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Geological context of the Paleozoic Terranes of northern South America

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Resumen: *CONTEXTO GEOLÓGICO DE LOS TERRENOS PALEOZOICOS DEL NORTE DE SUDAMÉRICA.* Este artículo discute los avances recientes en la comprensión de la evolución paleozoica del norte de América del Sur a través de datos radiométricos, en particular U/Pb en zircones, y sus interpretaciones basadas en categorías geográficas. La investigación actual a menudo utiliza términos fisiográficos modernos, como "Cordillera Central" y "Valle del Magdalena", para describir procesos geológicos paleozoicos; sin embargo, tales interpretaciones pasan por alto movimientos tectónicos significativos y terrenos desplazados resaltados por evidencia estratigráfica más antigua. En particular, el artículo critica las suposiciones de autóctono respecto a los bloques andinos, sugiriendo que sus configuraciones paleozoicas difieren de estos modelos. El artículo también revisita la interpretación de varios terrenos geológicos, como los bloques Tahamí y Chibcha, y examina el papel de sistemas de fallas como la Otú-Pericos en la configuración de la geología regional. Estudios recientes proponen continuidad geológica entre estos bloques, desafiando modelos previos que designan límites distintos. Se han propuesto modelos contrastantes respecto a los terrenos precámbricos mexicanos del ciclo Grenvilliano, sugiriendo su colisión con el norte de América del Sur en el Triásico Tardío y la posterior separación durante la apertura del océano Atlántico. Esto contradice modelos anteriores de amalgamación de terrenos por la colisión de Báltica y Amazonia durante el Proterozoico. Las similitudes geológicas, las edades comunes y la estratigrafía comparable entre sectores del sur de México y Colombia indican una historia geológica compartida desde el Precámbrico. Hallazgos significativos incluyen el descubrimiento de moluscos del Cámbrico, faunas del Ordovícico y secuencias sedimentarias del Devónico, que revelan conexiones tectónicas y biogeográficas complejas durante el Paleozoico

Abstract: This paper discusses recent advancements in the understanding of the Paleozoic evolution of northern South America through radiometric data, particularly U/Pb in zircons, and their interpretations based on geographical categories. Current research often uses modern physiographic terms, such as "Central Cordillera" and "Magdalena Valley," to describe Paleozoic geological processes, yet such interpretations the overlook significant tectonic movements and displaced terranes highlighted by older stratigraphic evidence. In particular, the paper critiques assumptions of autochthony regarding Andean blocks, suggesting that their Paleozoic configurations differ from these models. The paper also revisits the interpretation of various geological terranes, like the Tahami and Chibcha blocks, and examines the role of fault systems such as the Otú-Pericos in shaping regional geology. Recent studies propose geological continuity between these blocks, challenging previous models that designate distinct boundaries. Contrasting models have been proposed regarding the Mexican Precambrian terranes of the Grenvillian cycle, suggesting their collision with northern South America in the Late Triassic and subsequent separation during the Atlantic Ocean's opening. This contradicts earlier models of terrane amalgamation by the collision of Baltica and Amazonia during the Proterozoic. The geological similarities, common ages, and comparable stratigraphy between sectors of southern Mexico and Colombia indicate a shared geological history since the Precambrian. Significant findings include the discovery of Cambrian mollusks, Ordovician faunas, and Devonian sedimentary sequences, which reveal complex tectonic and biogeographic connections during the Paleozoic.

Palabras clave: Paleozoico. Terrenos. Paleogeografía.

Key words: Paleozoic. Terranes. Paleogeography.

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Introduction

The existence of the paleocontinent Pangaea and its reconstructions imply the closure of the paleo-Atlantic Ocean and the alignment of the American coast with Africa and Europe. This alignment is relatively straightforward given the geographical similarities of the continental margins of North America, Europe, South America, and Africa. However, the overlap of continental Central America, Mexico, and northern South America requires further explanation (Figure 1). According to magmatic evolution models for the Phanerozoic, as deduced by various authors (Cardona *et al.*, 2010; Cochrane *et al.*, 2014; Spikings *et al.*, 2015; Van der Lelij *et al.*, 2016), northern South America can be considered autochthonous in nature. Thus, the terrane to the east of the San Jerónimo Fault System (also referred to as Romeral in some studies), as proposed in several works (Tschanz *et al.*, 1974; Etayo-Serna *et al.*, 1986; Restrepo and Toussaint, 1988; Forero, 1990; Bellizzia and Pimentel, 1994; Moreno-Sánchez *et al.*, 2020), would actually correspond to fixed blocks attached to Gondwana from the Neoproterozoic to the Mesozoic (Figures 2, 3). Furthermore, it is assumed that the Mexican Precambrian terranes, of the

Figure 1. Map of the overlap of tectonic blocks between North America, Central America and South America (lax version). **1**- Oaxaca-Ciudad Victoria; **2-** Mixteco; **3-** Maya-Yucatán; **4-** Chiapas; **5-** Chortis-Chuacus; **6-** Sevilla - Sierra Nevada de Santa Marta; **7-** Eastern Chibcha - Mérida; **8-** Payandé-San Lucas and Payandé; **9-** Cajamarca-Tahamí; **10-** Amotape-Tahuín. K, sectors with Cretaceous oceanic basement./**Figura 1.** *Mapa de la superposición de bloques tectónicos entre Norteamérica, Centroamérica y Sudamérica (versión laxa).* **1-** *Oaxaca-Ciudad Victoria;* **2-** *mixteco;* **3-** *Maya-Yucatán;* **4-** *Chiapas;* **5-** *Chortis-Chuacus;* **6-** *Sevilla-Sierra Nevada de Santa Marta;* **7-** *Chibcha Oriental - Mérida;* **8-** *Payandé-San Lucas y Payandé;* **9-** *Cajamarca-Tahamí;* **10-** *Amotape-Tahuín. K, sectores con basamento oceánico del Cretácico.*

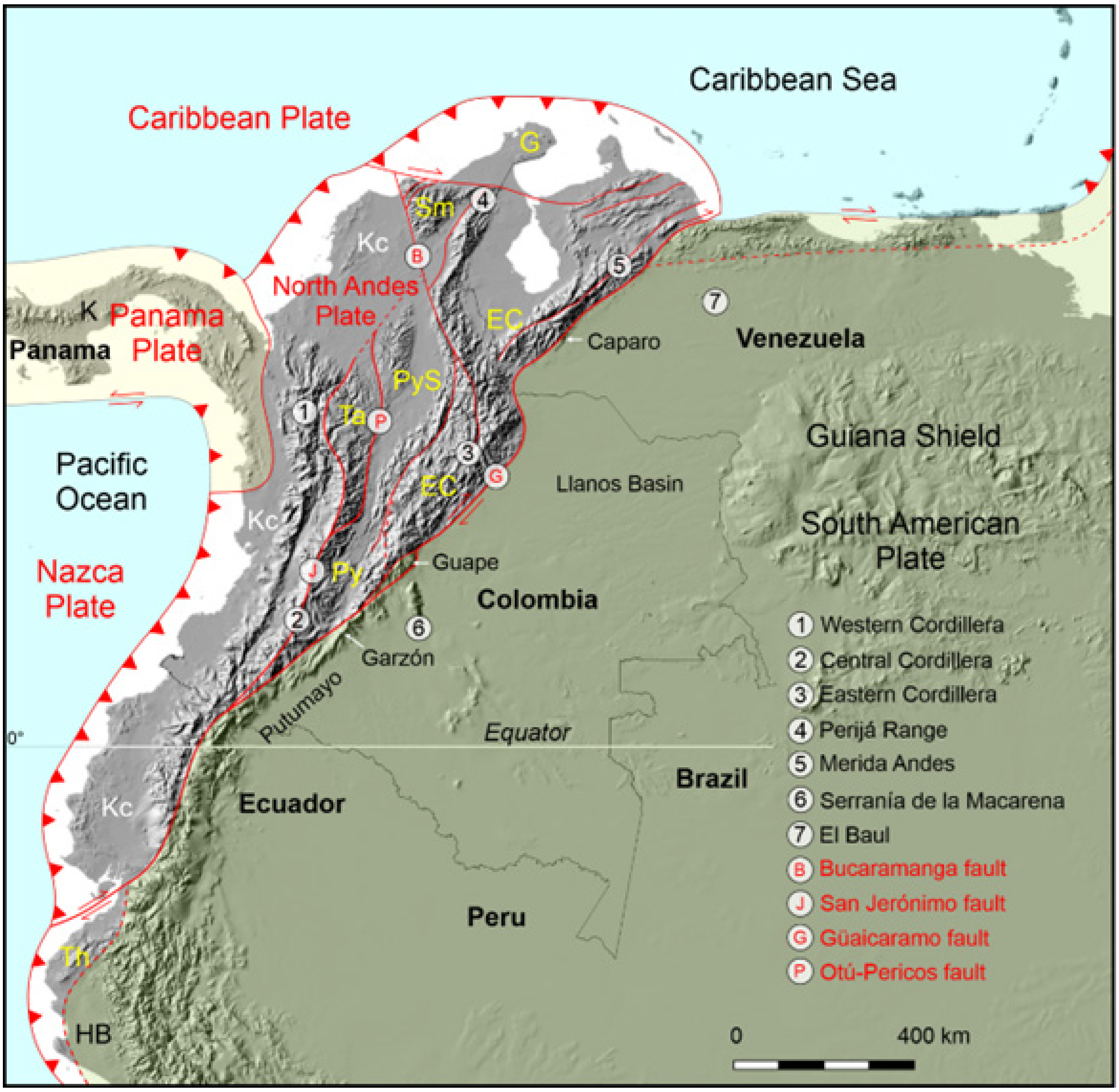


Figure 2. Map that shows the main faults, block and terrane in Colombia. Abbreviations: Py, Payandé; Ec, Eastern Chibcha; PyS, Payandé-San Lucas; Ta, Tahamí; Sm, Sierra Nevada de Santa Marta; G, Guajira; Kc, Cretaceous oceanic basement; Th, Tahuin-Amotape block; K, Cretaceous, Hb Huacabamba./**Figura 2.** *Mapa que muestra las principales fallas, bloques y terrenos de Colombia. Abreviaturas: Py, Payandé; Ec, Chibcha Oriental; PyS, Payandé-San Lucas; Ta, Tahamí; SM, Sierra Nevada de Santa Marta; G, Guajira; Kc, basamento oceánico del Cretácico; Th, bloque Tahuin-Amotape; K, Cretácico, Hb Huacabamba.*

Grenvillian cycle (Oaxa- quia Orogeny) collided with northern South America during the Late Triassic and subsequently separated during the opening of the Atlantic Ocean (Cardona *et al.*, 2010). This proposal contradicts earlier models that suggested these regions of Mexico and northern South America were part of terranes amalgamated by the collision of the paleocontinents of Baltica and Amazonia during the Proterozoic (Restrepo-Pace *et al.*, 1997; Keppie and Ortega-Gutiérrez, 1999; Weber *et al.*, 2010; Ibañez-Mejia *et al.*, 2020).

Campa and Coney (1983) conclude that the Chihuahua and Caborca Terrane were part of North America (Laurentia). Conversely, the Mayan, Mixteco, Chortis, and Oaxaca block (Zapoteco Terrane) correspond to tectonic blocks of an allochthonous nature (Dengo, 1985; Sedlock *et al.*, 1993).

The geological similarity, common ages and comparable stratigraphy have been interpreted as the result of a common geological history between sectors of southern Mexico (e.g. Zapoteco Terrane), continental Central America and areas of the

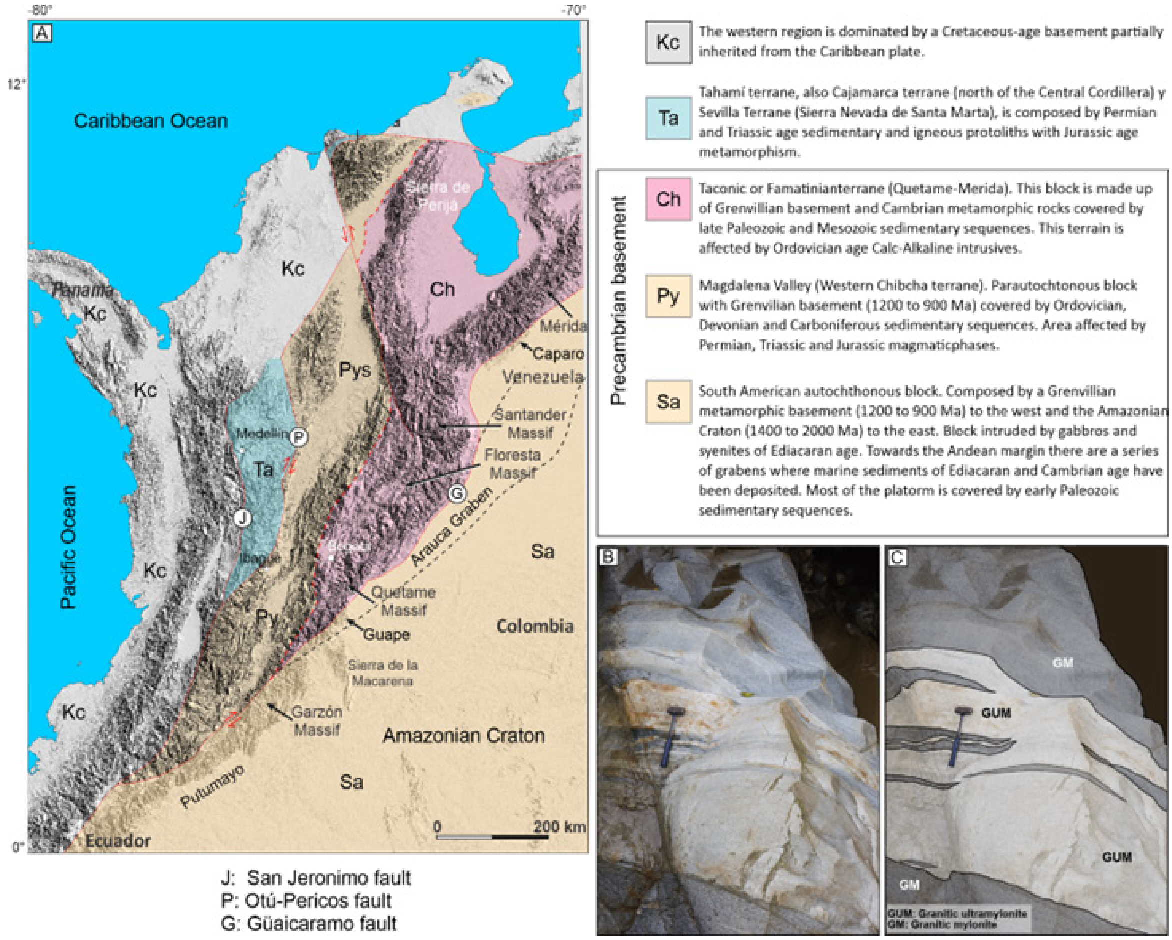


Figure 3. a- Geological terrane map and relief of Colombia and neighboring jurisdictions. Modified from Restrepo and Toussaint (1988). **b, c-** Milonites and ultramylonites of the Ibagué Batholith resulting from the fault systems and the boundary of the Otú-Pericos terrane./**Figura 3. a-** *Mapa del terreno geológico y relieve de Colombia y jurisdicciones vecinas. Modificado de Restrepo y Toussaint (1988).* **b, c-** *Milonitas y ultramilonitas del Batolito de Ibagué resultantes de los sistemas de fallas y del límite del terreno Otú-Pericos.*

Magdalena Valley (Payandé and Payandé-San Lucas blocks), Garzón Massif and Sierra Nevada de Santa Marta (Ibanez-Mejia *et al.*, 2011, 2020).

In principle, two contrasting models of land organization have been proposed for northern South America and southern Laurentia during the Neoproterozoic and Phanerozoic intervals:

• Grenvillian accretion model (Restrepo-Pace, 1995; Keppie and Ortega-Gutiérrez, 1999; Weber *et al.*, 2010; Ibanez-Mejia *et al.*, 2011, 2020). The Oaxaca block (Zapoteco Terrane) is formed due to the collision of the paleocontinents of Baltica and Amazonia during the Stenian-Tonian period (Figure 4). As a result, blocks originating from the late Grenvillian cycle can be found in northern South America, Mexico, and continental Central America. In this model, the Payandé and Payandé-San Lucas blocks (Magdalena Valley and parts of the Central Cordillera), Sierra Nevada de Santa Marta, and the northern Guajira Peninsula (Macuira) consist of Precambrian metamorphic basement. The Otú-Pericos fault is regarded as the tectonic limit between the Tahamí Terrane (Cajamarca) and the Precambrian basement terranes to the east.

