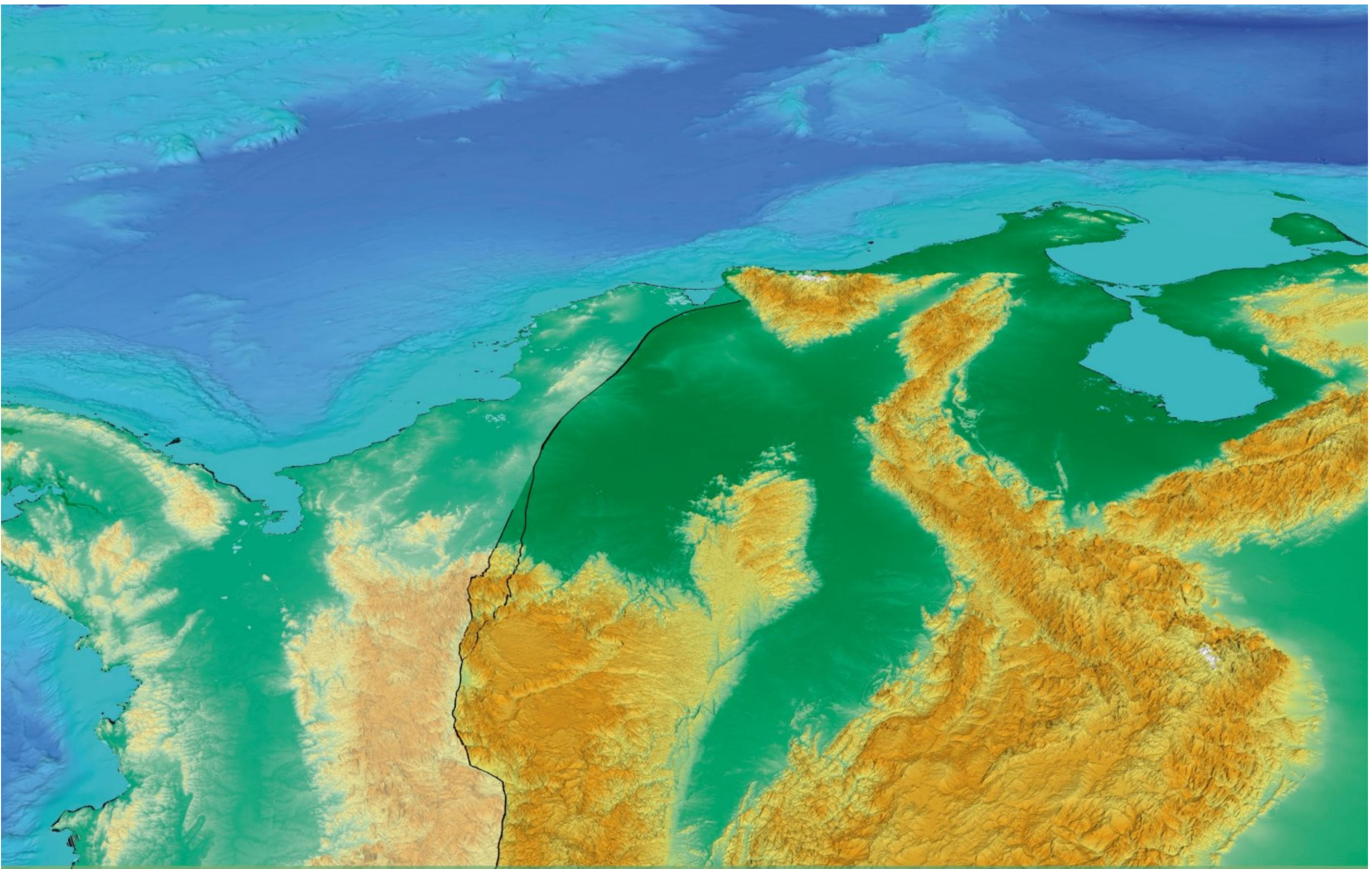

Evolution of sedimentary systems during the Late Cretaceous in the northwestern margin of South America

factors, processes and events that controlled sedimentary infilling of basins

Carlos A. Giraldo Villegas

PhD Thesis

Doctoral Programme in Earth Sciences

University of Granada

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Supervisors

Francisco Javier Rodríguez Tovar

Andrés Pardo Trujillo

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Evolución de los sistemas sedimentarios durante el Cretácico tardío en la margen noroccidental de Suramérica: factores, procesos y eventos que controlaron el relleno sedimentario de las cuencas

Thesis submitted by Carlos A. Giraldo-Villegas for the degree of Doctor in Earth Sciences by the University of Granada.

Carlos A. Giraldo-Villegas

This Doctoral Thesis has been supervised by PhD Francisco J. Rodríguez-Tovar, Professor of the Department of Stratigraphy and Palaeontology at the University of Granada (Spain), and PhD Andrés Pardo Trujillo, Professor of the Department of Geology at the University of Caldas (Colombia).

Francisco J. Rodríguez Tovar

Andrés Pardo Trujillo

Doctoral Programme in Earth Sciences

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Departamento de Estratigrafía y Paleontología

Ciencias

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Ichnology & Palaeoenvironment Research Group

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Ciencias

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A mamá y papá

A ti, compañera de vida

A ti, hermano

A todos aquellos que ven o crean barreras que impiden cumplir sus sueños. Sal de ahí de donde sea que estes, crea oportunidades, afuera el mundo te espera. Atte: un orgulloso campesino

Ramiro Giraldo, después de un productivo día de trabajo…orgullo puro!!!!

This thesis is a tribute to farmers around the world…and all those who, even when all the circumstances are aligned to achieve something, decide to take another path —perhaps the most difficult one at that moment— decide to break processes, to change their story. The opportunities will always be there, it is your responsibility to look for them and take advantage of them.

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them”

William Lawrence Bragg

To expect common sense from people proves you´re lacking it yourself.

Creer en el sentido común es la primera falta de sentido común

Eugene O'Neill

CONTENTS

EXTENDED ABSTRACT

The Cretaceous was a geological period in which several global events occurred synchronously, including the formation of Large Igneous Provinces (LIPs), Oceanic Anoxic Events (OAEs), eustatic changes, and finally the impact of an asteroid at the Cretaceous-Paleogene boundary. In the extreme NW of South America, two different geological domains developed during this period. A western domain of allochthonous origin, directly related to the evolution of the Caribbean Plate, which accreted at the margin of South America during the Late Cretaceous, and an autochthonous eastern domain associated with the South American Plate. The geological history of each domain and their subsequent interaction allowed the simultaneous establishment of two regional sedimentary basins during the Campanian-Maastrichtian, a forearc basin in the west and a backarc basin in the east, separated by a central volcanic arc formed by subduction between the Caribbean and South American plates. Both basins share a geological history during this period, preserving the record of the processes, factors and events that controlled the accumulation of sediments, associated with the collision of the Caribbean Plate.

During this period, the western forearc basin was relatively homogeneous in terms of sedimentary environments and types of deposits. It was characterized by the dominance of deep marine environments, accumulating from coarse-grained deposits associated with submarine canyons and basin-floors fan lobes, to fine-grained deposits related to abyssal plains, through turbiditic and suspended fall-out depositional processes, respectively. The bottoms of this basin were colonized by a relatively homogeneous tracemakers community, characterized by a low diversity and abundance, irregularly distributed within the basin, but without significant variations in relation to the deposits. This community is represented by several ichnotaxa, such as *Chondrites*, *Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Sphyrophyton*, *Thalassinoides* and *Zoophycos*, belonging to the *Zoophycos* ichnofacies. The main paleoenvironmental (i.e., depositional and ecological) parameters that controlled the establishment and development of this macrobenthic community were hydrodynamic energy and oxygenation.

In the eastern backarc basin, which was an epeiric basin throughout the Cretaceous, known as the La Luna epeiric sea during the Late Cretaceous, the sedimentary environments, types of deposits and depositional processes were highly variable in relation to the final stages of the marine basin filling. According to this variability, three sectors are distinguished in the basin: western, central and eastern, which behaved differently in terms of sedimentation at the same time. During the early Campanian, the western sector represented the most distal environments of the basin, where mainly fine-grained sediments accumulated by suspended fall-out in shelf environments. The central sector was dominated by the accumulation of sandy deposits by wave processes in shoreface environments. The eastern sector was characterized by fluvial and wave processes that accumulated coarse-grained deposits in fluvial-dominated delta-front environments. In the late Campanian, a major change is recorded in the central and eastern sectors of the basin. The western sector continued to represent the most distal environments of the basin, with suspension sedimentation in shelf environments, while the central and eastern sectors accumulated fine-grained deposits by suspended-fall-out and fluvial processes in offshore and fluvial-dominated prodelta environments, respectively. In the early Maastrichtian, the central and eastern sectors change again. Fine-grained sedimentation continues in the western sector, dominated by suspended fall-out and wave processes in shelf and offshore environments, while in the central and eastern sectors sandy deposits associated with wave and fluvial processes accumulate again in shoreface and fluvial-dominated deltaic front environments, respectively. At the end of the Maastrichtian, fluvial processes dominated in the three sectors, associated with different systems, such as fan delta complexes and anastomosed rivers in the west, mainly characterized by conglomeratic and sandy deposits, and lacustrine and deltaic systems in the central and eastern parts, mainly accumulating mudstones and coals.

