Mérida Block. Additionally, the Silurian fossil assemblages between those areas show connection during that time interval. The braquiopod assemblage of El Horno Formation (Venezuela) is similar to the braquiopod assemblage of the Ciudad Victoria (Mexico) and Rhenish–European Province (Boucot et al., 1972, 1997; Stewart et al., 1999).

Late Silurian to Pragian rocks are not known in the Eastern Cordillera. The Angosturas Formation (Buchely et al., 2015a) corresponds to a remnant of Lower Devonian shales and sandstones that crops out to the south of the serranía de La Macarena but without any relation to the Eastern Cordillera deposits. In Perijá, Santander, and Quetame Massifs, the marine to continental sequences range from Emsian to Famennian (Tournaisian at El Iman). Lochkovian – Pragian deposits are absent. The Devonian record, as observed in the Floresta Massif, begins with a transgressive cycle with a maximum marine invasion towards the upper part of the Floresta Formation. The regressive phase culminates with the deltaic deposition of the Cuche Formation.

Santa Marta Fault has an accumulated horizontal offset of 120 km (Dewey & Pindell, 1985), but when restored to the pre–Miocene position, Floresta Massif rests to the west of the Labateca area. Middle Devonian sandstones at Labateca suggest the proximity of the basin margin. Frasnian – Famennian continental deposits of the Cuche Formation are coeval with the marine deposits of the El Iman Formation (Payandé Terrane), suggesting that the source area of the sedimentites had to be located to the east, towards the South American Craton.

Despite the presence of magmatic zircons (Cardona et al., 2016; Horton et al., 2010), there are no proofs of volcanic deposits attributable to proximal volcanism in the Devonian El Tíbet, Floresta, and Cuche Formations. The detrital zircons detected in the sedimentites could come from reworked deposits outside of the basin or from ash rains coming from a distant volcanic source. Lithic sandstones (Cardona et al., 2016) and detrital muscovite on the Devonian formations point to an erosion of the metamorphic basement.

The biogeographical data point to a proximity or a connection between South America (west Gondwana) and Laurussia during Devonian times. The late Lochkovian terrestrial paleoflora assemblage from Brazil and Argentina (SW Gondwana) shows close similarities to the Laurussia Province (Edwards et al., 2009). Additionally, in northern South America, the number of species in common with Europe is sizable for the Middle and Upper Devonian interval (Berry, 1997; Berry & Fairon–Demaret, 2001; Meyer–Berthaud et al., 2003). Early and Middle Devonian brachiopod associations of northern South America show common elements with southern North America and are included in the Eastern Americas Realm (Barrett, 1985) or Appalachian Province (Boucot, 1985). However, Devonian fossil fish from the Perijá and Floresta deposits indicate a connection with Laurussia but still present elements in common with Gondwana (Burrow et al., 2003; Janvier & Villarroel, 2000; Young & Moody, 2002a).

The climate during the Devonian, at least for the north of South America, was characterized by being relatively warm (greenhouse climate) with increasing temperatures during the Famennian (Joachimski et al., 2002). According to most of the paleogeographic reconstructions of Gondwana (Barrett, 1985; Barret & Isaacson, 1988; Heckel & Witzke, 1979; Scotese et al., 1979), Colombia and Venezuela would be close to 40° S latitude and would have a wet temperate climate (Barrett, 1985). For Laurussia, we prefer a paleogeographic position close to the north of Gondwana such as the Barrett (1985) reconstruction, which is more in line with the biogeographical data (Figure 26).

A hiatus, that covers much of the Mississippian time, separates the Devonian and Carboniferous sequences. San Antonio, Caguancito Creek, Cerro Neiva, and "Calizas y Arenitas de La Batalla" are the southern remnants of a late Carboniferous shallow marine basin that extended from the northern margin of Colombia and Venezuela to Ecuador (Macuma Formation). The Carboniferous and Permian systems in northern South America, unlike the Devonian, are characterized by the presence of large beds of limestones and occasional evaporitic bodies. Carboniferous magmatism of Venezuela and Central America (Maya Block) suggests the closure of a remnant ocean basin between North and South America.