• Triassic accretion model (Cochrane *et al.*, 2014; Spikings *et al.*, 2015; Bustamante *et al.*, 2017). A continuous Permian-Triassic metamorphism is assumed along the Colombian Central Cordillera to the Cordillera Real in Ecuador due to the collision of the Oaxaca block (Zapoteco Terrane). The Otú-Pericos Fault is considered a tectonic feature unrelated to terrane boundaries. It is excluded that a Precambrian basement exists in sectors of the Central Cordillera and Magdalena Valley.

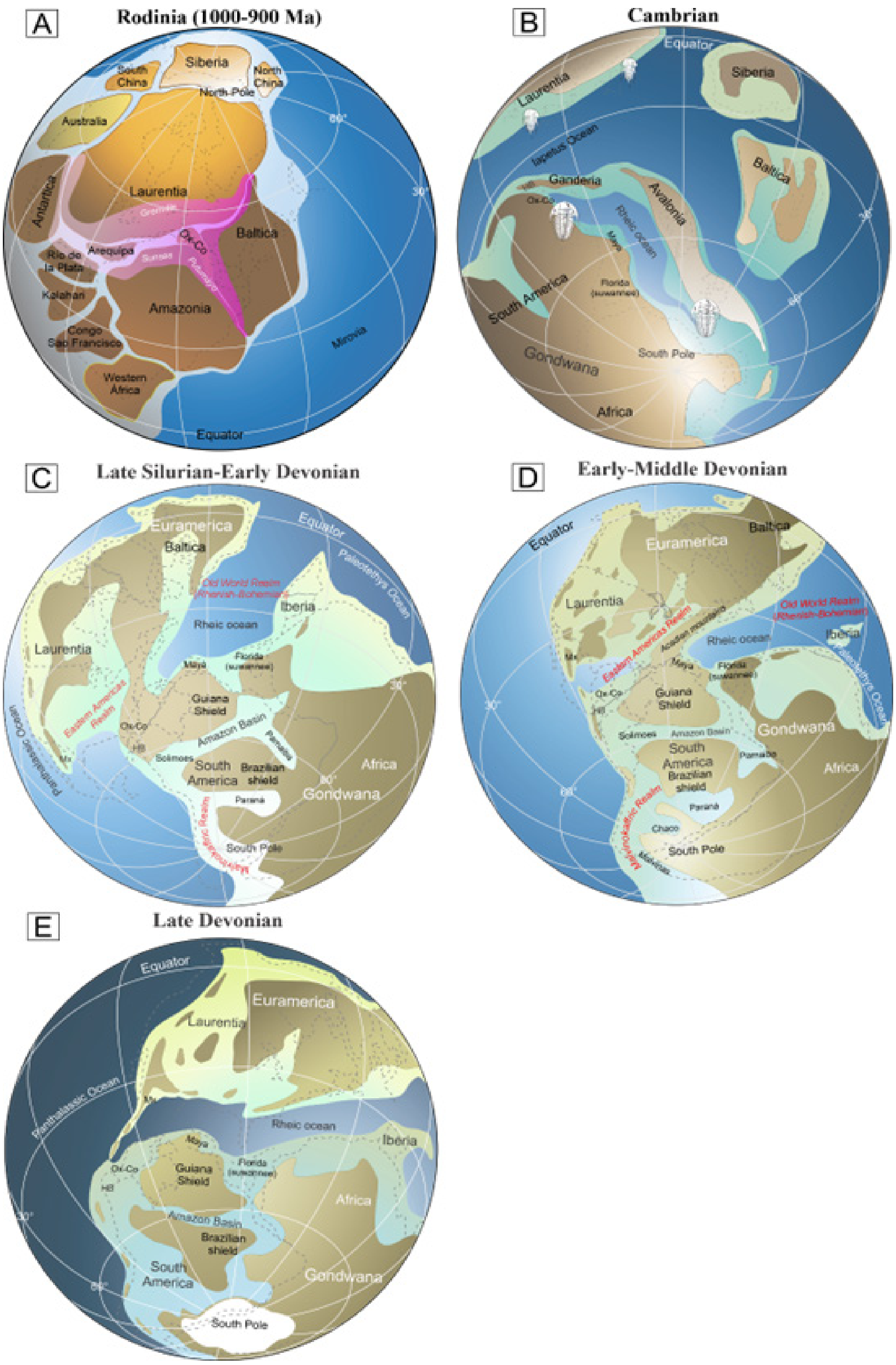


Figure 4. Paleogeographic reconstruction, modified of Barret and Isaacson 1988; Barrett 1985; Heckel and Witzke 1979; Scotese *et al.* 1979. **a-** Rodinia supercontinent (1000-900 Ma). **b-** Cambrian. **c-** Late Silurian - early Devonian. **d-** Early-middle Devonian. **e-** Late Devonian. Abbreviations: Ox-Co, Oaxaca-Colombia terrane; Hb, Huancabamba; Mx, Mexico../**Figura 4.** *Reconstrucción paleogeográfica, modificada de Barret e Isaacson 1988; Barrett 1985; Heckel y Witzke 1979; Scotese* et al. *1979.* **a-** *Supercontinente Rodinia (1000-900 Ma).* **b-** *Cámbrico.* **c-** *Silúrico tardío - Devónico temprano.* **d-** *Devónico temprano-medio.* **e-** *Devónico tardío. Abreviaturas: Ox-Co, terreno Oaxaca-Colombia; Hb, Huancabamba; Mx, México.*

The geochronological and geochemical data presented in recent studies may become ineffective if they are not contextualized within the complete geological framework. Geological evolution models must also incorporate field evidence that offers stratigraphic, paleontological, and structural insights. The aim of this work is to provide the geological context, which is frequently overlooked in studies concentrating on the geochemistry of igneous rocks, for the advancement of geological evolution models for northern South America.

Methodology

For the elaboration of this article, the concepts of terrane geology were utilized to characterize the Paleozoic geological history of the geological blocks with Precambrian basement in Colombia. In this work, the term "block" is employed to define relatively stable cortical sectors limited by faults.

The blocks with similar geological histories were grouped into larger categories constituting the terranes referred to in this study. Most of the terranes mentioned for Colombia could correspond to blocks transported by strike-slip dislocation.

Much of the foundational information used to establish the stratigraphic relationships comes from field data obtained by the authors of this work. Complementary sources included reports and geological maps prepared on large and medium scales (1:100,000).

The relative ages of the stratigraphic units were adjusted using paleontological information and published radiometric dating. The stratigraphic relationship schemes presented here are a simplified product of the data verified in the field and those cited in the geological literature.

Precambrian

The oldest sedimentary rocks in Colombia are found near the border with Brazil and correspond to coastal and marine sequences of late Mesoproterozoic age (Santos *et al.*, 2003). The Ediacaran strata are recognized in the subsurface of the Llanos basin and crops out in the Guape salient (Eastern Cordillera) (Arminio *et al.*, 2013; Dueñas-Jiménez and Montalvo–Jónsson, 2020).

Precambrian metamorphic rocks, in northern South America, form part of the basement of the Andean zone east of the Otú-Pericos Fault and the platform of the Llanos and Amazon basin (Cordani *et al.*, 2016; Etayo-Serna *et al.*, 1986). The Amazon Craton (Restrepo-Pace, 1995; Tassinari and Macambira, 1999; Restrepo-Pace and Cediel, 2018), made up of metamorphic rocks from the Proterozoic, constitutes the basement of a large part of the Amazon basins and the Eastern plains. Precambrian rocks of the Grenvillian cycle form the basement of the Putumayo Basin, Garzón Massif, Magdalena Valley, Serranía de San Lucas (northern of the Central Cordillera, and Sierra Nevada de Santa Marta. The Bucaramanga gneiss and the Silgará schists, of Grenvillian affinities, they form the Proterozoic basement of the Santander Massif (Ward *et al.*, 1973; Kroonenberg, 1982; Restrepo-Pace, 1995; Restrepo-Pace and Cediel, 2010; Ibanez-Mejia *et al.*, 2011) .

The Precambrian Andean basement has been interpreted as the result of the collision of Baltica against Amazonia (Figure 4a). The Mexican (Zapotec-Oaxaca), Chortis and partially Maya terranes were adjacent blocks against the northern margin of South America for much of the Neoproterozoic until the breakup of Pangea (Keppie and Ortega-Gutiérrez, 1999; Keppie *et al.*, 2001; Weber *et al.*, 2010; Culí *et al.*, 2022).

Ediacaran

The Ediacaran and Cambrian sequences accumulated in two separate basins between faulted blocks: the Arauca and Mantecal grabens. (Bartok, 1993; Muñoz, 1991; Arminio *et al.*, 2013). The Arauca Graben was the depocenter of mature marine sedimentary rocks from which Ediacaran acritarch drill cores have been collected, including *Kildinosphaera* spp. (*K. verrucata* and *K. chagrinata*) *leiosphaeridia* spp., *Coneosphaera arctica, Cymatiosphaera* spp., *Dictyodinium* spp. *Kildinella* spp. *Lophosphaeridium* spp. *micrhystridium* spp. and other unidentified acanthomorphic acritarchs (Arminio *et al.*, 2013; Dueñas–Jiménez *et al.*, 2020).

To the south and on the eastern flank of the Eastern Cordillera, in the Guape salient, a sequence of Ediacaran and Cambrian rocks outcrops made up of platform limestone covered by turbiditic deposits crossed by MORB intrusive (Ariari metagabbro) (Toro-Toro *et al.*, 2014). The basal unit, Ariari Formation, yielded occasional algal mats. The age of the Ariari Formation limestones is defined by the ages of detrital zircons taken in the upper part of the unit and the intrusion of the Ariari Metagabbro of late Ediacaran age (Buchely *et al.*, 2015b). The Ariari Formation is unconformably covered by the Guape Formation, made up of basaltic flows, arkose and marine mudstones formed by turbidite processes.

The western sector of the plains basin and the Guape salient constituted an extending margin during the Ediacaran because of the rupture of Rodinia, a phase that began during the Cryogenic period with Syenitic intrusives. Buchely *et al.* (2015a) obtains ages (U/Pb) in the Caño Veinte Syenite (Sierra de la Macarena) of 621.7 ± 7.5 Ma and 634 ± 13 Ma. Arango *et al.* (2012) report a U/Pb age of 577.8 ±6.3 Ma for the Nepheline Syenite of San José del Guaviare. This alkaline magmatic phase culminates with the formation of basic rocks (Ariari Metagabro) on the ocean floor at the end of the Ediacaran (Figure 5a, b). This

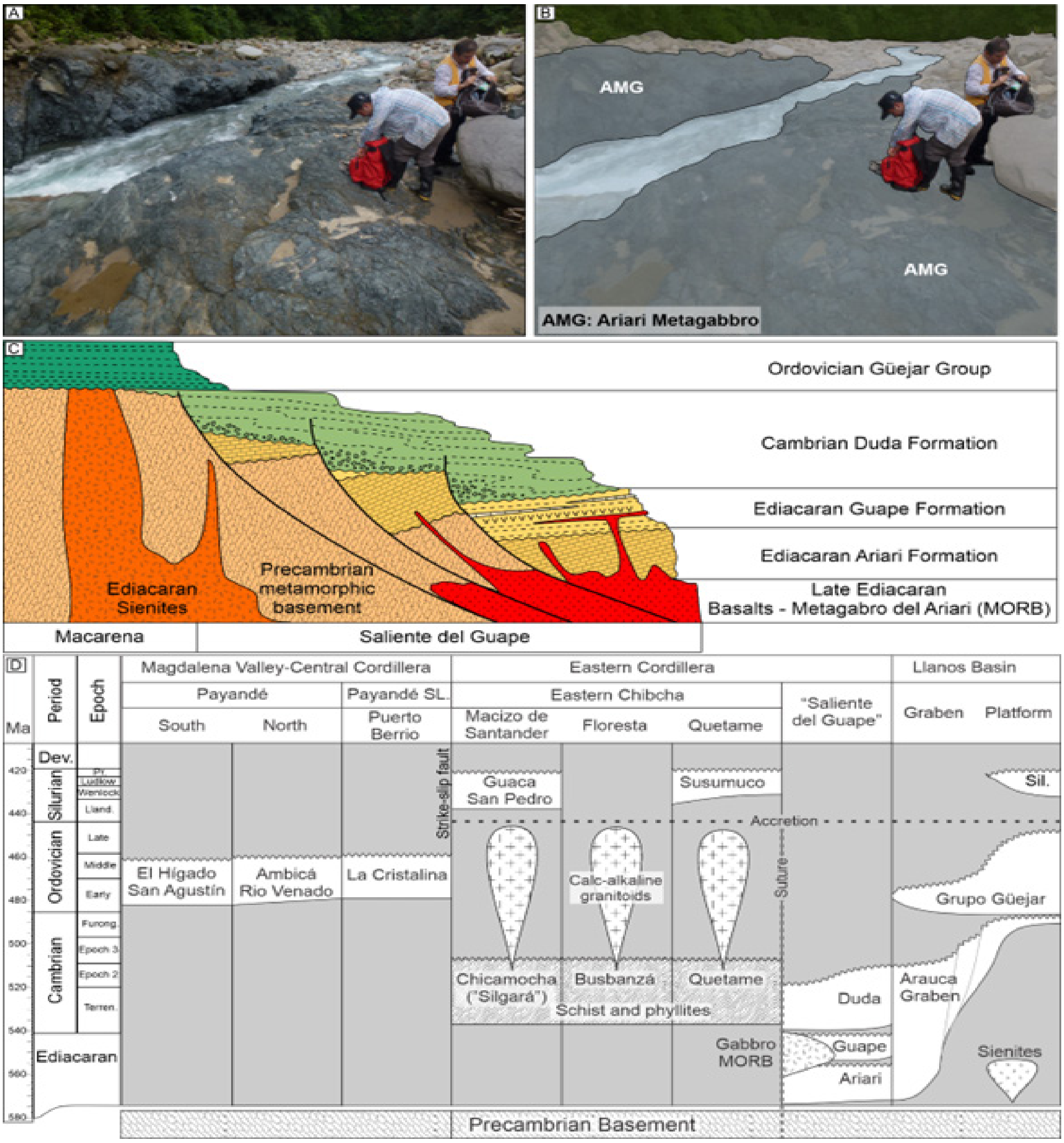


Figure 5. a, b- MORB gabbro from the Ariari region, east of the Eastern Cordillera. Late Ediacaran. **c-** Scheme of stratigraphic relationships of the Saliente del Guape (limit zone between the Llanos Orientales Basin and the Macarena). **d-** Stratigraphic relationships of early Paleozoic units between geological blocks east of Otu-Pericos fault./**Figura 5. a, b-** *Gabro MORB de la región de Ariari, al este de la Cordillera Oriental. Ediacárico tardío.* **c-** *Esquema de relaciones estratigráficas del Saliente del Guape (zona límite entre la Cuenca de los Llanos Orientales y la Macarena).* **d-** *Relaciones estratigráficas de unidades del Paleozoico temprano entre bloques geológicos al este de la falla Otu-Pericos.*

stage of extension and alkaline intrusions is coeval with the formation of the Mantecal and Arauca grabens during the separation of Baltica and Amazonia that culminates with the formation of the Rheic and Iapetus oceans.

To date, the only sector with Ediacaran sedimentary units is found in graben to the west of the Eastern Llanos Basin (Bartok, 1993; Arminio *et al.*, 2013). Furthermore, seafloor gabbros and syenites are also located along this limit on what must be a passive platform on the margin of Iapetus (Toro-Toro *et al.*, 2014).

Cambrian

Outcrops of Cambrian sedimentary rocks in northern South America are reported in the Baúl Massif in Venezuela (Viscarret *et al.*, 2012) and in the Guape Salient in Colombia (Figure 5c, Figure 5d). In the subsurface of the Llanos basin, marine Cambrian sediments are origin is deposited on the Ediacaran sequences of the Arauca Graben. In the Cravo Norte area (Graben de Arauca), sclerites of the middle Cambrian mollusk *Wiwaxia* were recovered from drill cores in the subsurface of the eastern plains basin (Smith *et al.*, 2016). This is the first record of this fossil in South America from a locality that remained in mid to high latitudes in cold waters during the Cambrian (Torsvik and Cocks, 2013). The wide latitudinal distribution of this genus suggests that this organism could have been a generalist basal mollusk without biogeographic restriction (Smith *et al.*, 2016).