Specifically, the conglomeratic deposits of the fan delta complexes in the west were formed by three adjacent sedimentary systems, such as distal alluvial fans, distributary fluvial channel systems and marine-influenced mouth bars. Debris flows and laminar flows characterized the distal alluvial fans, while fining-upward successions generated by traction processes represented the channel fills of the distributary fluvial systems. Deposits with coarsening-upward trends, with structures associated with oscillatory processes and bioturbation of marine origin, formed the marine-influenced mouth bars.

These changes in the sedimentary environments and depositional processes determined a variable response of the macrobenthic tracemaker communities that colonized the bottoms of this backarc basin, showing two important moments of colonization, one in the early Campanian and the other in the early Maastrichtian. In the early Campanian, only *Thalassinoides* are punctually recorded in the western sector, while in the central and eastern sectors macrobenthic tracemaker communities are established with higher and lower development, respectively. In the central sector an abundant and diverse macrobenthic community develops, represented by *Arenicolites*, *Arthrophycus*, *Asterosoma*, *Crossopodia*, *Cylindrichnus*, *Diplocraterion*, *Gordia*, *Helminthopsis*, *Laevicyclus*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos*, assigned to the *Cruziana* ichnofacies. The record from the eastern sector was comparatively less diverse and abundant, represented by *Ophiomorpha*, sometimes in monospecific association, *Rhizocorallium* and *Thalassinoides*, associated with the *Rosselia* ichnofacies. In the late Campanian, the seafloor of this basin presented unfavorable conditions for the colonization by macrobenthic tracemakers, as suggested by the absence of bioturbation. In the early Maastrichtian, the bottoms in all three sectors of the basin were again occupied by a diverse and abundant tracemaker community. In the western sector an assemblage composed of *Arenicolites*, *Asterosoma*, *Chondrites*, *Gyrochorte*, ?*Gyrolithes*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Schaubcylindrichnus*, *Scolicia*, *Skolithos*, *Spongeliomorpha*, *Taenidium*, *Teichichnus*, and *Thalassinoides* belonging to the *Cruziana* ichnofacies, suggest favorable paleoenvironmental conditions at the bottom. Favorable living parameters can also be interpreted for the central sector, with an assemblage composed of *Arenicolites*, *Arthrophycus*, *Asterosoma*, *Crossopodia*, *Cylindrichnus*, *Diplocraterion*, *Gordia*, *Helminthopsis*, *Laevicyclus*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos* also associated with the *Cruziana* ichnofacies. In the eastern sector, *Conichnus*, *Ophiomorpha*, *Palaeophycus,* *Planolites*, *Rhizocorallium*, *Skolithos*, *Taenidium*, *Teichichnus*, and *Thalassinoides* associated with the *Rosselia* ichnofacies represent the macrobenthic community activity on this side of the basin. In the late Maastrichtian, associated with the dominance of fluvial conditions, the bottoms were poorly colonized. The *Ophiomorpha* ichnofabrics identified in the fan delta complex deposits of the western sector suggest short episodes where marine conditions dominated over prevailing fluvial conditions. The main factors that controlled the establishment and development of tracemaker macrobenthic communities in this backarc basin during the Campanian-Maastrichtian were the energy associated with wave processes that continuously agitated the bottoms in the western and central sectors, the constant input of organic matter, salinity and turbidity in the eastern sector, and relative sea-level changes, possibly associated with channel avulsion or local tectonic phenomena.

The two basins, forearc to the west and backarc to the east, although coeval and separated by the same volcanic arc, developed stratigraphically in different ways in response to the variable influence of allogenic and autogenic controls. In the larger forearc basin, there was a more extensive redistribution of sediment, whereas the backarc basin, bounded at both sides by emerged input areas, received more sediment and had less space for its redistribution, resulting in the amalgamation of sediments and generating the wide variability of sedimentary environments and processes. This, together with a higher erosion rate on the eastern flank —directly connected to the backarc basin— compared to the western flank —directly connected to the forearc basin— of the volcanic arc associated with differential uplift, were important depositional factors in the filling of the basins. Bottom and alongshore currents, tides and upwelling phenomena were other processes that acted only in the eastern backarc basin.

RESUMEN EXTENDIDO

El Cretácico fue una época geológica en la que ocurrieron diversos eventos globales de manera sincrónica, entre los que destacan, el origen de Grandes Provincias Ígneas (*LIPs*), los Eventos Anóxicos Oceánicos (*OAEs*), cambios eustáticos, y finalmente el impacto del asteroide en el límite Cretácico-Paleógeno. En el extremo NW de Suramérica, dos dominios geológicos diferentes se desarrollaron durante esta época. Un dominio occidental con un origen alóctono, relacionado directamente con la evolución de la Placa Caribe, que se acrecentó en el margen de Suramérica durante el Cretácico Tardío, y un dominio oriental autóctono asociado con la Placa Suramericana. La historia geológica particular de cada dominio y posteriormente su interacción, permitió el establecimiento coetáneo de dos cuencas sedimentarias regionales durante el Campaniense-Maastrichtiense, una de antearco (*forearc*) al occidente y otra de retroarco (*backarc*) al oriente, separadas por un arco volcánico central, formado por la subducción entre las placas Caribe y Suramericana. Ambas cuencas comparten una historia geológica durante este periodo, preservando el registro de los procesos, factores y eventos, que controlaron la acumulación de sedimentos, asociados con la colisión de la Placa Caribe.

Para este periodo, la cuenca occidental de antearco fue relativamente homogénea en términos de ambientes sedimentarios y tipos de depósitos. Esta se caracterizó por el dominio de ambientes marinos profundos, acumulando desde depósitos de grano grueso asociados con cañones y abanicos submarinos, hasta depósitos de grano fino asociados con llanuras abisales, a través de procesos deposicionales turbidíticos y de suspensión, respectivamente. Los fondos de esta cuenca fueron colonizados por una comunidad de organismos generadores de trazas relativamente homogénea, caracterizada por presentar baja diversidad y abundancia, distribuida de manera irregular dentro de la misma, pero sin variaciones importantes en relación con los depósitos. Esta comunidad estuvo representada por organismos generadores de *Chondrites*, *Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Sphyrophyton*, *Thalassinoides* y *Zoophycos*, pertenecientes a la icnofacies de *Zoophycos*. Los principales parámetros paleoambientales (i.e., deposicionales y ecológicos) que controlaron el establecimiento y desarrollo de estas comunidades macrobentónicas fueron la energía hidrodinámica y la oxigenación.

En la cuenca oriental de retroarco, la cual fue una cuenca epírica durante todo el Cretácico, conocido como mar epírico La Luna durante el Cretácico tardío, los ambientes sedimentarios, tipos de depósitos y procesos deposicionales fueron altamente variables, en relación con las etapas finales de relleno de la cuenca marina. De acuerdo con esta variabilidad, se diferencian tres sectores en la cuenca: occidental, central y oriental, los cuales, en términos de sedimentación, se comportaron coetáneamente de manera diferente. En el Campaniense temprano, el sector occidental representó los ambientes más distales de la cuenca, donde se acumularon principalmente sedimentos de grano fino por suspensión en ambientes de plataforma. En el sector central dominó la acumulación de depósitos arenosos a través de procesos de oleaje en ambientes de *shoreface*. El sector oriental estuvo caracterizado por procesos fluviales y de oleaje que acumularon depósitos de grano grueso en ambientes de frente de delta fluvio-dominados. En el Campaniense tardío se registra un cambio importante en los sectores central y oriental de la cuenca. El sector occidental continuó representando los ambientes más distales de la cuenca, con sedimentación por suspensión en un ambiente de plataforma, mientras que en los sectores central y oriental se acumularon depósitos de grano fino por procesos de suspensión y fluviales, en ambientes de *offshore* y prodelta fluvio-dominado, respectivamente. En el Maastrichtiense temprano los sectores central y oriental vuelven a cambiar. Continúa la sedimentación fina en el sector occidental, dominada por procesos de suspensión y oleaje en ambientes de plataforma y *offshore*, mientras que en los sectores central y oriental se acumulan nuevamente depósitos arenosos asociados a procesos de oleaje y fluviales en ambientes de *shoreface* y frente deltaico fluvio-dominado, respectivamente. A finales del Maastrichtiense, los procesos fluviales dominaron en los tres sectores, asociados a diferentes sistemas, como complejos de abanico deltaico (*fan delta complex*) y ríos anastomosados al occidente, caracterizados principalmente por depósitos conglomeráticos y arenosos, y sistemas lacustres y deltaicos en la parte central y oriental, los cuales acumularon principalmente lodolitas y carbones.