The Bocas Formation age is an Early Jurassic sequence since *Piazopteris branneri* (*Phlebopteris branneri*), a matoniaceae fern, and *Classopollis* sp. occur in this formation (Remy et al., 1975). Ambiguous ages (Carboniferous to Permian) obtained in the Bocas Formation are apparently the result of ill–defined mapping contacts between Paleozoic and Mesozoic deposits.

In comparison to the Devonian climate, the Carboniferous was dominantly cool (icehouse) with alternating warming and cooling stages. During the Moscovian – Kasimovian, the climatic tendency was towards the decreasing temperatures, but during the Kasimovian – Gzhelian, the trend is to cooler temperatures (Bruckschen et al., 1999). The upper Paleozoic of northern South America was characterized by sedimentation in a coastal domain with alternating marine and continental influences. According to the reconstruction of Raymond et al. (1985) and despite the global cooling of the climate, the north of South America enjoyed a warmer climate due to the displacement towards latitudes close to 15–20°S. Braun (1979) suggests that the largest fluctuations are related to epeirogenic movements and the minor phases were produced by climatic influence. The geological section of Caguancito could be considered the typical example of the Pennsylvanian cyclothemes. At the interglacial stages, the dominant deposits were marine carbonates with oolitic layers. During the cold stages, deltaic deposits occurred associated with red beds and plant macrofossils.