In the Eastern Cordillera, in the Guape salient, in limestone fragments, the trilobites *Ehmania akanthophora, E. amphibola, Paradoxides* sp. have been recovered and a peronopsid agnostoid have been recovered (Harrington and Kay, 1951; Rushton, 1963). The fragments have been attributed to the Duda Formation, a clastic sedimentary unit that overlies the Guape Formation (late Ediacaran). The recognized trilobites, according to Rushton (1963), indicate a middle Cambrian age with biogeographic affinities with the Avalonian “Atlantic Province”. Tremadocian trilobites from the Tiñú Formation (Oaxaca) show affinities with contemporary South American faunas (Robinson and Pantoja-Alor, 1968).

The Atlantic trilobite province corresponds to an exotic terrane in North America (Secor *et al.*, 1983) that was part of a series of continental fragments, including Ganderia and Carolina, separated from Gondwana by rifting during the late Ediacaran or early Paleozoic. The Atlantic Province encompassed the microcontinent of Avalonia that includes southwestern Great Britain, southern Ireland, sectors of Belgium, Germany, and the eastern margin of North America (Landing *et al.*, 2022). This province also includes northwest Africa and northern South America (Colombia). The faunal similarities between Avalonia and Gondwana during the Cambrian suggest proximity between these areas. One possible scenario could suggest that Avalonia begins to separate from Gondwana during the Cambrian with the development of the Rheic ocean floor (Figure 4b). The second possibility assumes that the ocean-floor gabbros (Ariari) were the result of Baltica rifting and the opening of the Iapetus Ocean at the end of the Ediacaran (Toro-Toro *et al.*, 2014).

Ordovician

Most of the Ordovician of northern South America are found in the subsurface of the basins east of the Andes. In the Negritos Well of the Llanos Basin, Ulloa *et al.* (1982) cite faunas from the range Tremadocian to Darriwilian that include the graptolites “*Janograptus*” sp., *Expansograptus extensus*, a trilobite of the genus *Triarthrus*, and the brachiopod *Acrotreta*.

In the Heliera Well (Negritos Formation) Tremadocian *Rhabdinopora flabelliformis* and *Jujuyaspis* sp. were collected (Ulloa *et al.*, 1982). Tremadocian *Helieranella negritoensis*, *Jujuyaspis truncaticonis*, *Jujuyaspis colombiana* and *Peltura* sp. are also mentioned (Baldis *et al.*, 1984).

In the Paisa-1 well of the Llanos Basin Kroeck *et al.* (2020) cite the acritarchs *Arbusculidium*, *Barakella*, *Coryphidium*, *Dactylofusa*, *Striatotheca* and

Veryhachium, which indicate an Early and Middle Ordovician age. Some of the species mentioned are characteristic of the Peri-Gondwanan acritarch province (Kroeck *et al.*, 2020). The presence of late Ordovician faunas is additionally reported in some oil wells in the same basin (Rubinstein *et al.*, 2019; Dueñas-Jiménez and Montalvo–Jónsson, 2020; Rubinstein *et al.*, 2021).

In the north of the Sierra de la Macarena, a sequence of marine turbidite platform margin deposits emerge that together have been included in the Güejar Group (Figure 6). The age of the reported faunas extends from the late Cambrian to the early Ordovician. Harrington and Kay (1951) report trilobites from genera related to *Basiliella*, *Kainella*, *Pseudokainella*, *Raphiophorus*, *Symphysurus*, *Westergardia*, and the genera *Tropidopyge*, *Geragnostus*, *Megalaspis* and *Niobella*. Brachiopods include *Acrotreta*, *Apheoorthis*, *Lingulella* and *Nanorthis*. Also mentioned are the brachiopods *Obolus elongatus*, *O. salteri* and the trilobites *Kainella meridionalis*, *Kainella lata*, and possibly *Asaphellus* sp. (Trumpy, 1943; Trumpy, 1949). In the Sanza River, a tributary of the Güejar River, *Acrograptus filiformis*, *Baltograptus varicosus* and *B. turgidus* were collected, indicating a Floian age (Moreno-Sánchez *et al.*, 2014), *Tetragraptus* sp. and *Goniograptus* sp. (Figure 7b) are also recognized. *Kainella colombiana*, cited by Harrington and Kay (1951), is referred to the genus *Naustia* by Vaccari and Waisfeld (2010) which suggests that the basal sequence

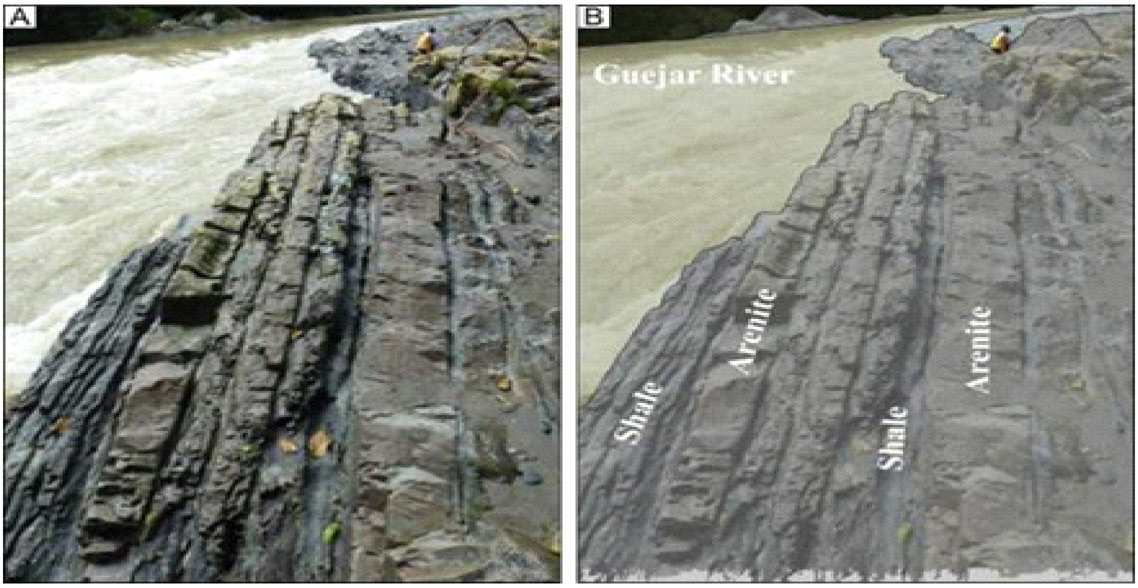


Figure 6. (a,b) Floian age turbiditic deposits of the Güejar River (Sierra de la Macarena)./**Figura 6. (a,b)** *Depósitos turbidíticos de edad Floiense del río Güejar (Sierra de la Macarena).*

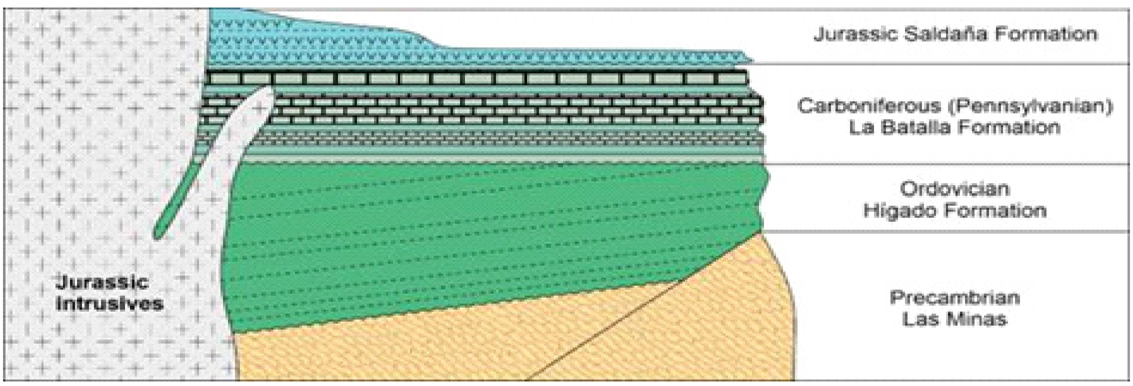


Figure 7. Scheme of stratigraphic relationships of the Upper Magdalena Valley and eastern flank of the Central Cordillera (Payandé block)./**Figura 7.** *Esquema de relaciones estratigráficas del Valle del Alto Magdalena y flanco oriental de la Cordillera Central (bloque Payandé).*

of the Macarena dates to the late Cambrian.

On the northern margin of the Llanos de Venezuela basin the Caparo Formation outcrops, a platform clastic sequence, which includes *Nemagraptus gracilis*, *Dicranograptus ramosus*, *D. furcatus* and *Archiclimacograptus meridionalis* that indicate a Sandbian age (Gutiérrez-Marco *et al.*, 2011). Finally, fossils of acritarchs of Areningian to Tramedocian age are reported *Dasydiacrodium* sp., *Acanthodiacrodium angustum*, *Acanthodiacrodium contrictum*, *Baltisphaeridium* sp., *Priscotheca raia*, *Acanthodiacrodium* sp., *Dasydiacrodium eichwaldi*, *Veryhachium valiente*, *Acanthodiacrodium* cf. *serotinum*, *Polygonium spinosum*, *Leiosphaeridia* sp., and *Veryhachium trispinosum* (Théry *et al.*, 1986).

To the north of the Upper Magdalena Valley or Payandé Block sensu Etayo-Serna et al. (1986) (Figure 7), in the section of the Venado River, a sedimentary succession emerges coeval with that of the Güejar River. In this sequence, platform turbiditic deposits are reported to lie on conglomerates with Precambrian gneiss clasts. The strata contain the graptolites *Acrograptus filiformis*, *Baltograptus kurcki*, *Phyllograptus* cf. *ilicifolius* and *Expansograptus* cf. *extensus* of late Floian age (Moreno-Sánchez *et al.*, 2014) (Figure 8a).

To the south of the Upper Magdalena Valley, in the El Hígado Formation (Figure 7), Darriwilian graptolites are reported along with reworked conodonts from the Tremadocian (Mojica *et al.*, 1988; Borrero *et al.*, 2007). The graptolites and conodonts are within the *Lenodus variabilis* and *Eoplacognathus suecicus* biozones indicating that the succession reaches the early Darriwilian (Borrero *et al.*, 2007; Gutiérrez-Marco *et al.*, 2007). A little further south, in the town of San Agustín, strata like those of the El Hígado Formation emerge, where the presence of graptolites *Didymograptus* sp (Figure 8c), cephalon of trinucleid trilobites (Figure 8d, e, f).

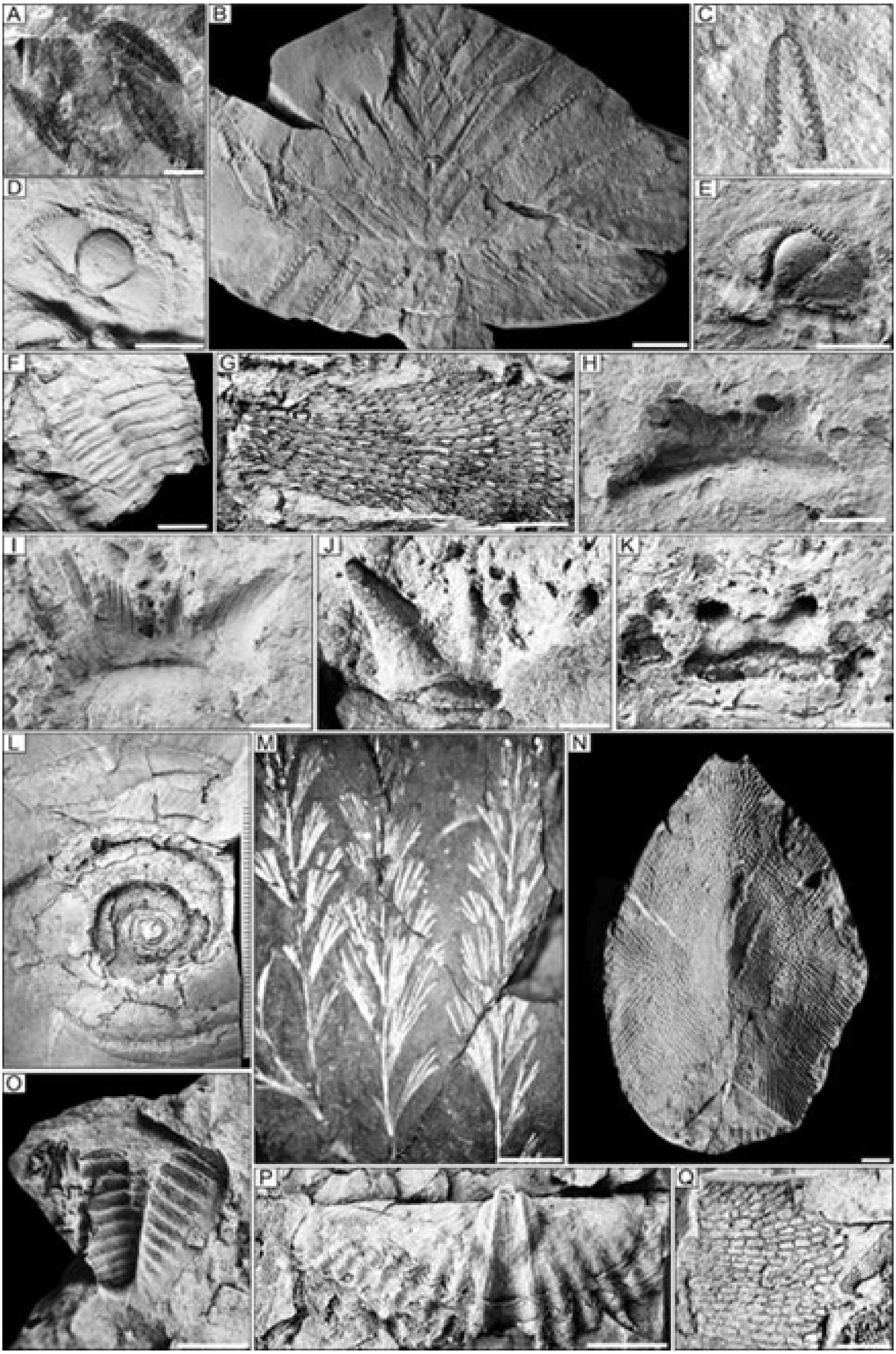
The La Cristalina Formation (Figure 9), in the Payandé-San Lucas block (Etayo-Serna et al., 1986), outcrops a sedimentary sequence with low-grade metamorphism that at the base is made up of quartzites that grade to shales and turbiditic strata that contain *Didymograptus* cf. *murchisoni*, *Pseudamplexograptus* latus and *Glossograptus hincksii* of Darriwilian age (Almanza-Melendez, 2019). The Ordovician sequences in both the crystalline and the Higado Formation are deposited on a basement made up of Precambrian gneisses from the Grenvillian cycle.

The Ordovician sedimentary units of the Magdalena Valley (Payandé and Payandé-San Lucas) and the Eastern Llanos Basin correspond to mature platform units deposited on a passive continental margin (Moreno-Sánchez *et al.*, 2020). The faunal composition of the Ordovician sequences of Colombia and Venezuela are like those of Argentina and Bolivia, which in turn are typical of the Gondwana margin. There are also elements shared with Baltica, which at the time was a short distance from Gondwana (Kroeck *et al.*, 2020; Moreno-Sánchez *et al.*, 2014).

In the massifs of Quetame, Floresta (Figures 10, 11), Santander, Mérida, and Sierra de Perijá, metamorphic sequences of Precambrian gneisses and Paleozoic schists intruded by calc-alkaline granitoids of Ordovician age are prominent (Ward *et al.*, 1973; Renzoni, 1968, 1969; Ulloa *et al.*, 2008). Ordovician magmatism in the Eastern Cordillera is recognized in the Quetame, Floresta, and Mérida massifs (Boinet *et al.*, 1985, 1986; Horton and Fuentes, 2016). In Santander, the banded intrusive (‘‘orthogneiss’’) of Bucaramanga yields ages of 413–450 Ma (Ward *et al.*, 1973; Shagam *et al.*, 1984; Boinet *et al.*, 1985). The Cambrian metamorphism and Ordovician magmatism of the Quetame and Floresta Massifs, as well as the basement of the Sierra de Mérida, are often interpreted as an extension of the Famatinian orogeny into northern South America (Ramos, 2009).