De manera específica, los depósitos conglomeráticos de los complejos de abanico deltaico en el occidente estaban formados por tres sistemas sedimentarios adyacentes, como fueron abanicos aluviales distales, sistemas de canales fluviales distributarios y barras de desembocaduras con influencia marina. Los flujos de escombros y flujos laminares caracterizaron los abanicos aluviales distales, mientras que sucesiones granodecrecientes generadas por procesos de tracción, representaron los rellenos de canales de los sistemas fluviales distributarios. Depósitos con tendencias granocrecientes, con estructuras asociadas a procesos de oscilación y con bioturbación de origen marino, conformaron las barras de desembocadura con influencia marina.

Estos cambios en los ambientes sedimentarios y procesos deposicionales determinaron una respuesta variable de las comunidades macrobentónicas bioturbadoras que colonizaron los fondos de esta cuenca de retroarco, mostrando dos momentos importantes de colonización, uno en el Campaniense temprano y otro en el Maastrichtiense temprano. En el Campaniense temprano, el sector occidental sólo registra puntualmente *Thalassinoides*, mientras en los sectores central y oriental se establecen comunidades macrobentónicas generadoras de trazas con mayor y menor desarrollo, respectivamente. En el sector central se desarrolla una abundante y diversa comunidad macrobentónica, representada por *Arenicolites*, *Arthrophycus*, *Asterosoma*, *Crossopodia*, *Cylindrichnus*, *Diplocraterion*, *Gordia*, *Helminthopsis*, *Laevicyclus*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* y *Zoophycos*, asignada a la icnofacies de *Cruziana*. El registro del sector oriental fue comparativamente poco diverso y abundante, representado por *Ophiomorpha*, en ocasiones en asociación monoespecífica, *Rhizocorallium* y *Thalassinoides*, asociados a la icnofacies de *Rosselia*. En el resto del Campaniense, los fondos marinos de esta cuenca presentaron condiciones desfavorables para la colonización de los organismos macrobentónicos bioturbadores, tal y como lo sugiere la usencia de bioturbación. En el Maastrichtiense temprano, los fondos son nuevamente habitados por una diversa y abundante comunidad generadora de trazas, en esta ocasión en los tres sectores de la cuenca. En el sector occidental una asociación compuesta por *Arenicolites*, *Asterosoma*, *Chondrites*, *Gyrochorte*, ?*Gyrolithes*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Schaubcylindrichnus*, *Scolicia*, *Skolithos*, *Spongeliomorpha*, *Taenidium*, *Teichichnus*, y *Thalassinoides* pertenecientes a la icnofacies de *Cruziana*, sugiere condiciones paleoambientales favorables en el fondo. Buenas condiciones de vida pueden también interpretarse para el sector central, con una asociación compuesta por *Arenicolites*, *Arthrophycus*, *Asterosoma*, *Crossopodia*, *Cylindrichnus*, *Diplocraterion*, *Gordia*, *Helminthopsis*, *Laevicyclus*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* y *Zoophycos* asociada también a la icnofacies de *Cruziana*. En el sector oriental, trazas de *Conichnus*, *Ophiomorpha*, *Palaeophycus, Planolites*, *Rhizocorallium*, *Skolithos*, *Taenidium*, *Teichichnus*, y *Thalassinoides* asignadas a la icnofacies de *Rosselia* representan la actividad de la comunidad macrobentónica en este lado de la cuenca. En el Maastrichtiense tardío, asociado al dominio de condiciones fluviales, los fondos fueron poco colonizados. Icnofábricas de *Ophiomorpha* identificadas en los depósitos de los complejos de abanico deltaico del sector occidental sugieren episodios cortos donde predominaron las condiciones marinas sobre las condiciones fluviales preponderantes. Los principales factores que controlaron el establecimiento y desarrollo de las comunidades macrobentónicas generadoras de trazas en esta cuenca de retroarco durante el Campaniense-Maastrichtiense fueron la energía asociada a los procesos de oleaje, que agitaban continuamente los fondos en los sectores occidental y central, el constante aporte de materia orgánica, la salinidad y la turbidez en el sector oriental, y cambios relativos del nivel del mar, posiblemente relacionados con la avulsión de canales o con fenómenos tectónicos locales.

Ambas cuencas, de antearco al occidente y de retroarco al oriente, aunque coetáneas y separadas por el mismo arco volcánico, evolucionaron estratigráficamente de manera diferente, en respuesta a la influencia variable de controles alogénicos y autogénicos. En la cuenca de antearco, de mayor tamaño, se produjo una redistribución más extensa del sedimento, mientras la cuenca de retroarco, limitada a ambos bordes por áreas de aporte emergidas, recibía mayor cantidad de sedimento y tenía menor espacio para su redistribución, dando lugar a la amalgamación de sedimentos y generando la amplia variabilidad de ambientes y procesos sedimentarios. Esto, acompañado de una mayor tasa de erosión en el flanco oriental —conectado directamente con la cuenca de retroarco— comparado con el flanco occidental —conectado directamente a la cuenca de antearco— del arco volcánico asociado a levantamientos diferenciales, fueron factores deposicionales importantes en el relleno de las cuencas. Corrientes de fondo, así como a lo largo de la costa, mareas y fenómenos de surgencia fueron otros procesos que actuaron únicamente en la cuenca oriental de retroarco.

THESIS SCOPE

1. RESEARCH MOTIVATION AND HYPOTHESIS

Two distinct geological domains formed the NW margin of South America during the Late Cretaceous. A western domain dominated by compressional tectonics in a forearc basin setting, directly related to the origin, evolution and collision of the Caribbean Plate, and an eastern domain with extensional tectonics in a backarc basin setting associated with the evolution of the South American Plate (Fig. 1). The interaction of diverse geological processes, factors and/or events linked to each of the domains and/or their interplay, as well as to other processes associated with global geologic evolution (e.g., eustasy, climate, oceanographic phenomena), determined, in a variable range, the stratigraphic filling of these sedimentary basins.

The complex tectonic-collisional geological history of the western forearc domain, along with the lack of high-resolution cartographic and biostratigraphic studies, has significantly limited the knowledge of the Cretaceous sedimentary deposits of this area. Currently, the sedimentary records of the Albian-Coniacian and Campanian-Maastrichtian periods are known, the oldest being associated with the basement of the Caribbean Plate and the youngest with the sedimentary cover associated with the forearc context. In contrast, the extensional nature of the eastern backarc domain allows for a relatively continuous record of Cretaceous sedimentation. Therefore, both domains share Albian-Coniacian and Campanian-Maastrichtian sedimentation histories, with the Campanian-Maastrichtian period, —when the Caribbean Plate collided with the northern margin of South America— being of particular importance.

At present, a discontinuous record of Campanian-Maastrichtian sedimentary rocks of the forearc western domain, directly related to the Caribbean Plate, is partially preserved in Colombia, Ecuador, Panama, Costa Rica and the Lesser Antilles. In Colombia, they are recorded in both the current Caribbean and Pacific regions. These deposits include rocks of the Cansona Formation in the Caribbean region, which crop out in the Sinú-San Jacinto Basin (SSJB), and rocks of the Espinal, Cisneros, Penderisco, and Nogales formations in the Pacific region, cropping out to the west of the Romeral Fault System-RFS, along the western flank of the Central Cordillera and the Western Cordillera. In the eastern backarc domain, directly associated with the South American Plate, the Campanian-Maastrichtian sedimentary record is also preserved in Colombia and Ecuador. In Colombia, it is represented by rocks in the present-day Eastern Cordillera, Upper and Middle Magdalena Valley, Cesar-Rancheria, Catatumbo, Caguán-Putumayo and Eastern Llanos basins, including the La Luna, La Renta/Umir, Cimarrona, La Tabla, Guaduas, and Lisama formations, and the Guadalupe and Olini groups.