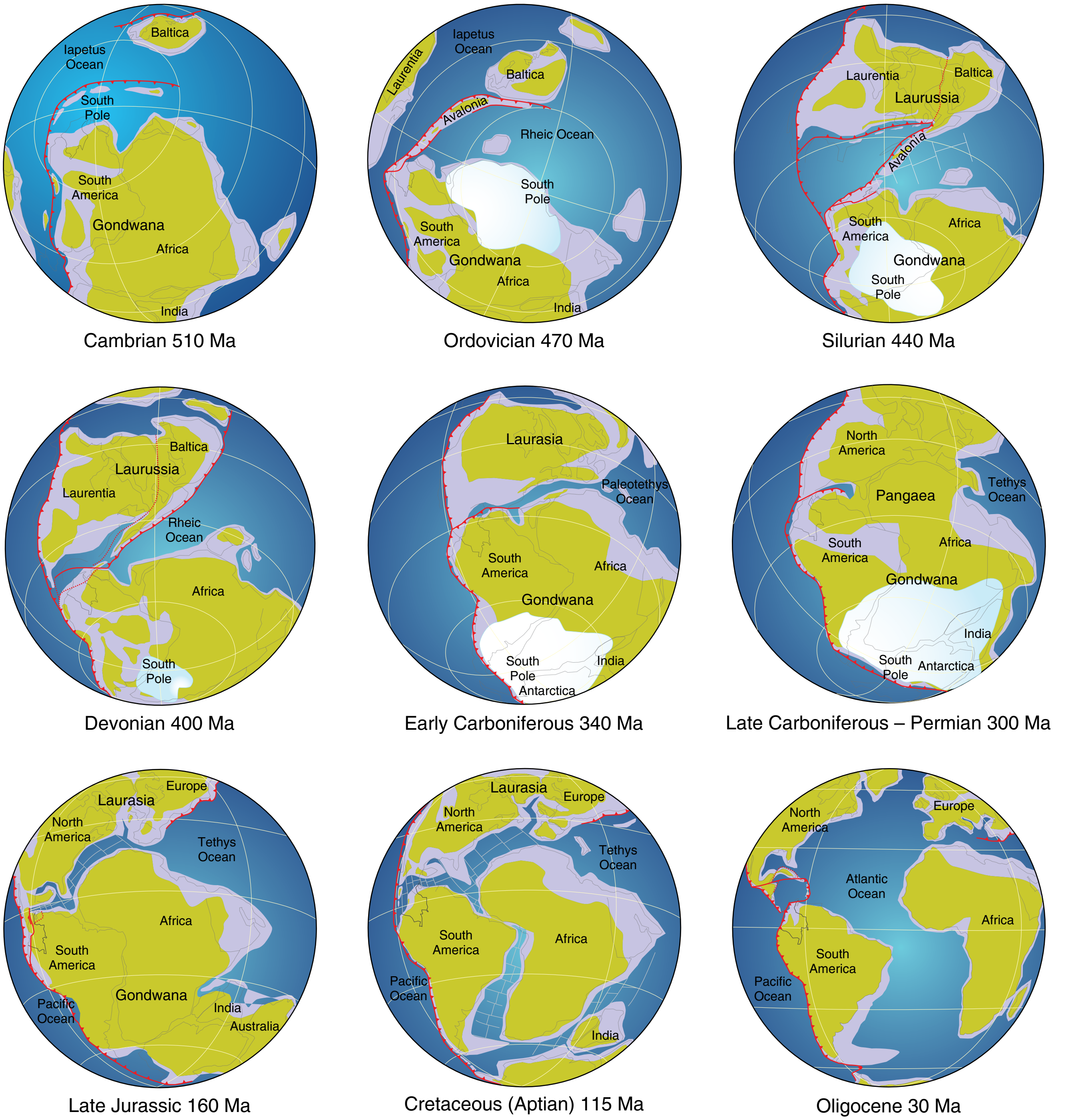

Figure 26. Paleogeographic reconstructions of Gondwana (modified of Barret & Isaacson, 1988; Barrett, 1985; Heckel & Witzke, 1979; Scotese et al., 1979).

The Tahamí Terrane (Cajamarca) is separated from the Payandé Terrane (Western Chibcha Terrane) by the Otú–Pericos dextral Fault. The activity of this tectonic structure is presumed to be Late Jurassic or Early Cretaceous because the fault affects Jurassic intrusives (Gómez & Bocanegra, 1999). Therefore, the Tahamí Terrane should be located farther south of their present position. For the Tahamí Terrane and western Payandé Terrane, Cochrane et al. (2014) suggest a first compressive event during middle Permian to Early Triassic (275–240 Ma) related to the amalgamation of western Pangea. This event can be associated with the phase of uplift and erosion that creates the erosive hiatus, from Lopingian (late Permian) to Middle Triassic, recorded in the Santander Massif.

The Permian record of northern Colombia and Venezuela, limited to the Cisuralian to Guadalupian, is made up of thick basal conglomerate layers covered by platform limestones, shales, evaporites, and sandstones. The sandstones, which are interpreted as sea level fall deposits, contain a fossil macroflora similar to the Road Canyon Formation of Texas (Ricardi–Branco et al., 2005). Eustatic changes of climatic origin begin to lose influence at the end of the Permian due to the rapid retreat of the glaciers in Gondwana (Crowell, 1995). The Lopingian (late Permian) to Middle Triassic hiatus is interpreted as the result of uplift and erosion associated with regional compression during the formation of Pangea. Additionally, Cochrane et al. (2014) deduce a rifting event during Middle to Late Triassic (240 to 225 Ma), an event that coincides with the start of sedimentation of the Luisa and Payandé Formations (Middle? to Late Triassic of Payandé and Payandé San Lucas Terranes).

There are no known fossiliferous Permian deposits in the Magdalena Valley. The Luisa Formation, underlying the Payandé Formation of the Late Triassic, is a continental succession constituted of sandstones, reddish shales, and matrix–supported conglomerates with clasts of granites. This formation, apparent unfossiliferous, correlated with the El Sudán Formation on the Payandé–San Lucas Block that is attributed to the Permian – Triassic lapse by Geyer (1982).

11. Conclusions

The lower Paleozoic sedimentary sequences of the Llanos Basin and the La Macarena and Magdalena Valleys (Payandé and Payandé–San Lucas Terranes) were deposited on the pericratonic margin of South America. During the early Paleozoic, the Quetame–Mérida Terrane (eastern part of the Chibcha Terrane) developed a more complex tectonic and thermal history than the Payandé and Payandé–San Lucas Terranes (Figure 27).

The record at the Cubarral region of the Ediacaran sienites and Ediacaran – Cambrian gabbros (MORB), suggests the opening of an ocean basin during the formation of the southern Iapetus Ocean on the current boundary between the Eastern Cordillera and the Llanos Basin controlled by the detachment of Avalonia.

The Sierra Nevada, Payandé, and Payandé–San Lucas Terranes (Etayo–Serna et al., 1983) are interpreted as Grenvillian lithospheric clasts detached from the pericratonic margin of Gondwana (autochthonous basement) and dragged to the north along strike–slip faults and then superimposed on the front of the Quetame–Mérida Terrane.