It is noteworthy that the Famatinian magmatism and metamorphism, which occur almost continuously along the western margin of South America (Mišković *et al.*, 2009; Ramos, 2009), are interrupted south of the Huanca-Bamba Deflection (Balsas intrusive, dated at 477 Ma in the Marañón Arc) and reappear to the north at 3.5° in the Colombian Eastern Cordillera (Ward *et al.*, 1969).

It is then possible to define for the Andean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in the region east of Otú-Pericos two sectors with Grenvillian cycle basement but with distinctive Paleozoic stratigraphy:

• Eastern Chibcha terrane. Northern sector of the Eastern Cordillera (Quetame, Floresta, Santander Massifs) and Serranía de Mérida with Ordovician metamorphism affected by Ordovician volcanic arc magmatism and related to the Taconic or Famatinian orogeny.

• Western Chibcha terrane (Payandé, Payandé - San Lucas, Sierra Nevada de Santa Marta blocks) southern sector of the Eastern Cordillera (Garzón Massif), southern sector of the Central Cordillera and Magdalena valley with Ordovician sedimentary sequences without magmatism or orogenic metamorphism from the early Paleozoic. The blocks attributable to this sector show more affinities with those of the Sierra de la Macarena, Llanos and Putumayo basins.

The Eastern Chibcha Terrane with Precambrian metamorphic basement (Grenvillian cycle) and an early Paleozoic metamorphic succession is interpreted as a parautochtonous of Famatinian or Taconic origin. The Western Chibcha block is a displaced portion of the autochthonous basement (Grenvillian cycle) with close geological similarity to Mexican terranes, the Llanos Basin and Sierra de la Macarena basin (Moreno-Sánchez *et al.*, 2020). Eastern Chibcha Terrane may have partial continuation with Chortis and Maya-Yucatán blocks in Mexico.

Silurian

The sedimentary rocks of Ordovician age in the Llanos Basin occur as a segmented sequence deposited on Ordovician sedimentites of the Negritos Formation. In this unit the acritarches *Domasia bispinosa*, *Dactylofusa* spp. and *Eupoikilofusa* sp. (Rubinstein *et al.*, 2019; Dueñas-Jiménez and Montalvo–Jónsson, 2020; Rubinstein *et al.*, 2021).

In the Eastern Cordillera, near Villavicencio, a clastic unit of Silurian age is reported lying on an igneous-metamorphic basement of Cambrian – Ordovician age (Quetame Group). This sequence is cited as the "Silurian of Susumuco". From this sector *Ambitisporites avitus*, *A. dilutus*, *Retusotriletes warringtonii*, *R. minor*, *Archaeozonotriletes chulus*, *Synorisporites lybicus* have been collected, whose age is placed in the late Silurian (Grösser and Prössl, 1991). Royo y Gómez (1943), according to data from E. A. Scheibe, cites the presence of Silurian deposits in the Quebrada Honda (Quetame Massif). In the Santander massif, a succession of shales and meta-sandstones is known, which has provided still unidentified trilobites and the brachiopod *Aenigmastrophia* sp. of Ludlow age (Forero, 1990).

The Silurian fossils reported for Colombia are scarce, making it difficult to establish their biogeographic relationships. While Silurian-age deposits in Colombia are dominated by fine sediments and occasional turbidites, in Venezuela, the El Horno Formation is notably rich in fossils.

Figure 8. a- Photograpth of UCAL-095-2099 Phyllograptus Venado River (Huila). **b-** UCAL-548-057-2100 Goniograptus Sanza Formation (Meta). **c-** UCAL-0328-2101 Didymograptus sp San Agustin (Huila). **d-** UCAL-0328-2102 cephalon of Trinucleids San Agustín (Huila). **e-** UCAL-0328-2103 cephalon of Trinucleids San Agustín (Huila). **f-** UCAL-0328-2104 thoracic segmentof trilobite San Agustin (Huila); **g-** UCAL-1323-2105 Polypora sp Floresta Formation (Boyacá). **h, I, j, k-** UCAL-0317-1147-2106 to 2109 teeth of Xenacanthimorpha Floresta Formation (Boyacá). **l-** UCAL-1147-2110 Pharciceratina Floresta Formation (Boyacá). **m-** UCAL-2111 Archaeopteris macilenta Cuche Formation (Boyacá). **n-** UCAL-1288-2112 Anterior median dorsal plate of Asterolepis cf. radiata Cuche Formation (Boyacá). **o-** UCAL-087-0358-2113 Paladin sp. Iman Formation (Tolima). **p-** UCAL-087-0358-2114 Spiriferid Iman Formation (Tolima). **q-** UCAL-087-0358-2115 Fenestellid Iman Formation (Tolima). Scale a, c, d, e, h, i, j, k, o, q bar represents 5mm; b, f, g, m, n, p bar 1cm; L bar in mm. The fossils have been whitened with magnesium oxide, except for a, g, m, n./**Figura 8. a-** *Fotografía del río Phyllograptus Venado UCAL-095-2099 (Huila).* **b-** *UCAL-548-057-2100 Formación Goniograptus Sanza (Meta).* **c-** *UCAL-0328-2101 Didymograptus sp San Agustín (Huila).* **d-** *UCAL-0328-2102 cefalón de Trinucleidos San Agustín (Huila).* **e-** *UCAL-0328-2103 cefalón de Trinucleidos San Agustín (Huila).* **f-** *UCAL-0328-2104 segmento torácico del trilobite San Agustín (Huila); G, UCAL-1323-2105 Formación Polypora sp Floresta (Boyacá).* **h, I, j, k-** *UCAL-0317-1147-2106 a 2109 dientes de la Formación Xenacanthimorpha Floresta (Boyacá).* **l-** *UCAL-1147-2110 Formación Pharciceratina Floresta (Boyacá).* **m-** *UCAL-2111 Formación Archaeopteris macilenta Cuche (Boyacá).* **n-** *UCAL-1288-2112 Placa dorsal mediana anterior de Asterolepis cf. Formación radiata Cuche (Boyacá).* **o-** *UCAL-087-0358-2113 Paladín sp. Formación Imán (Tolima).* **p-** *UCAL-087-0358-2114 Formación Imán Espiriférido (Tolima).* **q-** *UCAL-087-0358-2115 Formación Imán Fenestélido (Tolima). La barra de escala a, c, d, e, h, i, j, k, o, q representa 5 mm; b, f, g, m, n, p barra 1cm; Barra L en mm. Los fósiles han sido blanqueados con óxido de magnesio, excepto a, g, m, n.*

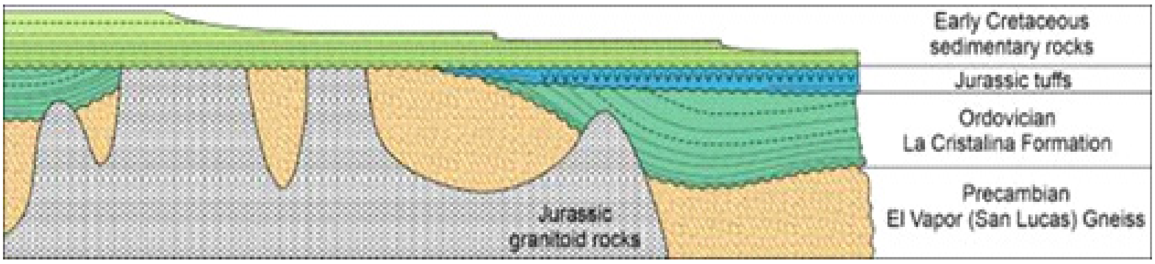

Figure 9. Scheme of stratigraphic relationships in the eastern flank of the Central Cordillera (Payandé-San Lucas block)./**Figura 9.** *Esquema de relaciones estratigráficas en el flanco oriental de la Cordillera Central (bloque Payandé-San Lucas).*

The platform sequence of the El Horno Formation in Venezuela is notably fossil-rich and includes patches of the tabulate coral Halysites. There are marked faunal similarities between the El Horno Formation of Venezuela and the Cañón de Caballeros Formation in Ciudad Victoria, Mexico (Boucot *et al.*, 1997). In these two sectors, which were formerly contiguous, Silurian fossils (Wenlock–Ludlow) have been identified. These fossils consist of genera absent in the North American faunal province but recognized in both northern South America (Venezuela) and the European Province (Boucot *et al.*, 1972; Stewart *et al.*, 1999).

The Silurian sedimentary rocks extend from the Llanos Basin to the Mérida Mountain Range, Quetame Massif, and Santander Massif. The stratigraphic relationships indicate that during the Silurian, these blocks were amalgamated with the South American basement. Additionally, the faunas shared between Venezuela and Mexico suggest that the Oaxaca block (Zapoteco Terrane) was part of northern Gondwana during the Silurian. In the Colombian Andes, the stratigraphic gap between the late Silurian and the basal Devonian is characteristic, suggesting a tectonic event during this phase (Figure 4c).

Devonian

The Silurian sedimentary rocks extend from the Llanos Basin to the Mérida Mountain Range, Quetame Massif, and Santander Massif. The stratigraphic relationships indicate that during the Silurian, these blocks were amalgamated with the South American basement. Additionally, the faunas shared between Venezuela and Mexico suggest that the Oaxaca block (Zapoteco Terrane) was part of northern Gondwana during the Silurian. In the Colombian Andes, the stratigraphic gap between the late Silurian and the basal Devonian is characteristic, suggesting a tectonic event during this phase (Figure 4c).

The base of the Devonian deposits of the Floresta Massif region, which contain Emsian palynomorphs (Grösser and Prössl, 1994), begins with the marine sandstones of the El Tibet Formation. This succession also provides corals, brachiopods and plant remains (Moreno-Sánchez *et al.*, 2020). The Devonian sequence of the Floresta Massif is like that of the Quetame Massif (Figure 13). The Gutiérrez Formation is correlated with the El Tibet Formation and the Floresta Formation has its equivalent in the shales of the Pipiral Formation (Figure 14a).

The first 30 meters of the base of the Floresta Formation, overlying the El Tibet Formation, contain trilobites from the late Emsian (Morzadec *et al.*, 2015) and an association rich in bryozoans, brachiopods, and crinoids that extends into the Eifelian to Givetian (Figure 8g). This rich fauna is often cited as correlating with the Onondaga Formation and Hamilton Group of eastern North America (Caster, 1939; McNair, 1940; Morales, 1965; Barret and Isaacson, 1988). The middle and upper parts of the Floresta Formation consist of marine laminated mudstones of anoxic origin, which are very poor in fossils. These beds, representing the phase of maximum marine advance, contain sparse calcareous levels with ammonoids, tentaculites, and orbiculoid brachiopods. Among the ammonoids, forms of Pharciceratina (Figure 8l) are notable, suggesting an age range from early Givetian to early Frasnian (written communica-

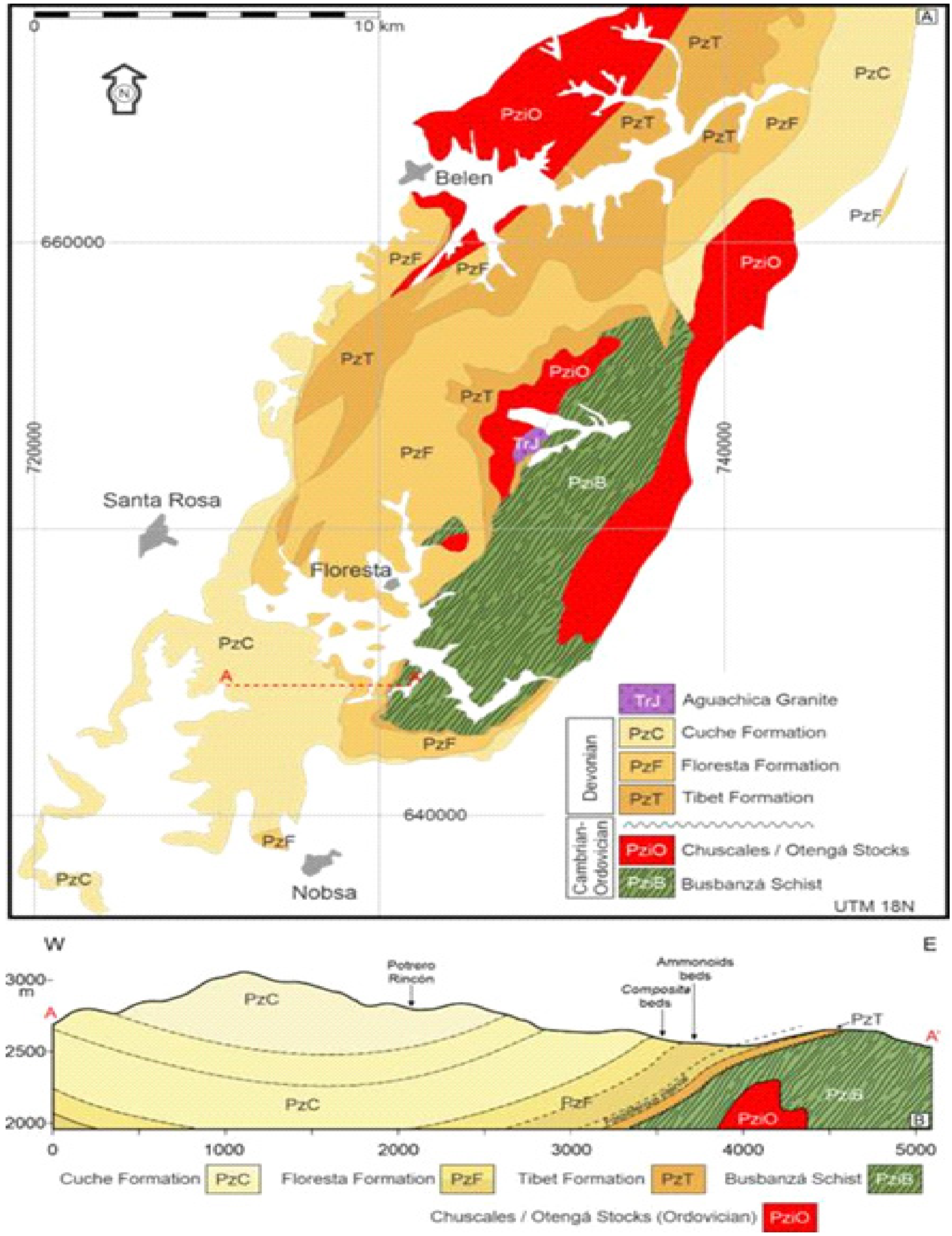

Figure 10. Geological Map of the Floresta Massif. UTM coordinates 18N. Modified from Ulloa *et al.* (1998). **b-** Devonian geological section of the Potrero Rincón Sector. Floresta Massif area. Line A-A' on the map./**Figura 10.** *Mapa Geológico del Macizo de Floresta. Coordenadas UTM 18N. Modificado de Ulloa* et al. *(1998).* **b-** *Sección geológica Devónica del Sector Potrero Rincón. Zona Macizo de Floresta. Línea A-A' en el mapa.*

tion by Ninon Allaire) (Figure 8l). In the intercalated black shales, fish scales and teeth of a large xenacanthiform shark stand out (Figure 8h, I, j, k). During the warm phases of the Middle Devonian, some genera of brachiopods from the Eastern American province reach Cocachacra in southern Peru and the Amazon basin (Boucot *et al.*, 1980) (Figures 4d, e).