Outcrop features, such as dense vegetation, restricted road access, intense deformation, and structural complexity, have severely limited the geological knowledge of the Campanian-Maastrichtian deposits in the Colombian western forearc domain. In contrast, the Campanian-Maastrichtian sedimentary rocks of the Colombian eastern backarc domain are well studied, driven by their relevance for the hydrocarbon industry. In both cases, however, detailed knowledge of the sedimentary parameters (physical and paleoecological) that controlled the accumulation, the depositional environments, their spatiotemporal variations and evolution, and the correlation with large-scale regional factors or events that influenced their origin and evolution remains scarce.

Sedimentology and ichnology have proven to be complementary tools in the detailed study of sedimentary basins. Traditionally, sedimentology has been a key to understanding the physical processes that generate specific types of deposits. Ichnology —a discipline that has seen significant growth in recent decades— provides valuable insights into the physicochemical conditions that prevailed during sedimentation by documenting the response of tracemakers to paleoenvironmental parameters. These conditions are reflected in the ichnological record through several features, including abundance, diversity, size and type of trace fossils, among others. The integration of sedimentological and ichnological analyses, together with other paleontological evidence (e.g., micro and macrofossils), in the study of sedimentary environments is highly successful, enabling comprehensive conclusions regarding the physical and ecological processes during deposition.

The Campanian-Maastrichtian deposits of the eastern backarc domain are important hydrocarbon reservoirs in the region. However, in response to global decarbonization policies, local authorities have initiated the exploration of alternative energy sources. Consequently, a detailed understanding of the sedimentary environments, their spatiotemporal evolution, and their heterogeneity is essential to identify reservoir deposits suitable for the development of new energy sources and/or carbon dioxide storage.

The motivation behind this thesis is therefore the integration of sedimentological and ichnological analysis to advance in the knowledge of the spatiotemporal evolution of sedimentary systems during the Late Cretaceous (Campanian-Maastrichtian) in the northwestern margin of South America, attending to scientific and economic interest. Thus, this thesis seeks to solve several research questions.

2. RESEARCH QUESTIONS AND HYPOTHESES

Research question 1. How did the sedimentary environments in the western/forearc and eastern/backarc domains/basins evolve spatiotemporally during the Campanian-

Maastrichtian, and what were the processes that controlled the accumulation of sedimentary deposits?

Research hypothesis: The sedimentary basins of both domains had an individual evolution, according to their tectonic context, sediment availability, sedimentary processes and settings, and dominant paleoenvironmental (physical and ecological) parameters.

Null hypothesis: Sedimentary deposits were the same in both the forearc and backarc basins, regardless of their connection to adjacent oceans, and their associated physical and ecological parameters, and the general geodynamic context, or they are in the same depositional profile as a response to a unique sedimentary basin.

Research question 2. How is the Caribbean Large Igneous Province (CLIP) collision recorded in the sedimentary deposits and depositional environments of these basins: western/forearc and eastern/backarc?

Research hypothesis: Vertical and spatial evolution of sedimentary deposits and depositional environments reflect the collision of the Caribbean Plate with the South American margin.

Null hypothesis: The Caribbean Plate collision had no tectonic effect on the South American margin and its associated marine sedimentary basins. Therefore, there is no evidence of this event in the sedimentary record. Alternatively, there was no collision, and the oceanic affinity rocks represent the lateral extension of a passive margin.

Research question 3. What caused the filling of the marine basins in the eastern domain, global sea-level fall or tectonic events associated with the CLIP collision, or both?

Research hypothesis: The combination of mainly regional geological events (e.g., tectonic uplift) and to a lesser extent global factors (e.g., eustasy) caused the filling of the marine basins in the eastern domain.

Null hypothesis: Sedimentation in this basin was mainly controlled by global eustatic changes, the filling of the marine basin being associated with the global sea-level fall during the Late Cretaceous.

Consequently, this thesis pursued major and specific objectives.

3. OBJECTIVES

The main objective of this thesis is to understand the spatiotemporal evolution of the depositional environments in the western/forearc and eastern/backarc geological domains/basins of the northwestern margin of South America during the latest Cretaceous, and to identify the main depositional parameters (allogenic and/or autogenic) that controlled the stratigraphic filling of the sedimentary basins, in relation to the Caribbean Plate collision.

This research has been conducted through an integrative and detailed analysis of the sedimentology, ichnology, and stratigraphy, combined with updated biostratigraphic (micro- and macro-paleontological) revisions of the sedimentary deposits. To address the main objective of this thesis, the following specific objectives were pursued:

1- Recognition of the depositional and ecological parameters involved in the accumulation of deposits, based on an integrative sedimentological and ichnological (ichnofacies and ichnofabrics) analysis.

2- Comprehensive interpretation of the sedimentary systems, their variation, and their spatiotemporal evolution in each of the studied areas.

3- Characterization of the response of the macrobenthic tracemaker community to changes in environmental (depositional and ecological) parameters and processes.

4- Recognition of influence of allogenic and autogenic depositional controls in the stratigraphic evolution of the basins.

5- Establishment of a detailed regional paleogeographic model to interpret the dominant depositional processes in each of the studied areas, based on the comparison/correlation between the obtained results and the integration of the existing information.

4. LAYOUT

The results obtained in the pursuit of these specific objectives have already been published in scientific journals with a high-impact factor. Thus, three scientific papers are organized in separate chapters in the results (Part II) after the introductory aspects (Part I), and before the discussion (Part III) and conclusions (Part IV). Accordingly, the present PhD thesis is organized as follows:

Part I: Introduction, geological framework and material and methods

Chapter 1. *Introduction*, which includes all aspects related to the motivation of the study, the geological characteristics of the research area, the state of knowledge related to the Colombian Cretaceous sedimentary basins., and a global geological scenario of the Late Cretaceous.

Chapter 2. *Geological framework* provides a general tectonic setting of the NW margin of South America, Colombia, and a local tectono-stratigraphic scenario of the studied areas.

Chapter 3. *Material and methods* describe in detail the materials and procedures used during the development of this thesis.

Part II: Results

Chapters 4, 5 and 6 correspond to the results obtained in both the western forearc (chapter 4) and the eastern backarc (chapters 5 and 6) domains (Fig. 1).

Chapter 4: *Western forearc geological domain: paleoenvironments and depositional controls*. This research focuses on the depositional and ecological factors dominant during sedimentation at the western forearc basin during the Campanian-Maastrichtian, providing new constraints on the sedimentary environments over the Caribbean Plate. In addition, a stratigraphic correlation was conducted for the rocks of the western domain of Colombia, through the integration of biostratigraphic information, providing for a better understanding about the distribution of sedimentary facies and depositional settings on a regional scale.

Chapter 5: *Eastern backarc geological domain: paleoenvironments and depositional controls*. The spatiotemporal history of the sedimentary environments of the eastern backarc domain is presented. An integrative sedimentological and ichnological analysis, together with a detailed and updated chronostratigraphic framework, is conducted from a comprehensive view of the evolution of depositional environments. Complementary regional paleogeographic work provides insight into the depositional parameters controlling sedimentation during the Campanian-Maastrichtian period. The coeval role of both allogenic and autogenic factors, and the importance of the geomorphological characteristics of the emerged areas and the land-ocean sediment transport systems on the resulting distribution of sedimentary deposits, and the macrobenthic tracemaker communities within the marine basin are approached.

Chapter 6: *Eastern backarc geological domain:* Ophiomorpha *ichnofabric in fan-delta complex depositional settings.* A detailed sedimentological and ichnological analysis is conducted on the deposits that mark the uplift generated in the central volcanic arc (proto-Cordillera Central) by the collision of the Caribbean Plate with the NW margin of South America during the Late Cretaceous-Maastrichtiano. Focusing on the *Ophiomorpha* ichnofabric record, the research provides valuable insights into depositional and ecological parameters affecting the tracemaker community during the evolution of fan-delta complexes. Moreover, this study shows one of the few records of bioturbation in fan-delta complex settings in the past, a challenging environment for the generation and subsequent preservation of the ichnological record. The *Ophiomorpha* ichnofabric helps to unequivocally identify the marine influence in the basin, enabling differentiation of each component of a fan delta complex and interpretation of several variable-range marine incursions in the sedimentary system. In addition, colonization strategies of the *Ophiomorpha*-producers and their relationships with the substrate features are discussed.

Part III: Integration and discussion

Chapter 7. *Tracking the evolution and dynamics of depositional parameters and sedimentary environments linked to the Caribbean Plate collision*. Here, the depositional parameters and controls of both forearc and backarc domains are integrated, compared and discussed to determine the similarities and differences between the deposits, their accumulation history, and their spatiotemporal evolution.

Part IV: Final remarks, conclusions and forthcoming research

Chapter 8. *Conclusions and forthcoming research*, provides an integrated and comprehensive synthesis of the main results and findings of the thesis, and offers an outline of future research questions and methodologies to be addressed to deepen the knowledge of the Late Cretaceous on the NW margin of South America.