U–Pb zircon ages of Tierradentro Gneisses and Amphibolites, Aleluya Complex, and Payandé Granitoids (Cochrane et al., 2014; Hernández–González & Urueña–Suárez, 2017) suggest Permian – Triassic thermal events spanning the west of the Payandé Terrane. A Permian to Triassic age for the Tierradentro Gneisses and Amphibolites, as interpreted by Bustamante et al. (2017), should be revised because it is not supported by field observations and local stratigraphy.

According to geochronological and paleontological data, the metamorphic rocks of the Quetame Group and the Chicamocha Schists (Santander Massif) would be of Cambrian age. The Quetame–Mérida Terrane (Eastern Chibcha) was an allochthonous microcontinent based on high–grade metamorphic rocks of Tonian age. The microcontinent and its volcanic arc along with a west–dipping subduction zone collide against the eastern pericratonic margin of South America at the end of the Ordovician times. An episode of magmatism and regional metamorphism (Quetame–Caparonensis, Famatinian or Taconic event) culminates during the continental collision and then is followed by a phase of erosion interrupted by a marine invasion during the middle Silurian. Similarities of Silurian fossil assemblages from Venezuela (El Horno) prove the geographical connection with eastern Mexico (Ciudad Victoria). During Pridoli to early Emsian, the area to the west of the Guicáramo Fault (suture zone of Quetame–Caparo Terrane) was affected by exhumation and erosion. However, there are marine incursions towards the south of the Llanos Basin (Angosturas Formation).

The Devonian deposition begins at the Emsian during a transgressive phase that reaches its maximum during the Frasnian. During the Frasnian – Famennian interval, a delta was formed, progradating to the west. Limestones are rare in the Devonian record of northern South America. The Devonian flora and fauna of Colombia and Venezuela maintained close ties with the Old–World Realm (Laurussia).

At the beginning of the Pennsylvanian in the Andean region of northern South America, there was an erosive phase. The initial flooding of the region produced the sandstones and mudstones at the base of the Pennsylvanian sequence. The sedimentation is followed by a succession of fossiliferous limestones and shales. During the Carboniferous, northern South America moved towards the equator, thus, the climate was warmer than during the Devonian. The sedimentation was influenced by the rise and fall of the sea level linked to the advances and retreats of glaciers in the polar areas. Despite the intermittence, Devonian and Carboniferous records in the northern Andes apparently extended from the Otú–Pericos Fault to the western limit of the Llanos Basin.

Evidence for a Late Pennsylvanian tectonic event is preserved in the core of the Santander Massif and Mérida Andes. This evidence consists of weakly metamorphosed sedimentary rocks covered unconformably by thick layers of early Permian conglomerates. In the north of South America, the Permian record is limited to areas in the Santander Massif, serranía de Perijá and the Mérida Andes. The Permian record consists mainly of limestones accumulated on a shallow marine platform and in warm weather conditions. The Pennsylvanian deposition cycle is interrupted at the Kasimovian and resumed at the beginning of the Sakmarian (early Permian).

The geochronology based on zircons is a set of high precision methods used for dating rocks inaccessible by other tech-