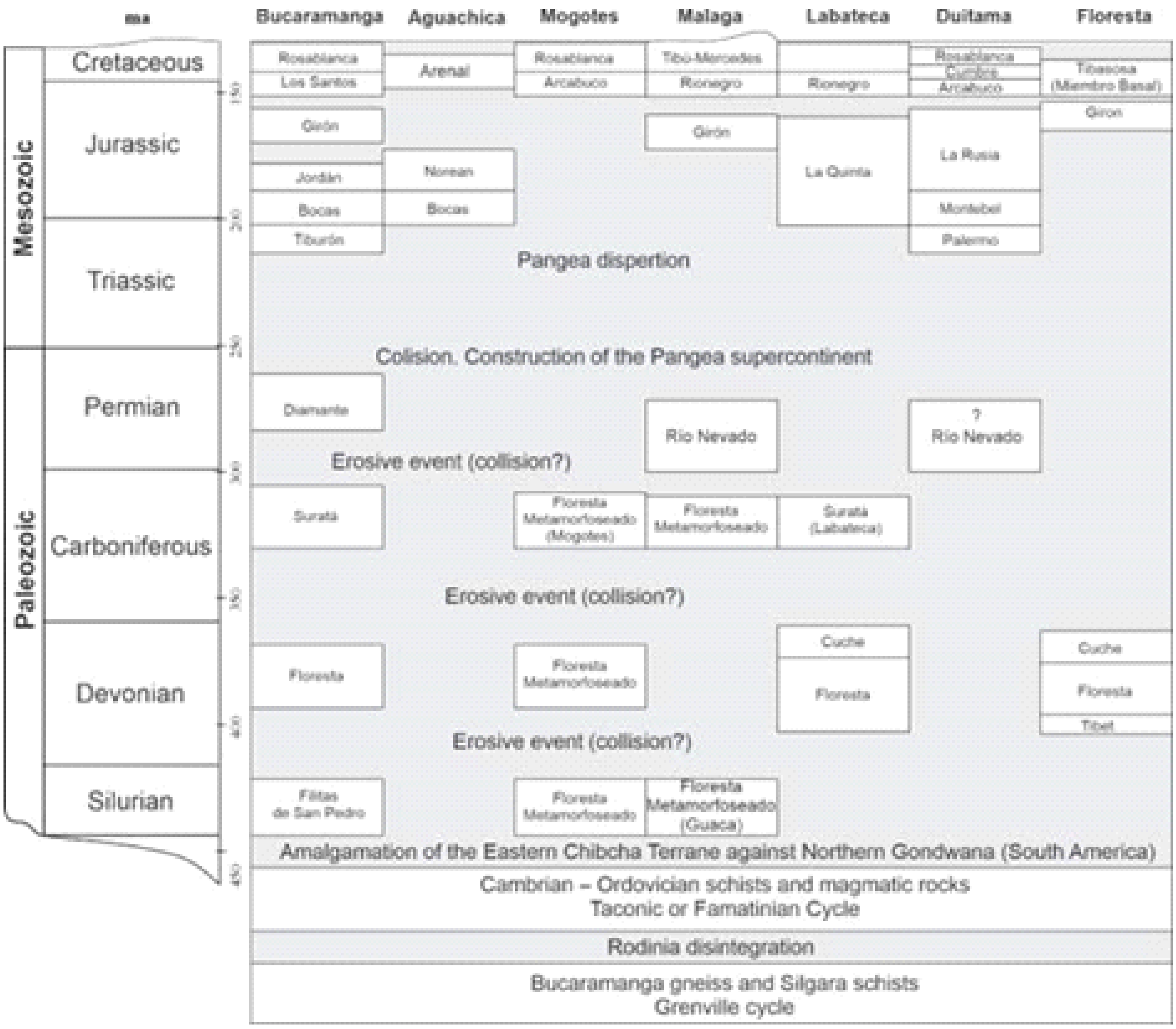

Figure 11. Chronostratigraphic scheme of the Santander and Floresta Massifs./**Figura 11.** *Esquema cronoestratigráfico de los Macizos de Santander y Floresta.*

In northern South America, the Devonian is characterized by successions of deltaic origin that culminate in red layers of river plains (Moreno-Sánchez *et al.*, 2020). The Cuche Formation (Figure 14b) covers the late Frasnian and Famenian, the most common plant fossils are an association of herbaceous lycopodia, *Archeopteris obtusa* and *Wattieza* sp. in flooded areas and forests of *Archeopteris halliana*, *A. notosaria* and *A. macilenta* in the drained areas (Moreno-Sánchez *et al.*, 2020) (Figure 8m). Fish remains with a wide geographical distribution including much of northern and eastern Gondwana are found in the channel deposits. Among this faunula, the chondrichthyan *Antarctilamna* sp. is recognized along with sarcopterygians, placoderms *Asterolepis* cf. radiata and primitive actinopterygians (Janvier and Villarroel, 1998, 2000; Burrow *et al.*, 2003; Janvier and Maisey, 2010; Mondéjar-Fernández and Janvier, 2014; Olive *et al.*, 2019) (Figure 8n).

Young and Moody (2002), based on miospores, establish the contact age of the Campo Chico and Caño del Oeste Formations to the upper Givetian. The upper member of the Campo Chico Formation, where remains of *Archeopteris* are reported, indicate a middle Frasnian age (Figure 15a).

The Eifelian to Frasnian strata of Venezuela and Colombia are known for the presence of placoderms with affinities with the quality waters of northern Gondwana and the southern margin of Euro-America (Janvier and Maisey, 2010). Boucot *et al.* (1980), based

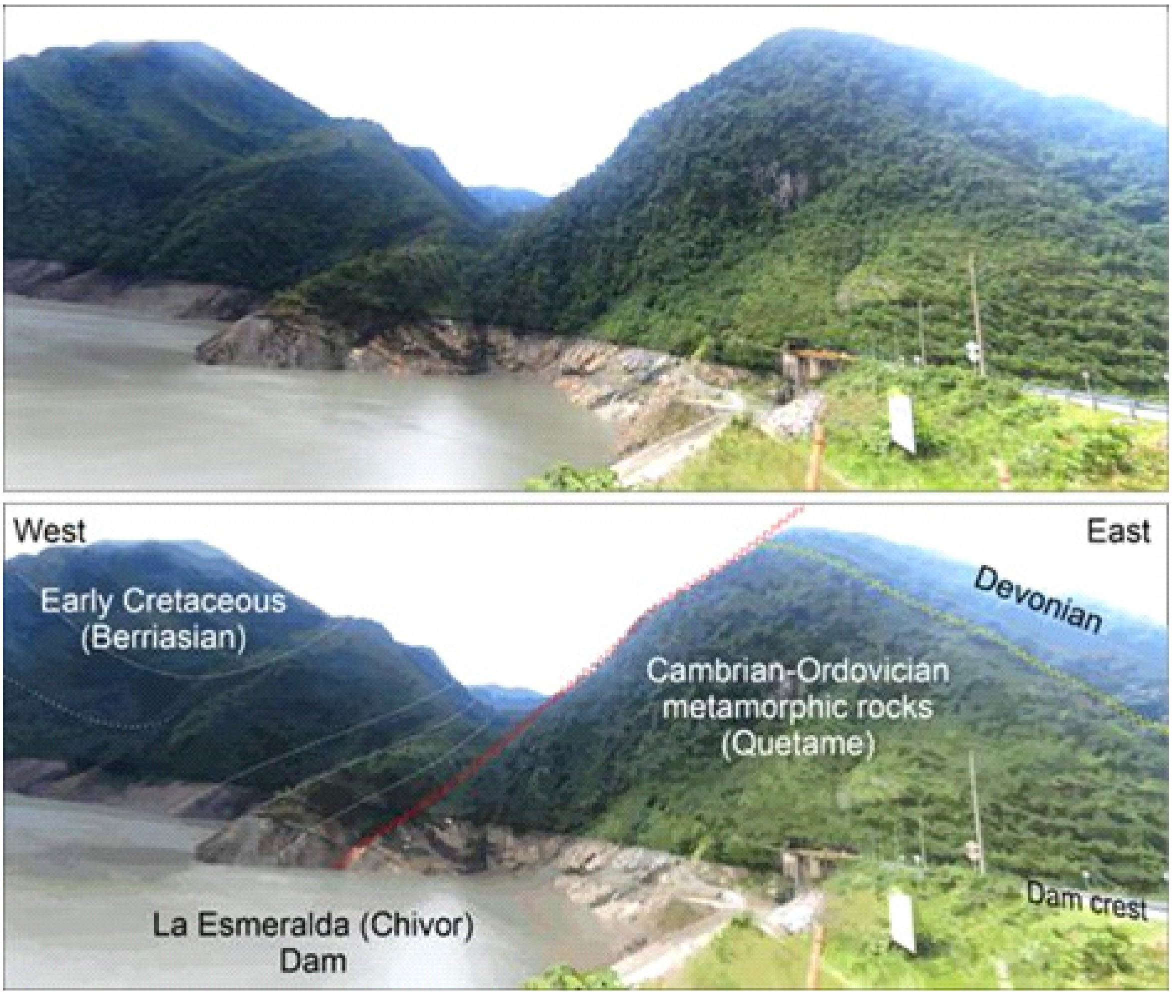

Figure 12. Paleozoic metamorphic and sedimentary succession at La Esmeralda (Chivor) dam./**Figura 12.** *Sucesión metamórfica y sedimentaria paleozoica en la presa La Esmeralda (Chivor).*

on brachiopod taxonomic affinities, includes northern South America and eastern North America in the Appalachian province or East American Kingdom. From the same source, the trilobites and fishes reported from the Venezuelan Devonian indicate geographical affinities with the North American province (De Carvalho and Moody, 2000; Young and Moody, 2002). A compilation of the Devonian fauna and flora from Colombia and Venezuela are presented by Pastor-Chacón *et al.* (2023a; 2023b) however, the stratigraphic range (FAD, LAD) is highly speculative given that there is no rigorous field control of the distribution of species in the stratigraphic columns used to this compilation.

The Hamilton (Givetian) faunas of North America also include some typical Early Devonian forms of the Rhenish-Bohemian sub-province of the Old World Realm which includes shallow-water (Rhenish) and deep-water Bohemian forms (Boucot *et al.*, 1969), 1969). Potvin-Leduc *et al.*, (2015) indicate that the global dispersal of vertebrates begins during the Middle Devonian and suggests that the "Hamilton fauna" originates during the Early Devonian in South America (Gondwana).

Provenance studies of detrital zircons from the Devonian formations (Tibet, Floresta, Cuche) of the Eastern Cordillera indicate sources in the basement of the Amazonian Craton (Horton, 2010, Cardona *et al.*, 2016). The first of these studies assumes that at least during the Devonian this area of the Eastern Cordillera was integrated into the margin of Gondwana. During the Early and Middle Devonian, the marine faunas of northern

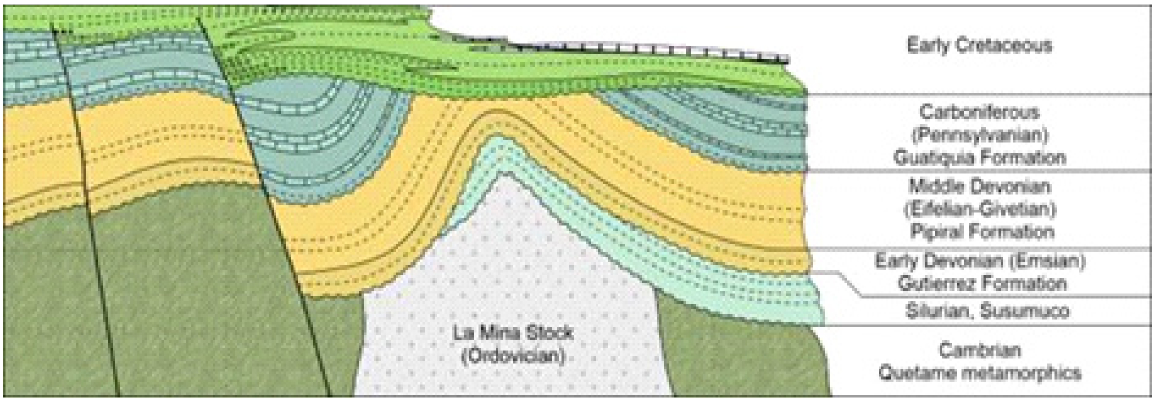

Figure 13. Scheme of stratigraphic relationships of the Quetame Massif (Eastern Chibcha terrane)./**Figura 13.** *Esquema de relaciones estratigráficas del Macizo de Quetame (terreno Chibcha Oriental).*

South America show notable similarities with those of the Appalachian province. During the Late Devonian, communication was established with the Old-World Province. It is noteworthy that during the Emsian, the Gutiérrez Formation sandstones and the El Tibet Formation are clastic units formed almost exclusively by quartz and mica sandstones of great compositional maturity with provenance in the Amazonian craton and nearby metamorphic massifs (Pastor-Chacón *et al.*, 2023b). During the Middle and Upper Devonian, the coastal margin of northern South America does not fit with a passive platform in its strictest sense. Pastor-Chacón *et al.* (2023a), based on detrital zircon stratigraphy, suggests the volcanic influence of the Maya Block according to data from Salazar-Juárez *et al.*(2007).

Carboniferous

The Carboniferous Andes of northern South America are limited to the Pennsylvanian rocks (Bashkirian and Moscovian), although in the subsurface of the Llanos Basin. Dueñas and Césari (2006), based on palynological assemblages, recognize material from the Mississippian (Tournaisian - Visean). The Colombian and Venezuelan Carboniferous is characterized by the alternation of platform limestones and deltaic deposits that culminate in red beds (Braun, 1979; Moreno-Sánchez *et al.*, 2020).

From Carboniferous basal strata of the Farallones Group (Quetame Massif) W. J. Clarke cites a fauna of late Mississippian age consisting of *Inflatia inflata*, *Ectogrammysia (Grammysia) hannibalensis*, *Aviculopecten* cf. *rugirostratus*, *Myalina* cf. *subquadrata*, *M. perattenuat*, *Spirifer increbescens* (Campbell and Bürgl, 1965). In the sandstones covering these deposits W. J. Clarke identifies *Spirifer increbescens*, *Derbya crassa*, *Myalina perattenuata*, *Composita* sp. *Linoproductus* sp. of Pennsylvanian age (Campbell and Bürgl, 1965). This suggests that Carboniferous sedimentation of the Farallones Group (Segovia, 1964; Braun, 1979) begins at the end of the Mississippian and extends through most of the Pennsylvanian (Moreno-Sánchez *et al.*, 2020).

Royo y Gómez (1943) report a marine fauna for the Gachalá region (north of the Quetame Massif), including crinoids, brachiopods, bryozoans, and mollusks, with a composition similar to that of the Pennsylvanian of Tarma and Ambo (Peru). Remains of a crossopterygian fish, trilobites of the genus *Ameura*, and a flora consisting of *Cordaites* sp., *Calamites cf. peruvianus*, and *Neuropteris stutzeri* are also mentioned (Scheibe, 1938).