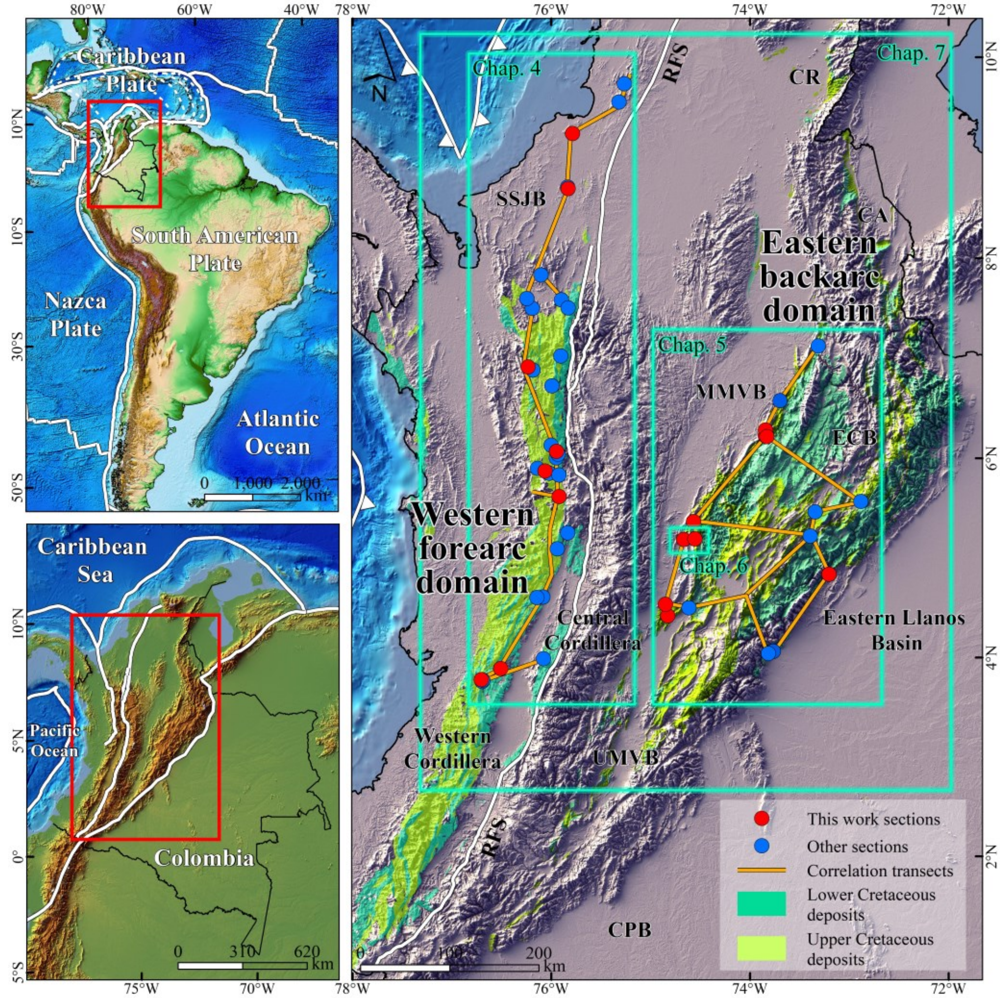
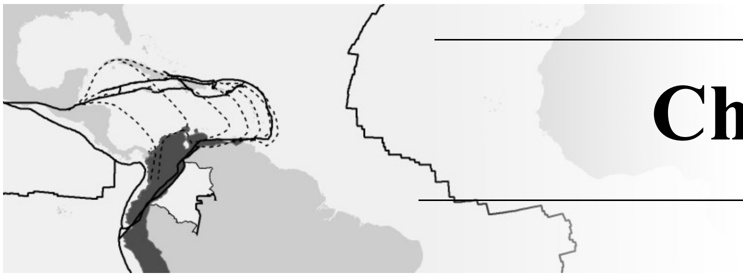


Figure 1. Location map showing Colombia in South America, and the focus of each of the results and discussion chapters (Chap. 4 – 7). CA: Catatumbo Basin, CR: Cesar-Ranchería Basin, CPB: Caguán-Putumayo Basin, ECB: Eastern Cordillera Basin, MMVB: Middle Magdalena Valley Basin, RFS: Romeral Fault System, SSJB: Sinú-San Jacinto Basin; UMVB: Upper Magdalena Valley Basin.

Part I: INTRODUCTION, GEOLOGICAL FRAMEWORK AND MATERIALS AND METHODS



Chapter 1

INTRODUCTION

What follows is a brief introduction to each of the themes covered in this research, highlighting some of the relevant elements within each. The themes or topics are developed in more detail in the introductory sections of each of the chapters that make up the findings as such.

1.1 Subduction zones and sedimentary systems: forearc and backarc basins and their depositional controls

Subduction zones formed by the interaction between continental and oceanic plates configure, in a general way, two sedimentary regions: forearc and backarc, and according to the position with respect to the volcanic arc (Fig. 1.1; Karig, 1971; Busby and Ingersoll, 1995; Balázs et al., 2022). Forearc basins are developed between the trench and the magmatic arc and shaped by the accretionary wedge dynamic, sediment influx and eustatic sea level. Backarc basins formed by extensional processes behind the arc on the overriding plate, are associated with the relationship between subduction and convergence velocities (Balázs et al., 2022; Artemieva et al., 2023).

The stratigraphic fill and sedimentary architecture of these basins depends on the relationship between the accommodation space and the sediment input (Schlager, 1993; Balász et al., 2016). In addition, forearc sedimentation is almost always associated with arc-related volcanism and plutonism, and subduction-related deformation and metamorphism (Busby and Ingersoll, 1995; Dickinson, 1995). The thickness of the deposits in forearc and backarc basins varies widely, being greater in basins associated with a continental margin and lesser in those associated with an island arc, reflecting more voluminous source sediments along continental margins. However, these thicknesses are the result of subsidence, which is mainly dominated by sedimentary and volcanic loading in the forearc basins, whereas in the backarc basins it is controlled by this loading and by crustal thinning, resulting in greater thicknesses in these backarc basins (Busby and Ingersoll, 1995).

The composition of the basement in modern forearc basins is often difficult to discern because it is buried under thick sedimentary deposits. However, well-preserved records from ancient basins suggest that their basement typically consists of rocks formed in marine settings, such as ophiolitic sequences and overthickened oceanic crusts (Busby and Ingersoll, 1995).

The backarc basins are produced by crustal extension through normal faults when the subduction rate is higher than the convergence velocity (Karig, 1971; Artemieva et al., 2023). They can be created on oceanic, continental and transitional crust. The first rift phase related to the basin formation result in extremely high subsidence rates (e.g., over 1 km/My in Miocene basins in northern Japan) (Busby and Ingersoll, 1995). The extensional processes can generate horst and graben structures, dividing the backarc basin into sub-basins by normal-fault bounded blocks or basement highs. Because they are associated with subduction zones, they are also directly influenced by the magmatic and volcanic activity of the arc. Other significant processes affecting backarc sedimentation include ocean currents, latitudinal controls on biogenic productivity and deposition, and input from land-ocean sedimentary systems (Busby and Ingersoll, 1995). The intra-basin uplift blocks and/or horst-graben structures associated with its origin have an important influence on sediment transport and dispersion, as well as depocenter distribution within the backarc basin (Taylor et al., 1991; Klauss et al., 1992).

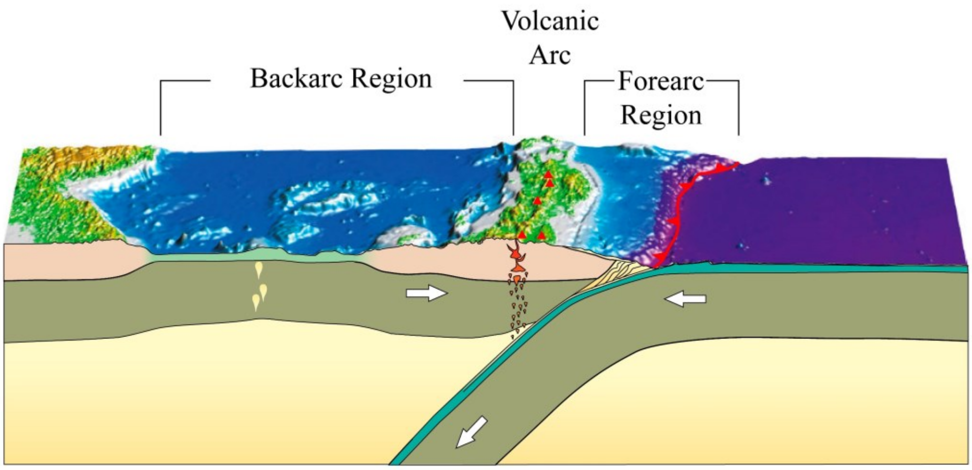


Figure 1.1. Oversimplified representation of types of sedimentary regions (i.e., backarc, forearc) in subduction zones between continental and oceanic plates (modified from Frisch et al., 2011).