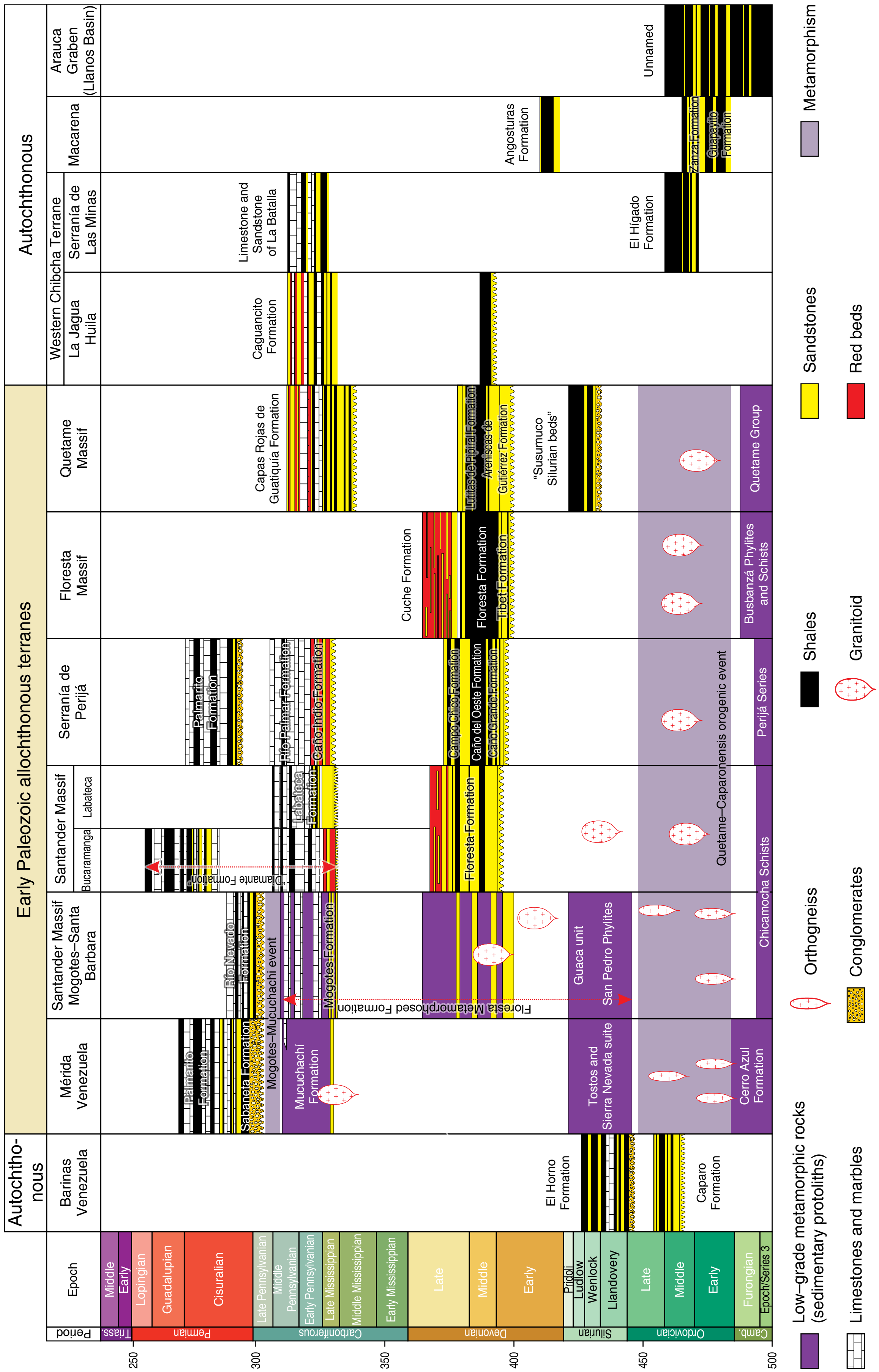

Figure 27. The chronostratigraphic chart that summarizes the main events east of the Otú–Pericos Fault.

niques. Zircon methods have become an essential tool in Earth science. However, the interpretation of long thermal structure and tectonothermal histories for igneous–metamorphic complexes should be contrasted using stratigraphic and paleontological data.

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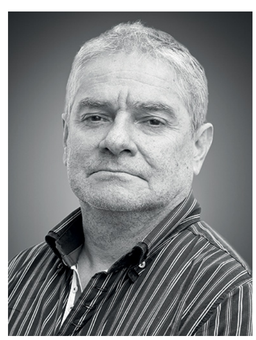

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José BUITRAGO–HINCAPIÉ is a Colombian field geologist and is currently working for the Servicio Geológico Colombiano. His contributions to the geology of Colombia have been the regional geological mapping of a sector of the cordillera Oriental and its foothills. His geological works also include mapping the Tumaco onshore and the Caguán–Putumayo Basin. His stratigraphic studies cover the Paleozoic units of the Quetame Massif, the Guape–Duda area (cordillera Oriental foothill), serranía de La Macarena, and the serranía de Chiribiquete (Amazon region).