The Río Palmar Formation, composed of platform limestone, extends along the Sierra de Perijá on the Colombian-Venezuelan border. In the Mérida Andes of Venezuela, the Mucuchachí Formation is characterized by an outer shelf marine succession dominated by shales with marine fossils and Pennsylvanian plants (Pfefferkorn, 1977; Odreman and Wagner, 1979). Interbedded with these deposits are occasional lava flows and volcanic deposits linked to

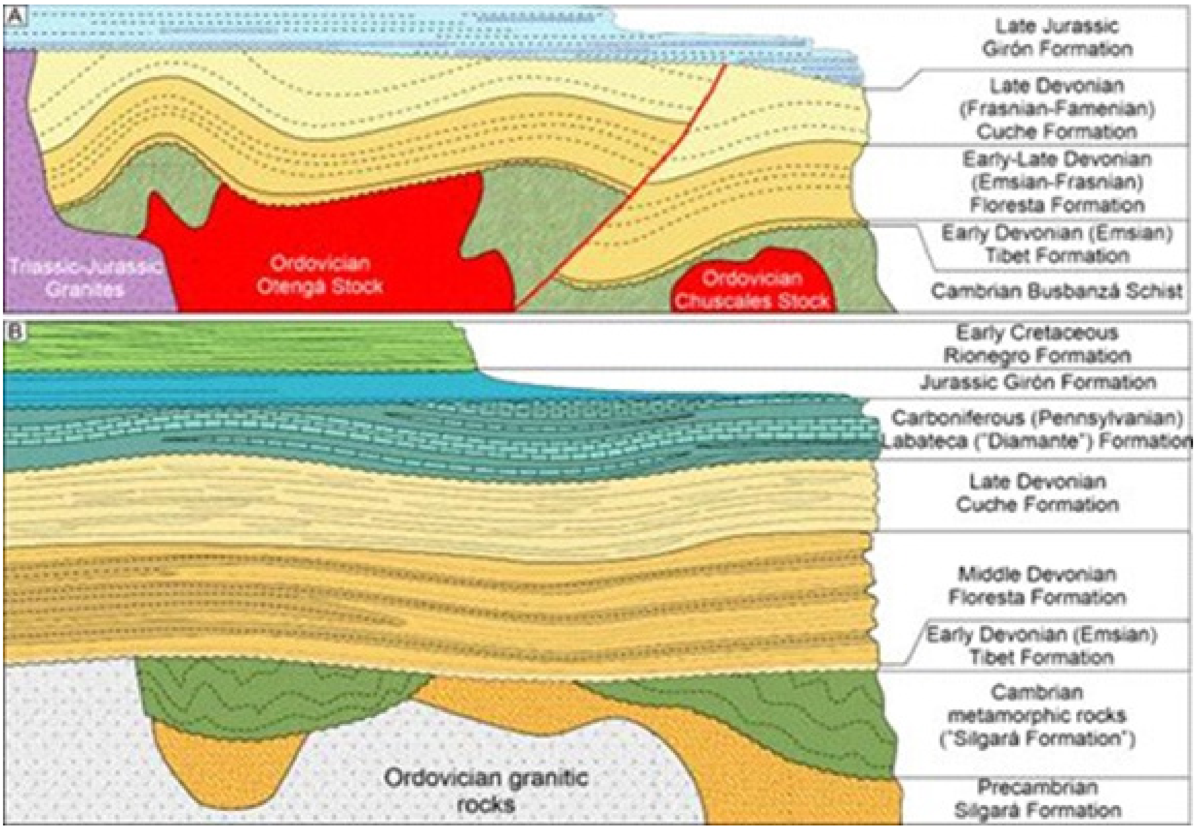

Figure 14. a- Scheme of stratigraphic relationships of the Floresta Massif (Eastern Chibcha Terrane, Eastern Cordillera). **b-** Scheme of stratigraphic relationships of the Chitagá River, near Labateca./**Figura 14. a-** *Esquema de relaciones estratigráficas del Macizo de Floresta (Terreno Chibcha Oriental, Cordillera Oriental).* **b-** *Esquema de relaciones estratigráficas del río Chitagá, cerca de Labateca.*

Carboniferous intrusives These volcanic deposits, recognized in northern Colombia and Venezuela (Moreno-Sánchez *et al*., 2020), are linked to Carboniferous intrusives. The Carboniferous deposits in some sectors of the Santander Massif and the Mucuchachí Formation of the Mérida Mountain Range were subjected to low-grade metamorphism, resulting in the formation of slate and marbles (Moreno-Sánchez *et al*., 2020). Similar events, related to the closure of the ocean basin between Laurentia and Gondwana during the Permian, are also recorded in the Carboniferous rocks of the Maya Terrane (Moreno-Sánchez *et al*., 2020).

The Bocas Formation is often cited as a Carboniferous unit (Royo y Gomez, 1943; Langenheim, 1961), or Permian (Van der Lelij *et al*., 2016) however new paleontological evidence places it in the Mesozoic (Remy *et al*., 1975; Alarcón *et al*., 2021). Royo y Gómez (1943) cite for the Bocas Formation: *Crania modesta*, *Dictyoclostus portlockianus*, *Dictyoclostus americanus*, *Buxtonia scabricola*, *Neospirifer goreii*, *Neospirifer* sp. of Carboniferous age. This assemblage, typical of the Paleozoic limestones of Suratá (Carboniferous-Permian,) was included in the Bocas Formation (Figure 15b). According to the notion of the time, the limestones of the Suratá Series constituted a continuous sedimentary succession with the less fossiliferous Bocas series to the top (Dickey, 1941; Royo y Gomez, 1943).

Angiolini *et al.* (2003) report in Cerro El Imán (near Rovira) brachiopods indicating a Carboniferous age (Bashkirian-Moscovian), however, a field review in the reported area indicates the presence of Triassic limestones of the Payandé Formation without a record of Paleozoic layers at the aforementioned site. On the other hand, in nearby areas brachiopods like those reported, suggesting that the fossils cited by Angiolini *et al.* (2003) were found out of place. The Iman Formation is also bears in trilobite *Paladin* sp. (Figure 8o), spiriferid brachiopods and bryozoan remains (Figure 8p, q).

The Pennsylvanian deposits of northern South America are related to both Central Ameri-

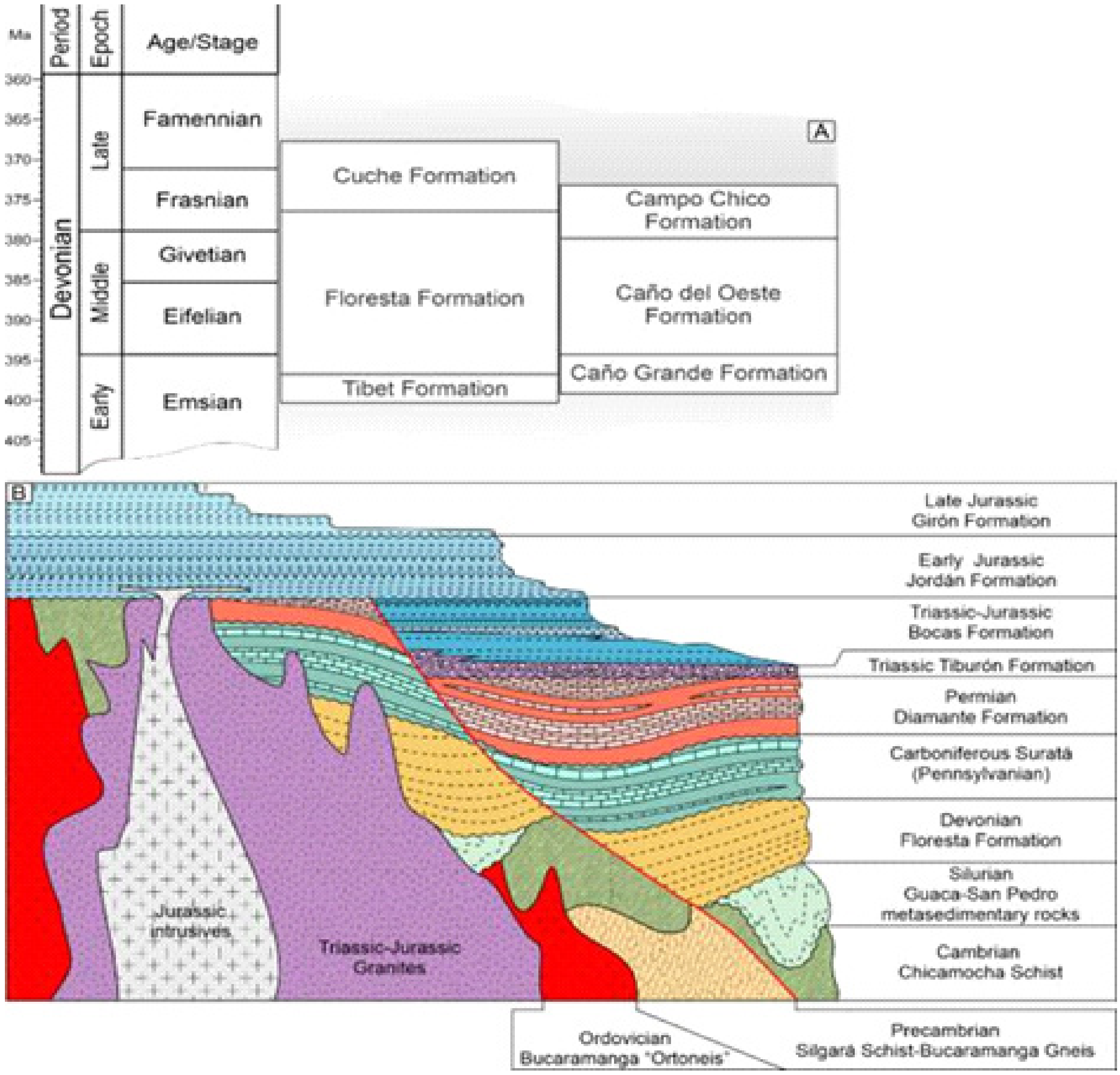

Figure 15. a- Chronostratigraphic correlation instead of scheme of the Campo Chico and Caño del Oeste formations. **b-** Scheme of stratigraphic relationships of the Santander Massif (Eastern Chibcha Terrane, Eastern Cordillera)./ **Figura 15. a-** *Correlación cronoestratigráfica en lugar de esquema de las formaciones Campo Chico y Caño del Oeste.* **b-** *Esquema de relaciones estratigráficas del Macizo de Santander (Terreno Chibcha Oriental, Cordillera Oriental).*

ca (Mayan Block) and other areas of western South America. The lithology is dominated by limestone and red beds suggesting warm waters (due to the movement of South America towards lower latitudes) and influenced by glacial eustatic cycles.

Permian

The Permian sedimentary of northern South America is distributed in the Sierra de Perijá, Andes de Mérida and Massif de Santander. In the Quetame Massif, possible fossils of Permian age are often cited, however the surest indication of the existence of layers of this age is a float block, with an ammonite of the genus *Mooreoceras*, found near Guayabetal (Campbell and Bürgl, 1965).

On the eastern flank of the Central Cordillera, a new stratigraphic unit (Rovira Formation) was recognized consisting of agglomerates, tuffs and basaltic lava flows (Figure 16a). This unit, often confused in cartography with the Saldaña Formation of Jurassic age, lies unconformably on sedimentites of Carboniferous age and unconformably underlies the red conglomerates of the Luisa Formation (Figures 17, Figure 18). Blocks of sedimentary rocks, gneisses, granitoids (Rovira Stock) and volcanic roc-

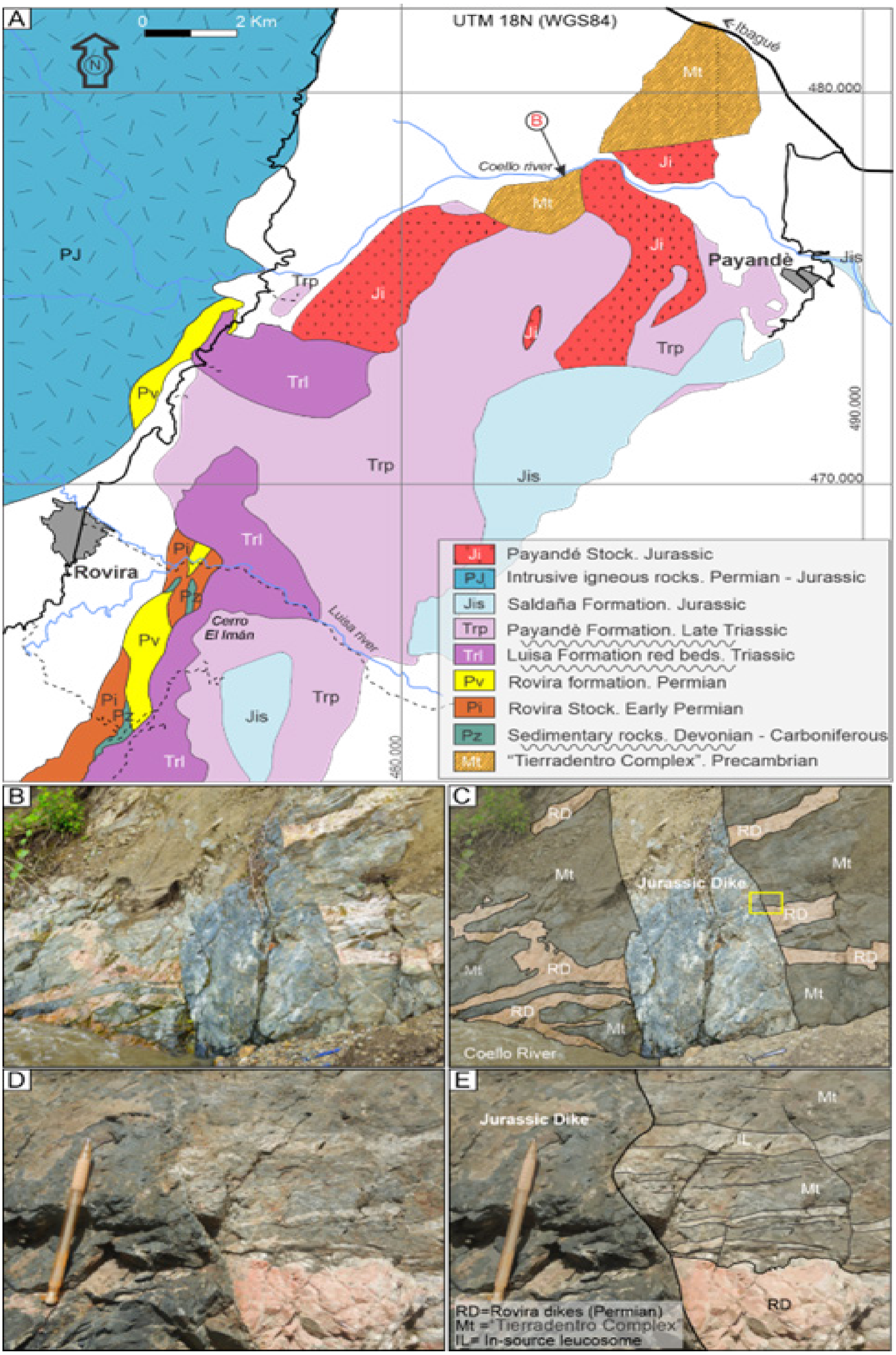

Figure 16. a- Geological Map of the Rovira (Tolima). UTM coordinates 18N. Modified from Nuñez and Murillo, 1982. **b-e-** metatexite migmatite of the Tierradentro complex (Precambrian) intruded by dikes of sienogranite from the Rovira Stock (Permian) and basalt dike from the Saldaña Formation (Jurassic)./**Figura 16. a-** *Mapa Geológico de la Rovira (Tolima). Coordenadas UTM 18N. Modificado de Nuñez y Murillo, 1982.* **b-e-** *migmatita metatexita del complejo Tierradentro (Precámbrico) intruida por diques de sienogranito del Stock Rovira (Pérmico) y dique basáltico de la Formación Saldaña (Jurásico).*

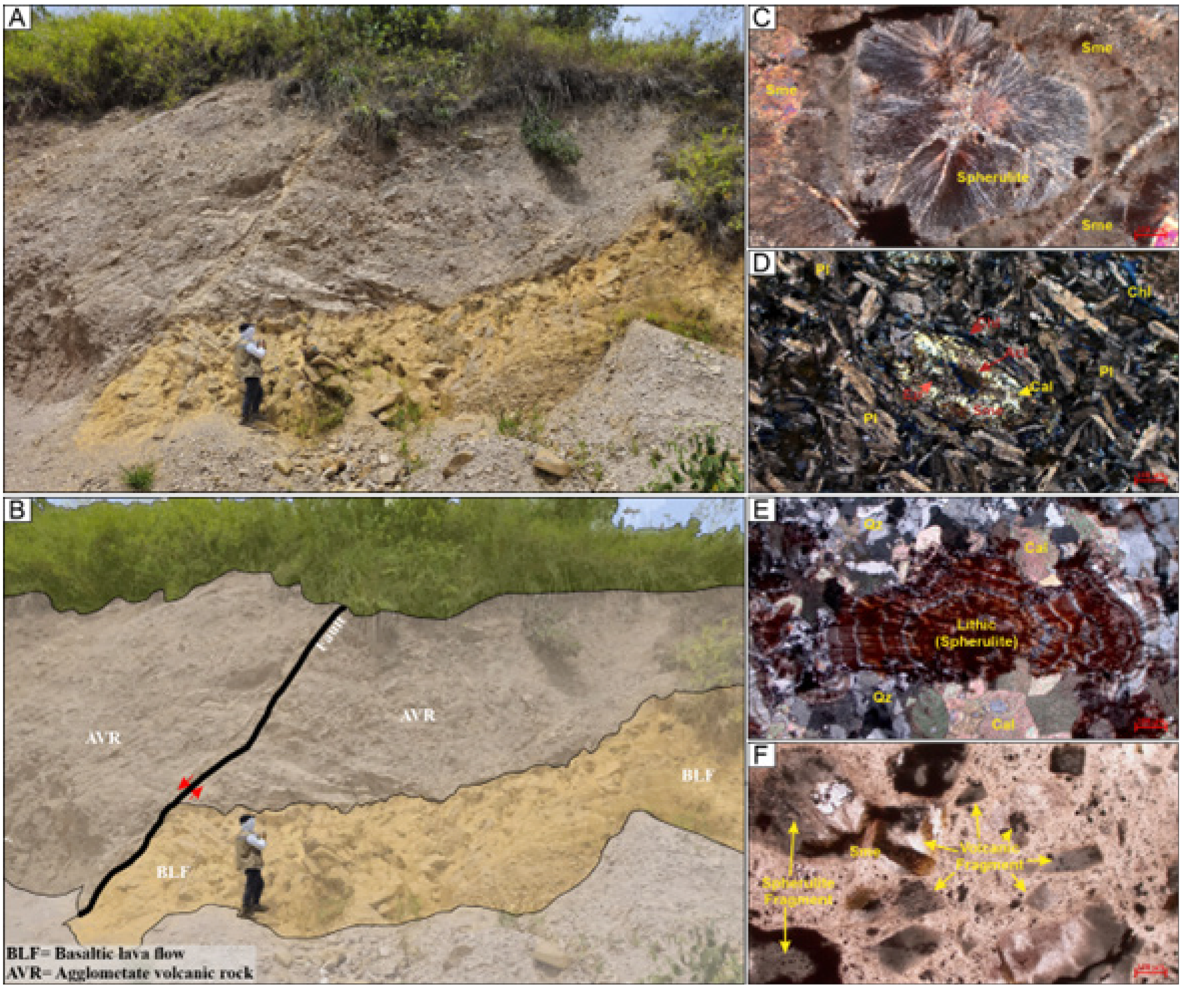

Figure 17. a, b- Lava flow of basaltic composition, tuffs, and agglomerates from the Rovira formation. **c-** volcanic lithic fragment with development of spherulites due to devitrification in the Luisa Formation. **d-** metabasalt in sub-greenschist facies, taken from the lava flows of the Rovira formation. **e, f-** volcanic lithic fragments and spherulite fragments due to devitrification in volcanic igneous clasts of the conglomeratic segments at the base of the Luisa Formation. Abbreviations: Pl, plagioclase; Qz, quarzt; Ep, epidote; Cal, calcite; Chl, chlorite; Sme, smectite group./**Figura 17. a, b-** *Flujo de lava de composición basáltica, tobas y aglomerados de la formación Rovira.* **c-** *fragmento lítico volcánico con desarrollo de esferulitas por desvitrificación en la Formación Luisa.* **d-** *metabasalto en facies subesquistoverde, extraído de las coladas de lava de la formación Rovira.* **e, f-** *fragmentos líticos volcánicos y fragmentos de esferulita debidos a la desvitrificación en clastos ígneos volcánicos de los segmentos conglomeráticos en la base de la Formación Luisa. Abreviaturas: Pl, plagioclasa; Qz, cuarzo; Ep, epidota; Cal, calcita; Chl, clorito; Sme, grupo de las esmectitas.*