As in all sedimentary basins, the filling of these backarc and forearc basins is controlled by the balance between the accommodation space and the sediment supply (Catuneanu, 2022). In general, when the sediment input is greater than the accommodation space, the stacking patterns in the basin are progradational; conversely, when the accommodation space is greater, the patterns are retrogradational; and when they are equal, the patterns are aggradational (Catuneanu, 2017). These two key controls are the answer to the interplay between allogenic and autogenic factors that can act either separately or together. The external or allogenic factors include subsidence, eustasy, and climate, while channel avulsion, delta lobe switching, relocation of alluvial channel belts and submarine fans are the main internal or autogenic depositional controls (Catuneanu, 2022). Other autogenic factors, perhaps less well known, are those associated with the internal transport mechanisms of the basin, such as bottom and alongshore currents, and productivity. These internal factors can in turn be influenced by external parameters such as latitudinal position and climate, reflecting the close relationship between the two (autogenic and allogenic) depositional controls and the complexity of distinguishing their relative influence.

1.2 Ichnology in sedimentary basin research

Ichnology is the study of the traces produced by organisms (both animals and plants) in response to changes in the physical and ecological factors of the environments in which they live (Buatois and Mángano, 2011). Perhaps known in a formal and/or specialized way since the 1960's as a tool in the fields of sedimentology and paleontology, ichnology is continuously growing, expanding its contribution in various disciplines of sedimentary geology (Fig. 1.2). Since the first works by Seilacher in the 1960s, the scientific world has become aware of the potential of the study of trace fossils in the field of sedimentary rocks. This progress has led to the implementation of new methodologies and novel study approaches, positioning ichnology as a fundamental tool in detailed basin sedimentary research, including interpretation of sedimentary environments, sequence stratigraphy, and paleoenvironmental analysis, among others (Mcllroy, 2004; Buatois and Mángano, 2011; Knaust and Bromley, 2012).

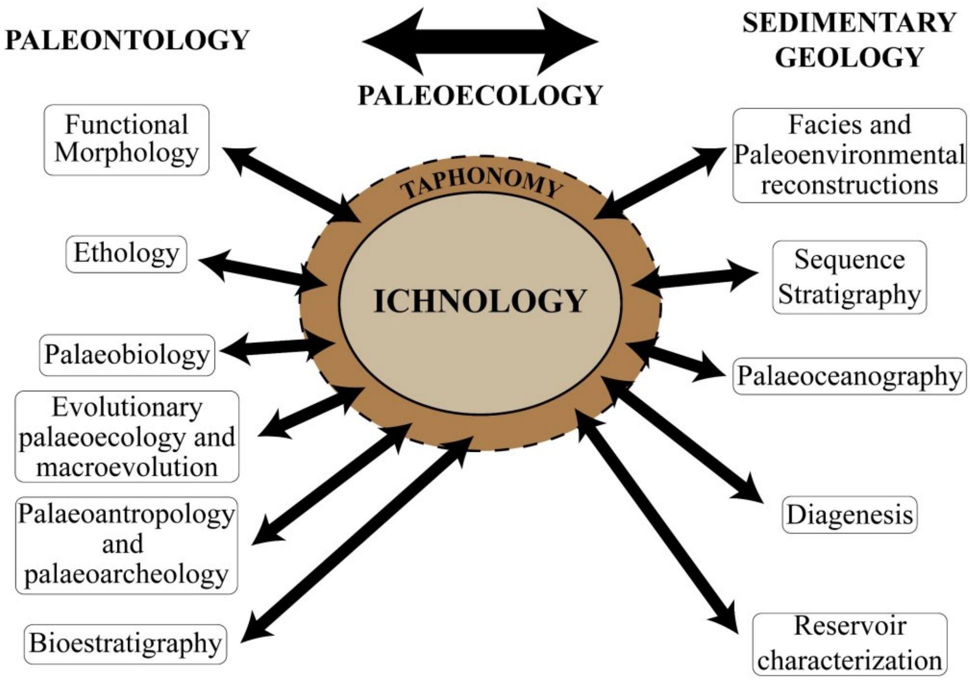


Figure 1.2. Ichnology and its multidisciplinary role in paleontology and sedimentary geology (modified from Mángano and Buatois, 2012; Rodríguez-Tovar and Hernández-Molina, 2018).

One of the disciplines where ichnological analysis proves to be a key tool is in facies analysis and interpretation of depositional environments, mainly by the application of two major paradigms such as the ichnofacies model and the ichnofabrics approach.

The ichnofacies model is conceptually based on the recognition of ichnoassemblages generated under specific environmental conditions and distributed in different time periods (Seilacher, 1964; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011). The ichnofacies model distinguishes between softground marine, substrate-controlled, and continental ichnofacies. The softground marine ichnofacies, as those addressed in this work, correspond to marine-influenced and -dominated ichnofacies: *Psilonichnus*, *Skolithos*, and *Cruziana*, commonly related to coastal and shallow marine environments, and *Zoophycos* and *Nereites* ichnofacies, usually linked to deep marine sedimentary systems (Fig. 1.3; Seilacher, 1964, 1967; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011). However, it is important to emphasize that the ichnofacies are not paleobathymeters, but respond to a set of paleoenvironmental parameters that may or may not be related to depth variations of the marine environments (Frey et al., 1990). Recently, the *Rosselia* and *Phycosiphon* ichnofacies, associated with delta front and prodelta environments, and the *Taenidium* ichnofacies, associated with estuarine environments, have been defined (Fig. 1.3; MacEachern and Bann, 2020, 2023; Gingras et al., 2024).

The ichnofabric approach includes all aspects related to rock texture resulting from bioturbation or bioerosion at any scale, including features such as bioturbation index, ichnodiversity, tiering, cross-cutting relationships, and primary sedimentary structures (Fig. 1.4; Ekdale and Bromley, 1983; Ekdale et al., 2012). The ichnofabrics are either simple, resulting from the activity of a single endobenthic community at a given moment, and therefore the product of a single bioturbation or bioerosion event, or composite, produced by the replacement of successive communities or by the upward migration of a tiered community and then associated with suites of ichnotaxa.

Both paradigms are widely used in facies analysis and the interpretation of sedimentary environments. However, the ichnofacies model is generally applied in depositional settings where paleoenvironmental parameters tend to be relatively stable over the long term, allowing for the establishment of a homogeneous macrobenthic community according to the prevailing conditions (MacEachern et al. 2007, 2012). In highly variable environments (e.g., coasts, deltas), where depositional conditions (physical and ecological) may exhibit strong and fast temporal and spatial changes, the standard (Seilacherian) ichnofacies model does not apply very well, leading in some cases to the definition of ichnofacies exclusive to these sedimentary environments (e.g., MacEachern and Bann, 2020, 2023; Gingras et al., 2024). So, in these cases it is advisable to use the ichnofabric approach, which provides a detailed understanding of the particular paleoenvironmental conditions and their variations (Celis, 2024).