ks from the underlying units are common in the conglomerates of the Luisa Formation (Figure 18b-c) contain zircons that provided U-Pb ages of 258 Ma and 264 Ma, which are assumed to represent the age of sedimentation (Cadavid *et al.*, 2023). This area is also affected by calc-alkaline intrusives, such as the Rovira and Ortega Stocks of Early Permian age (Figure 16b–e). In the El Baúl Massif (Venezuela), U-Pb ages from intrusive and volcanic rocks (rhyolites) indicate Permian volcanism in the 297–280 Ma interval (Viscarret *et al.*, 2012).

The brachiopods *Echnauris. E. lappacea*, *Echnauris* cf. *E. liumbona*, *Paucispinifera* cf. *P. sulcata*, *Cleiothyrina* cf. *C. nana*, *Composita* cf. *C. pilula* and *Neophricadotryris* cf. *N. crassibecca*, are reported in the Permian deposits of the Venezuelan Andes. This fauna recalls coeval assemblages from the Texas area (Road of Canyon Formation) and also shows similarity with those of the Roadian of North Africa (Ricardi-Branco, 2008).

The Permian flora of the Palmarito Formation, in the Venezuelan Andes, is closely related to the southwestern and central United States (Ricardi-Branco *et al.*, 1998, 2005; Ricardi-Branco, 2008).

In the Venezuelan Andes Ricardi-Branco (1998) reports a Permian flora that includes *Delnortea* sp. cf. *D. abottiae*, *Taeniopteris* sp. cf. *T. multinervis*, *Taeniopteris* spp., *Zamiopteris* sp. *Cordaicarpus* sp. *Cordaites* sp. and *Walchia* sp. The material shows that during the Permian, northern South America was connected to the floras of the southwestern and central United States. The flora cited for Venezuela and that reported by Weber (1997) for Mexican Permian strata of the Zapoteco Terrane (Oaxaca) show contiguity of these terrane during the Permian. Most Paleogeographic models agree that during the Late Permian Laurentia and Gondwana collided and gave rise to the continent of Pangea (Wegener, 1912; Pindell and Dewey, 1982; Scotese and McKerrow, 1990).

Horton *et al.* (2010) recognizes U-Pb ages from 539 ± 7 to 422 ± 4 Ma in granites (e.g. Otengá) from the Floresta Massif, with ages that indicate origin from the Amazonian basement (1000 Ma and 1600 Ma), in addition, they are recognized zircons from the Grenville cycle (1350–950 Ma). According to Horton *et al.* (2010), detrital zircon data suggest that northern Colombia during the Early Paleozoic was not a passive margin.

Van der Lelij *et al.* (2016) assume a Permian age for the lacustrine deposits of the Bocas Formation based on zircons from a dike that cuts the aforementioned formation. Furthermore, these authors mistakenly cite remains of *Glossopteris*, actually *Phlebopteris branneri*, which is also associated in the unit with *classopolis* sp. indicating an early Jurassic age (Remy *et al.*, 1975). Poorly preserved specimens of *Phlebopteris branneri* were previously referred by Langenheim (1961) to the carboniferous genus *Pecopteris* sp. (Langenheim, 1961). Complex tectonics and vegetation often lead to confusion of the Bocas Formation with underlying Paleozoic deposits.

During the early Permian, northern and western South America are interpreted as an active margin with volcanism recorded in both Venezuela and Colombia. This phase suggests the closure of the re-

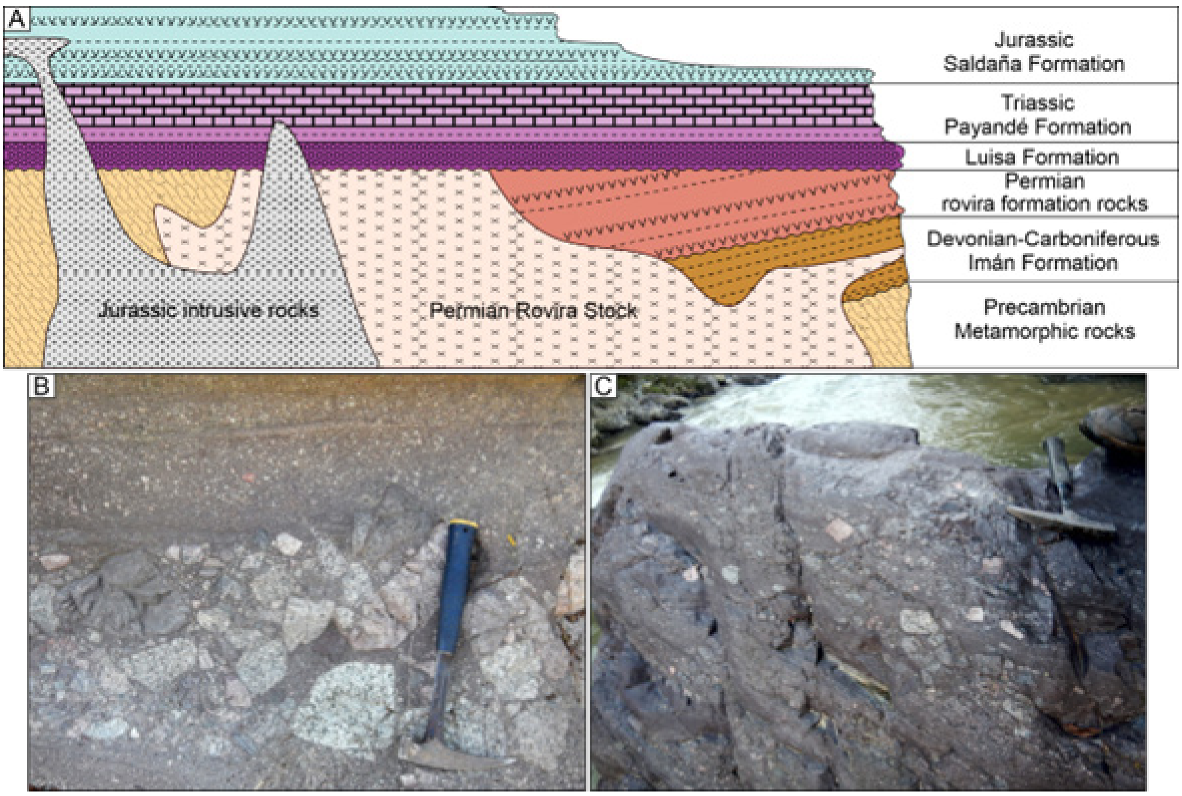

Figure 18. a- Scheme of stratigraphic relationships of the northern region of the Magdalena Valley (Payandé Block). **b, c-** Conglomerates from the Luisa Formation (Early Triassic) with granitoid clasts from the underlying Rovira Stock (Permian)./ **Figura 18. a-** *Esquema de relaciones estratigráficas de la región norte del Valle del Magdalena (Bloque Payandé).* **b, c-** *Conglomerados de la Formación Luisa (Triásico Temprano) con clastos granitoides del Stock Rovira subyacente (Pérmico).*

maining sea between South America and Laurentia that culminates with the formation of Pangea at the end of the Permian. Thus, the calcareous platforms extended from southern North America to northern South America. Floristic affinities between Venezuelan and Texas show the contiguity of these areas during the Permian. The Ortega Granite and Rovira Stock, corresponding to calc-alkaline intrusives of monzodiorites, quartzomonzonites, tonalites, grano-diorites, monzogranites and syenogranites composition with U/Pb crystallization ages from 294 to 263 Ma (early Permian) (Rodríguez-García *et al.*, 2019), similar to those reported for the La Plata Granite, with crystallization ages between 280 to 268 Ma (Rodríguez *et al.*, 2017; Leal-Mejía *et al.*, 2019).

Terrane review

The model of continental drift and the origin of the supercontinent Pangea, developed by Wegener (1920), was initially based on the geographical correspondence of the Atlantic Ocean coasts of Africa with South America and North America with Europe. Following the definitive establishment of the theory of plate tectonics, the concept of geological terranes emerged (Coney *et al.*, 1980). Terranes are defined as sectors of the Earth's crust with similar lithology, stratigraphy, structural style, and history, separated by faults (sutures) from other blocks with disparate characteristics.

The idea of terranes has early precedent in Colombia. Tschanz *et al.* (1974) establishes for the Sierra Nevada de Santa Marta four geological terranes with distinctive geology and separated by "geosutures": Provinces of Perijá, Sierra Nevada, Seville and Santa Marta. The Seville terrane of Etayo-Serna *et al.* (1986) follows the concept of Tschanz *et al.* (1974), in addition to being presented as the northern termination of the Cajamarca Terrane.

After the establishment of the theory of plate tectonics, geological and geophysical data were provided that confirmed the expansion model from the mid-ocean ridge that created the Atlantic Ocean and separated North America from Europe and South America from Africa. However, reconstructions of Pangea for the end of the Paleozoic lead to a strong mismatch between Mexico, Central America and northern South America. These areas would overlap geographically unless a reorganization of the geological blocks in this sector of America is allowed (Pindell and Dewey, 1982; Maze, 1984; Pindell, 1985; Bartok, 1993).

The adjustment of these blocks (crustal sectors with similar geology and bonded by faults) prior to the formation of Pangea fits a Rubik's Cube-type reorganization model. It is necessary to clarify that a large part of Central America and sectors of northern and western South America are made up of oceanic basement of Cretaceous age (Dengo, 1983, 1985; Maze, 1984; Ramos and Aleman, 2000). Terranes or geological blocks with Cretaceous oceanic basement are not relevant for paleogeographic reconstructions prior to the Mesozoic (K in Figures 1,2,3).

To the west of the San Jerónimo fault, oceanic bottom rocks emerge, no older than the Cretaceous, and related to the evolution of the Caribbean Plate. To the east of the Otú-Pericos Fault, the Chibcha Terrane is recognized (Restrepo *et al.*, 2011) whose Precambrian basement (Restrepo-Pace, 1995; Restrepo-Pace *et al.*, 1997; Ordoñez-Carmona, 1999; Restrepo-Pace and Cediel, 2018) is covered by Paleozoic sedimentary sequences and crossed by Permian and Jurassic batholiths.

The Tahamí Terrane (sensu Restrepo *et al.*, 2011) or Cajamarca Terrane (sensu Etayo-Serna *et al.*, 1986) is a sector of the north of the Central Cordillera limited to the west by the San Jerónimo Fault and to the east by the Otú-Pericos fault. This terrane is made up of micaceous and black schists, meta-sedimentary rocks, amphibolites, migmatites and orthogneisses (Ordóñez *et al.*, 2001b; Restrepo *et al.*, 2011). The protoliths include Permian carboniferous and magmatic sedimentary sources, the metamorphism recognized in this terrane dates back to the Permian – Triassic interval (Restrepo *et al.*, 1991; Ordóñez *et al.*, 2001a; Vinasco *et al.*, 2006; Cochrane *et al.*, 2014) with a late Jurassic event in its southern part (Blanco–Quintero *et al.*, 2014). The Cajamarca Terrane is intruded by Cretaceous batholiths (Ordóñez *et al.*, 2001b) and is covered by Early Cretaceous sedimentary rocks (Nelson, 1959, 1962; Etayo-Serna, 1985; Vakhrameev, 1991). The disparity of lithologies and the different degrees of metamorphism and magmatism gave rise to the concept of "Cajamarca Complex"(-Maya and González, 1995).

To the west of the San Jerónimo fault, oceanic bottom rocks emerge, no older than the Cretaceous, and related to the evolution of the Caribbean Plate. To the east of the Otú-Pericos Fault, the Chibcha Terrane is recognized (Restrepo *et al.*, 2011) whose Precambrian basement (Restrepo-Pace, 1995; Restrepo-Pace *et al.*, 1997; Ordoñez-Carmona, 1999; Restrepo-Pace and Cediel, 2018) is covered by Paleozoic sedimentary sequences and crossed by Permian and Jurassic batholiths.

The Chibcha terrane is divided into two separate sub-terranes by Moreno-Sánchez *et al.*,(2020):

• **Eastern Chibcha terrane** (Moreno-Sánchez *et al.*, 2020) with a Precambrian basement covered by metamorphic successions from the Late Cambrian to Ordovician and affected by calc-alkaline magmatism from the Ordovician. Sedimentary sequences from the Silurian to the Permian were settled on the metamorphic rocks (Chicamocha, Silgará, Busbanzá, Quetame, etc.). This terrane covers a large part of the center and north of the Eastern Cordillera, including the Serranías de Mérida and Perijá, the Quetame, Floresta and Santander massifs (Moreno-Sánchez *et al.*, 2020). The Mérida Terrane of Bellizzia and Pimentel (1994) is considered part of the Eastern Chibcha Terrane. This sector of the Chibcha terrane is often included as part of the Famatinian belt that borders much of the western margin of South America (Ramos, 2015).

• **Western Chibcha terrane** (Moreno-Sánchez *et al.*, 2020) with a Precambrian basement and covered by sedimentary sequences from the Ordovician to the Devonian and Carboniferous. It includes the Eastern region of the Sierra Nevada de Santa Marta. This block, which brings together the Sierra Nevada, Payandé-San Luca and Payandé de Etayo-Serna *et al.* (1986), is interpreted as a block transported to the north since it presents close geological similarities with the Paleozoic basement and cover of the Llanos Orientales basin (Moreno-Sánchez *et al.*, 2020).

Block displacements along the South American margin are supported by paleomagnetic data. Northward movement with respect to South America has been supported by data in the basal Triassic Luisa Formation (Scott, 1978). Likewise, Jurassic rocks from northern Colombia and Venezuela show similar displacements to the north (Maze, 1984; Maze and Hargraves, 1984; Bayona *et al.*, 2010).