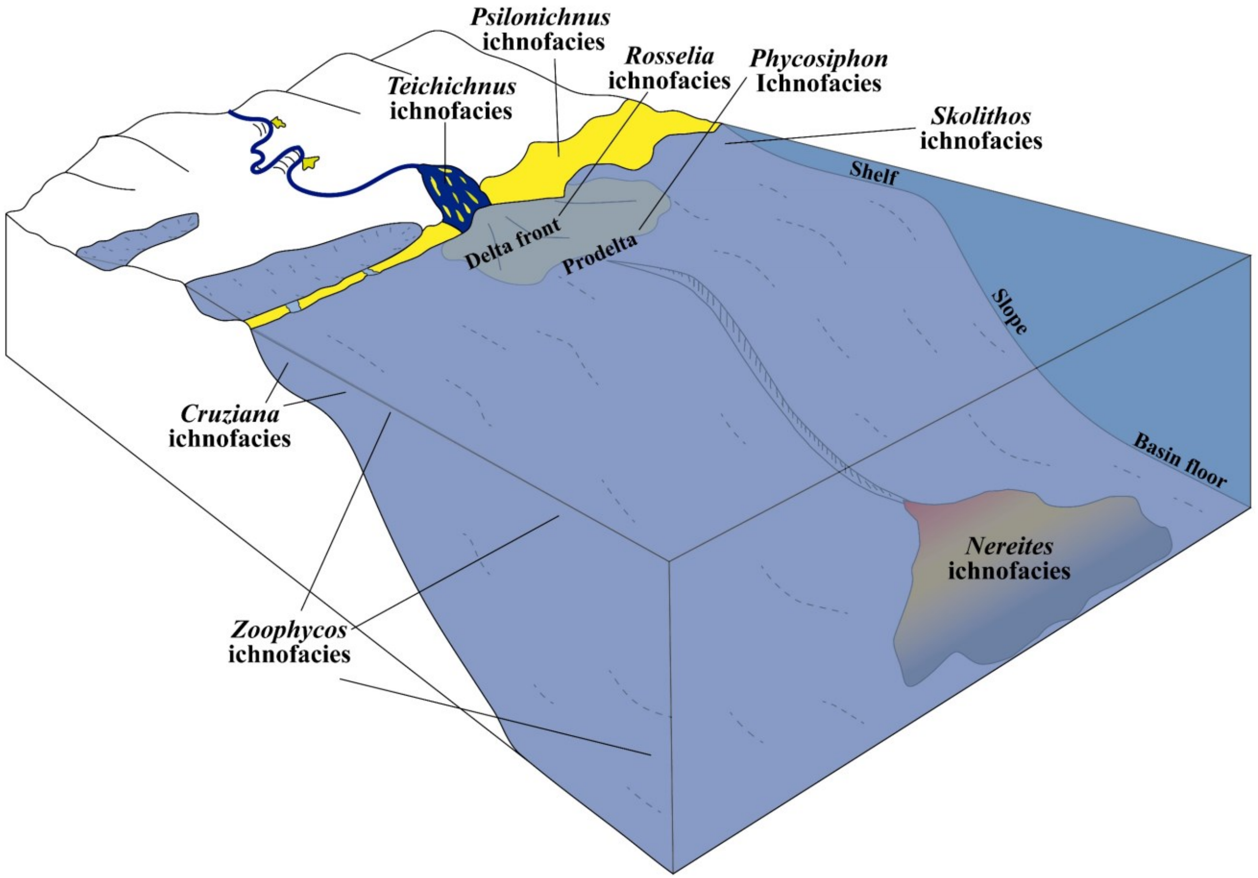


Figure 1.3. Schematic paleoenvironmental diagram and the softground marine, delta and estuarine ichnofacies and its associated depositional environments (taken and modified from Bromley, 1996; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011; MacEachern and Bann, 2020; Gingras et al., 2024).

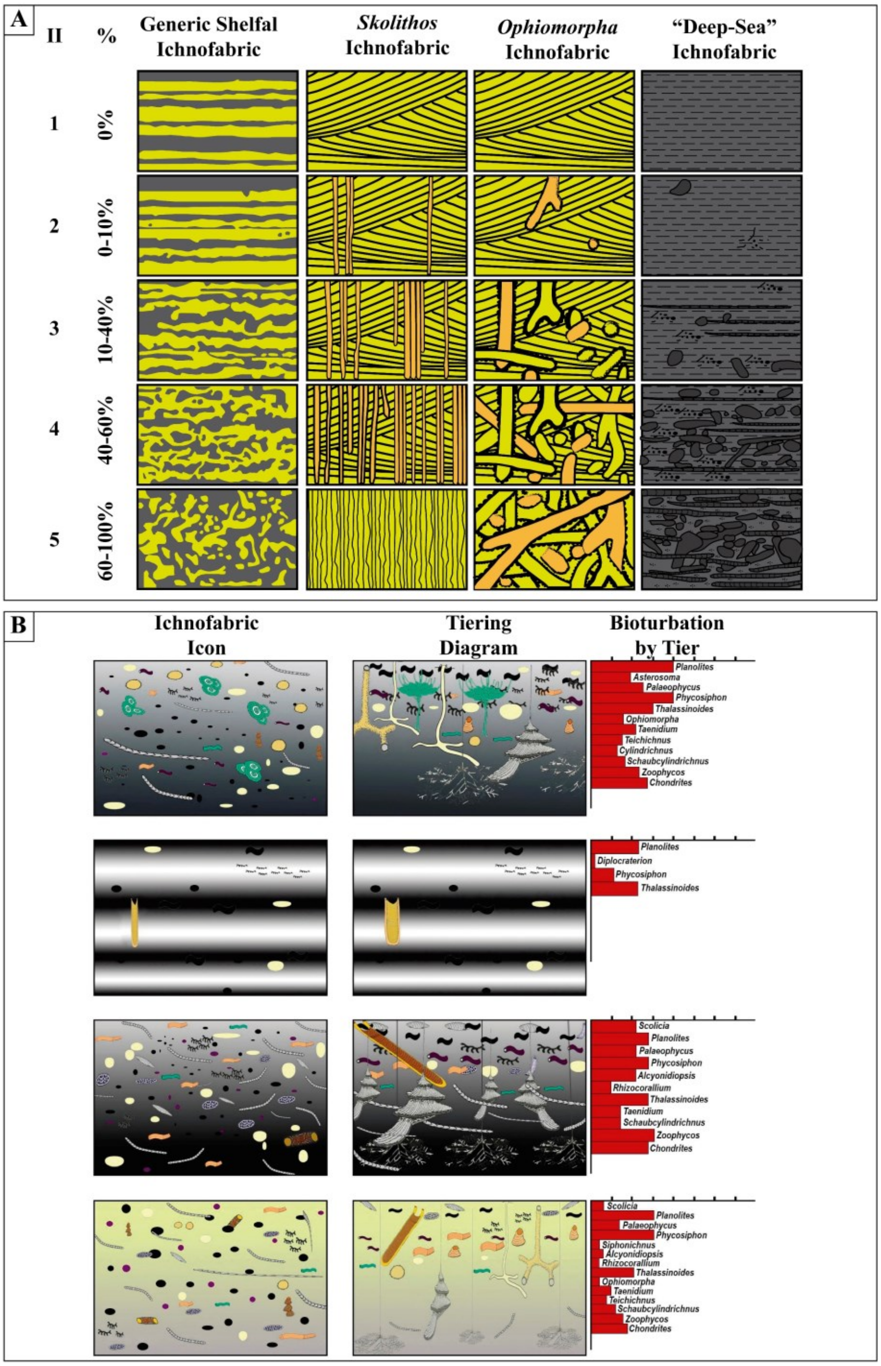


Figure 1.4. A. Schematic diagrams for ichnofabric index 1 to 5 of Droser and Bottjer (1989), dominated by *Skolithos*, *Ophiomorpha* and deep sea ichnofabrics (taken and modified from Mcllroy, 2004). **B.** Representation of ichnofabrics from Bromley (1996), based on illustration of the ichnofabric icon, tiering diagram and percentage of bioturbation per tier (from Giraldo-Villegas et al., 2016, modified from Bromley, 1996).

1.3 Campanian-Maastrichtian geological context: global and regional scales

The Late Cretaceous was an important period in the geological history of the Earth. Globally distributed events such as the Oceanic Anoxic Events (OAEs), climatic variability (greenhouse-icehouse) and the Large Igneous Provinces (LIPs) were important phenomena that controlled the evolution of the oceans and continents during this time (Scotese et al., 2024; Fig. 1.5). In the latest Cretaceous, specifically the Campanian-Maastrichtian period (83.6 – 66 Ma), significant global geological events occurred, such as the Deccan volcanism, and the sea-level drop during the late Campanian-early Maastrichtian (Keller et al., 2012; Davis and Simmons 2024; Scotese et al., 2024). In addition, the Earth`s transition from a hot phase during the mid-Cretaceous into a cold phase during the Late Cretaceous (Linnert et al., 2014). Although the dramatic end owing to the Chicxulub asteroid impact eradicated 76% of the species on Earth, including all non-avian dinosaurs, other biotic perturbations such as the "mid-Maastrichtian event-MME" —a global faunal turnover in response to a change in deep-ocean circulation— and the inoceramid clams extinction, also occurred during the Maastrichtian (MacLeod and Huber, 1996; MacLeod et al., 2000; Bralower et al., 2002; Dameron et al., 2017). Finally, a warming event took place in the latest Maastrichtian, coinciding with the onset of the main phase of Deccan volcanism, which caused sea surface temperatures to rise by 3 – 4 ºC (Thibault and Gardin, 2010).