Discussion

New papers have recently been presented with radiometric data, with emphasis on U/Pb in zircons, where they are interpreted based on groupings that are based on geographical categories (Rodriguez-Corcho *et al.*, 2021). This practice, based on current physiography, uses physiographic expressions such as "Central Cordillera", "Magdalena Valley", "Mérida Andes" to refer to the Paleozoic evolution of northern South America (Spikings *et al.*, 2015; Van der Lelij *et al.*, 2016; Spikings and Paul, 2019; Rodriguez-Corcho *et al.*, 2021); it is noteworthy that the magmatic history, based on the data presented in the cited articles, is rigorously interpreted. However, these authors (opus cit.) assume that for Paleozoic paleogeographic modeling the terrains and blocks mentioned in the literature can be dispensed with (see Etayo-Serna *et al.*, 1986; Restrepo and Toussaint, 1988; Ordoñez *et al.*, 2006; Restrepo *et al.*, 2011; Restrepo and Toussaint, 2020; Moreno-Sánchez *et al.*, 2020).

The presumption of autochthony of the Andean blocks of northern South America is controversial by stratigraphic evidence that is often ignored in geochemistry works. On the southern margin of the Güicaramo Fault, ocean-bottom gabbros emerge whose age is at the end of the Ediacaran. These pass through Precambrian limestones (Ariari Formation) and are unconformably covered by marine turbiditic deposits interbedded with basaltic flows. Above these there is a sequence of diamictites, sandstones and shales of Cambrian age from the Duda Formation of the Cambrian (Harrington and Kay, 1951; Rushton, 1963). The limestones of the Ariari Formation and the turbidites with vulcanites of the Duda Formation are formed during the Ediacaran in response to crustal stretching that culminates with the formation of Iapetus Ocean (Arminio *et al.*, 2013; Moreno-Sánchez *et al.*, 2020). Additionally, during the Ediacaran, in the Llanos and Serranía de la Macarena basin, the basement is crossed by a series of intrusives that include nepheline syenites (Arango *et al.*, 2012) that correspond to a stage of cortical stretching.

Bustamante *et al.* (2017) present arguments to suggest a geological contiguity during the Paleozoic between the Tahami and Chibcha block. Furthermore, like Van der Lelij *et al.* (2016) use the term "Central Cordillera", as a substitute for the Tahamí Terrane, as the unit of paleogeographic interpretation. Consequently, the Otú-Pericos fault system will be ignored as the limit of the Cajamarca terrane (sensu Etayo-Serna *et al.*, 1986) or Tahamí terrane (sensu Ordoñez *et al.*, 2006), with the Precambrian basement terranes to the east. It is necessary to clarify that the limit between the Tahamí (Cajamarca) and Chibcha terrane (Restrepo *et al.*, 2011), north of Ibagué, is problematic given that the term "Gneisses and Amphibolites of Tierradentro" (Figure 19) was used in the cartography (Barrero and Vesga, 1976) to refer to basic metamorphic rocks located both east and west of the Otú-Pericos fault (Figure 3b).

Cochrane *et al.* (2014) presents the rocks of the Cajamarca Complex as a continuous belt to Ecuador in the Cordillera Real. However, this idea, based on regional geological maps, is not correct:

- First, because the southernmost extension of this complex is located a few kilometers south of Ibagué. The apparent continuity of this metamorphic belt along the Central Cordillera is the product of a cartographic artifact. At the top of the Central Mountain Range, on the road to La Plata-Popayán, a series of Upper Cretaceous deposits emerge that are mapped due to their deformation as the "Cajamarca Complex".
- Second, because the metamorphic rocks of the Cajamarca Complex near Ibagué are of Jurassic age, creating another gap of Triassic metamorphism.

The Chibchan Western Terrane (Payadé and Payandé-San Lucas) (Figure 3) (Etayo-Serna, 1983; Cediel, 2019; Restrepo and Toussaint, 2020; Moreno-Sánchez *et al.*, 2020) is composed of a crystalline basement formed by a sequence of deformed metamorphic and intrusive igneous rocks, which include gneisses, amphibolites, migmatites, metagabbros, anorthosites, and granitic mylonites, represented by the Gneisses and Amphibolites of Tierradentro (Marquínez and Núñez, 1998), the Icarco Complex (Murillo *et al.*, 1982; Esquivel *et al.*, 1987), and the Davis Gneiss (Murillo *et al.*, 1982). Due to their lithological variability and structural complexity, these rocks are grouped under the name Tierradentro Complex (Bustamante *et al.*, 2017; Moreno-Sánchez *et al.*, 2020; Restrepo *et al.*, 2023). This sequence is affected by a series of Permian, Triassic and Jurassic calc-alkaline intrusions, corresponding to syntectonic granites of tonalitic to granodioritic composition and to a lesser extent gabbros, diorites, microdiorites and andesites (Barrero and Vesga, 1976; Muñoz and Vargas, 1981; Rodríguez-García *et al.*, 2019; Moreno-Sánchez *et al.*, 2020).

All this lithological variability, is affected by a superimposed medium and high-grade dynamic metamorphism product of the Otú-Pericos fault system, generating a mixture of mylonites from igneous rocks and metamorphic rocks (Osorio-Granada and Vallejo, 2014; Cediel, 2019; Restrepo and Toussaint, 2020; Moreno-Sánchez

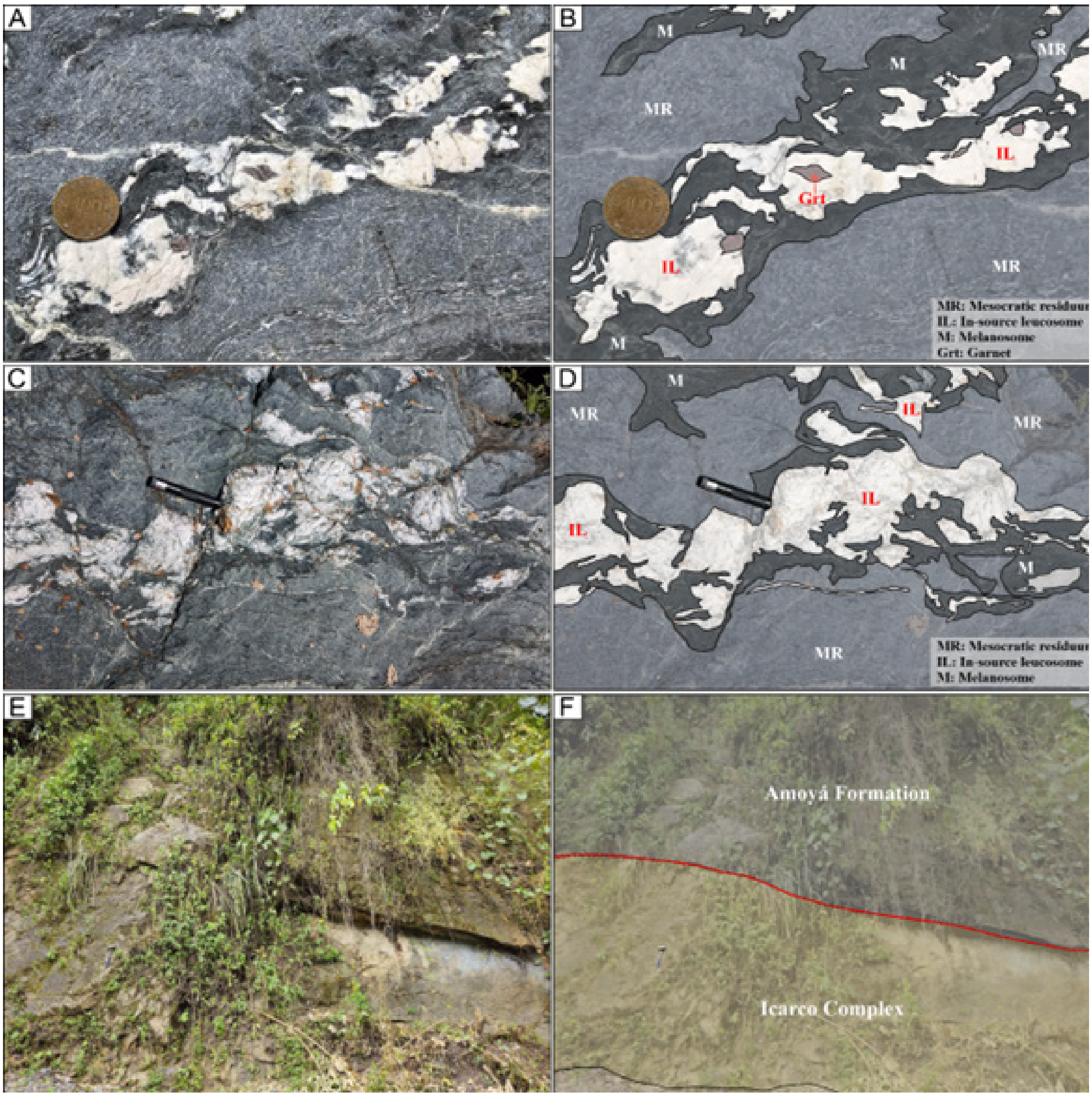

Figure 19. a, d- Migmatite metatexita type patch from the Tierradentro Complex near Mariquita (Payandé Terrane), showing garnet crystals and in-situ leucosomes of tonalitic composition. **e, f-** disconformity between gneisses of the Icarco Complex (Precambrian) and the Amoyá Formation (Devonian) near Chaparral (Payandé block)./**Figura 19. a, d-** *Parche tipo metatexita de migmatita del Complejo Tierradentro cerca de Mariquita (Payandé Terrane), que muestra cristales de granate y leucosomas in situ de composición tonalítica.* **e, f-** *discordancia entre gneises del Complejo Icarco (Precámbrico) y la Formación Amoyá (Devónico) cerca de Chaparral (bloque Payandé).*

et al., 2020; Zapata *et al.*, 2023) that at the macroscopic level present similar appearance to the shear rocks of the Tahamí Terrane. The Otú-Pericos fault system (Toussaint and Restrepo, 1994) separates the presumably Precambrian crystalline basement of the Chibcha Terrane from the medium and low-grade metamorphic rocks of Permo-Triassic age assigned to the Tahamí Terrane in the Central Cordillera (Restrepo *et al.*, 1991; Ordóñez-Carmona *et al.*, 2001a; Vinasco *et al.*, 2006).

Bustamante *et al.* (2017) argue that the Otú-Pericos fault is a pre-Jurassic structure and that it served as a preferential conduit for Jurassic intrusives east of the Central Cordillera. However, this fault in the Ibagué area corresponds to a band about 2 km wide where mylonites from the Ibagué Batholith (Jurassic) and tectonic lenses of Carboniferous sedimentary rocks are recognized. This is how this tectonic structure postdates the site of the Ibagué Batholith and could not serve as an area of weakness for the Jurassic intrusives.

The Huanca-Bamba Deflection demarcates two sectors with distinctive geological environments that separate the southern and northern margins of South America. The southern margin is demarcated by rocks of the Sunsas Formation which is cited as part of the Grenvillian metamorphic belt that originates from the diagonal collision of South America with Laurentia (ancestral North America). On the other hand, the northern sector was affected by the collision of Northern South America against the Baltic continent, which culminated around 900 Ma with the aggregation of the continent of Rodinia. During this phase, fragments of continental origin (partly Oaxaca, Mexico) are trapped by the collision between Amazonia and Baltica producing high-grade metamorphic rocks often included in the Grenville cycle but better defined in the Colombia-Oaxaca Orogeny. The Amazon Craton is exposed on the surface in two areas separated by the Amazon River valley: to the north in the Guyana shield and to the south in the Brazilian shield.

To the south of Ibagué, the Otú-Pericos fault joins the San Jerónimo fault system, isolating the Tahami block (Cajamarca) from other belts with Mesozoic metamorphism and similar history recognized in the Cordillera Real of Ecuador. To the south of this block there is often a band of metamorphic rocks attributed to the Cajamarca Complex and that extends along the Central Cordillera forming a continuous metamorphic band to Ecuador. Data obtained (fossils) in this project show that the rocks mapped as Cajamarca Complex (Ruíz and Marquínez, 2012), in the south of the Central Cordillera, really correspond to deformed sedimentites of Upper Cretaceous age (Figure 20). Due to its stratigraphic and tectonic history, the Tahami or Cajamarca block is an isolated terrane whose geological evolution, during the Paleozoic and Mesozoic (Triassic - Jurassic), suggests that it was formed further south of the area where it is currently located. The Cajamarca Terrane (Tahamí) could be related to the Tahuin-Amotape and Cordillera Real blocks in Ecuador and to segments of the Chiapas Massif in Mexico. The southernmost extension of this complex is located a few kilometers south of Ibagué. The apparent continuity of this metamorphic belt along the Central Cordillera is the product of a cartographic artifact. At the top of the Central Mountain Range, on the road to La Plata-Popayán, a series of Late Cretaceous deposits emerge that are mapped due to their deformation as the "Cajamarca Complex" (Figure 20).

The intricate mosaic of geological blocks from Mexico, Central America, and northern South America is analogous to that of a complex

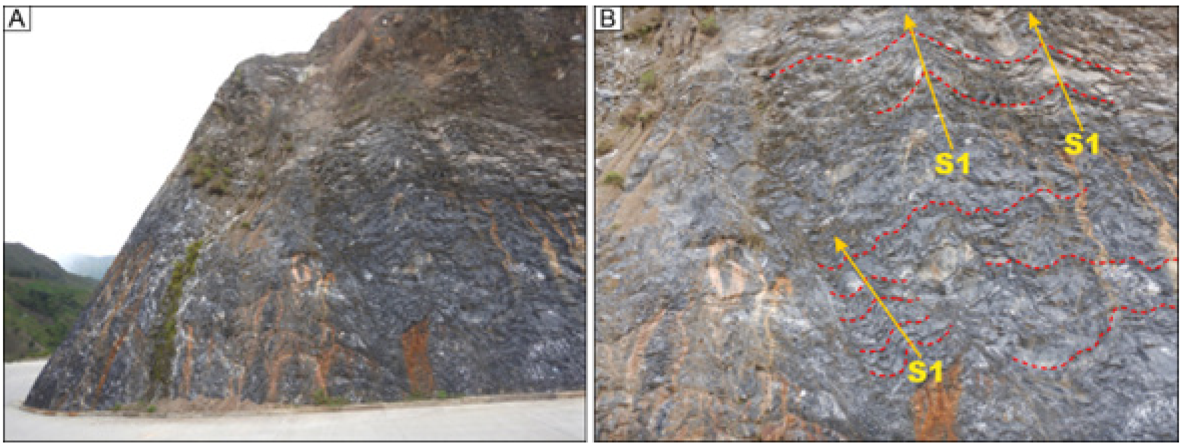

Figure 20. (a, b) Deformed sedimentary rocks of Upper Cretaceous age, with the development of foliation S1, near Inzá (Payandé block). These rocks have been erroneously mapped as the southern extension of the Cajamarca Complex (Permian-Triassic) at the top of the Cordillera Central./**Figura 20. (a, b)** *Rocas sedimentarias deformadas de edad Cretácico Superior, con desarrollo de foliación S1, cerca de Inzá (bloque Payandé). Estas rocas han sido mapeadas erróneamente como la extensión sur del Complejo Cajamarca (Pérmico-Triásico) en la cima de la Cordillera Central.*

Rubik's Cube system. The geographical overlap generated by linking America with Africa and Europe necessarily implies that many of these blocks have been displaced from their positions during the Paleozoic.

The presence of the clade of Asterolepis fishes in Colombia suggests connection between the Gondwana and Euramerica platforms during the Devonian. On the other hand, the asterolepis fish clade could have been adapted to environments of changing salinity (euryhaline) while the endemic genera cited for Colombia and Venezuela could suggest freshwater species that could not tolerate large fluctuations in salinity (stenohaline).

The resolution of these problems depends on understanding geological contexts whose sources (evidence) are multiple: paleontological, stratigraphic, geochemical, tectonic, geochronological, etc. However, the disciplinary fragmentation of geology has led authors, with very limited knowledge, to conceptually isolate themselves from topics that are beyond the scope of their disciplinary area. The arrival of Artificial Intelligence (AI) in the sciences could solve the problem of analyzing the huge amount of new data from different disciplines. It is necessary to create Scientific Big Data, with information from peer journals, which allows consulting, analyzing and interpreting geological evidence.

Modern geology provides a host of advanced techniques and new fields of research; however, field data are still essential to obtain the full context of the information provided by laboratories or specialized instruments. This problem is rightly referred to in the preface to the book by Coe *et al.* (2010):

"Without primary field data and geological samples of the highest quality, further scientific study such as sophisticated isotope measurements or the reconstruction of past life assemblages and habitats is at best without context, and at worst, completely meaningless".

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