While these events were taking place globally, on a regional scale, during the latest Cretaceous one of the LIPs generated in the Lower Cretaceous (Caribbean) collided with the northern margin of the South American Plate (Fig. 2.1). This collision was in the form of a zipper, first to the south, in the present-day Ecuador, and later to the north, in the present-day Colombia, causing the accretion of igneous and sedimentary rocks (Kerr et al., 1997b; Vallejo et al., 2006; Pindell and Kennan, 2009; Cardona et al., 2011; Rodríguez and Arango, 2013; Spikings et al., 2015; León et al., 2018; Pardo-Trujillo et al., 2020). This collision generated the establishment of two regional sedimentary basins, a forearc basin to the west and a backarc basin to the east, separated by the central volcanic arc associated with subduction between the Caribbean and South American plates. In Colombia, the western forearc rocks are preserved west of the Romeral Fault System (RFS), including the Western Cordillera and the Sinú-San Jacinto Basin (Fig. 1). The characteristics of the sedimentary deposits allow them to be associated with deep marine environments. To the east, on the South American Plate, the backarc basin developed linked to the Pangea breakup and the subsequent backarc extension, over which an epicontinental sea evolved. This includes the present-day Upper and Middle Magdalena Valley, Eastern Cordillera, Cesar-Ranchería, Catatumbo, Caguán-Putumayo and Eastern Llanos basins (Fig. 1; Etayo-Serna et al., 1983; Maze, 1984; Cooper et al., 1995; Sarmiento-Rojas, 2001, 2019; Cediel et al., 2003; Gómez et al., 2003, 2005a;

Sarmiento-Rojas et al., 2006; Spikings et al., 2015; Leal-Mejía et al., 2019; Guerrero et al., 2020; Bayona et al., 2021).

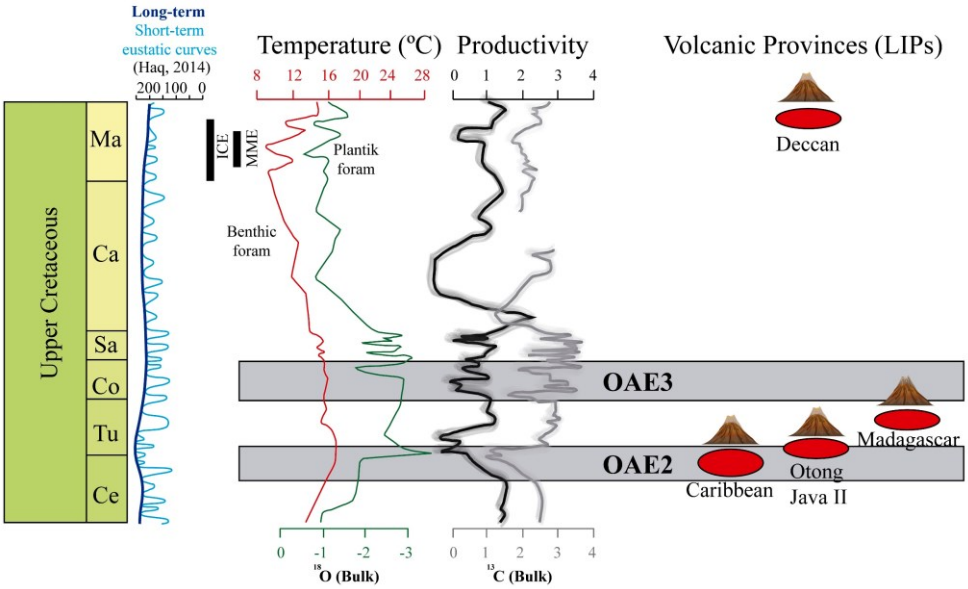


Figure 1.5. Summary of global geological events during the Late Cretaceous. Ce: Cenomanian, Tu: Turonian, Co: Coniacian, Sa: Santonian, Ca: Campanian, Ma: Maastrichtian. ICE: Inoceramid Claim extinction. MME: mid Maastrichtian event. OAE: Oceanic Anoxic Events. Based on data from Huber et al. (1995), Sepkoski Jr. (1996, 1997), Abreu et al. (1998), Li and Keller (1998, 1999), Courtillot and Renne (2003), Keller (2008), Ernst (2014), Dameron et al. (2017), and Keller et al. (2021).

1.3.1 Deep marine sedimentary depositional systems: western/forearc domain/basin

According to Reading (1996), deep marine sedimentary systems include slope and basin plain environments with their respective deposit types. In these settings the main sedimentary processes controlling the sediment accumulation are fall-out settlement, downslope density currents, and alongslope bottom currents, resulting in pelagic, turbiditic, and contourite deposits, respectively (Fig. 1.6; Reading 1996; Rebesco et al., 2014; Pickering and Hiscott, 2016; Stow and Smillie, 2020). However, these types of deposits are extremes, with a possible broad combination of them, referred to as mixed/hybrid sedimentary deposits (Rebesco et al., 2014; Rodrigues et al., 2022). Deep-sea and shallow marine sedimentation is generally controlled by tectonics, climate, and eustasy, with sediment supply being the most important factor associated with the sediment accumulation in these environments (Reading, 1996). In deep-sea environments, the sediments reach these environments through sediment gravity flows, density flows, or through river plumes carrying material off the continental shelves

(Pickering and Hiscott, 2016; Zavala, 2020). Bioturbation in these environments is an important element, considered, in some cases, as a diagnostic criterion to distinguish between different types of deposits (e.g., Rodríguez-Tovar and Hernández-Molina, 2018; Rodríguez-Tovar et al., 2019a, 2022; Rodríguez-Tovar, 2022). The ichnofacies model suggests that *Zoophycos* and *Nereites* ichnofacies are the main ichnoassemblages in such environments. The *Zoophycos* ichnofacies is linked to slope and basin plain environments, and the *Nereites* ichnofacies is associated with turbiditic deposits, with the graphoglyptids group being the diagnostic elements of this last trace fossil association, preserved as casts on the base of turbidite beds (Fig. 1.3; Bromley, 1996; Mcllroy, 2004; MacEachern et al., 2007; Buatois and Mángano, 2011; Rodríguez-Tovar et al., 2020).

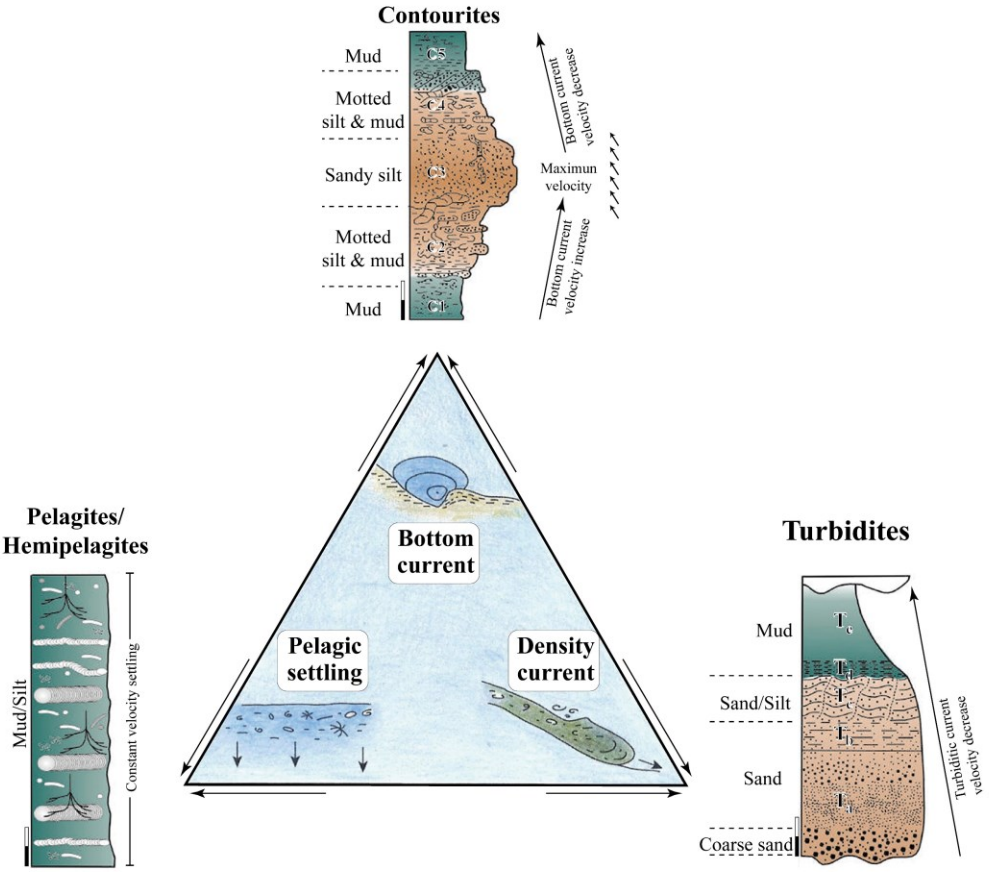


Figure 1.6. Conceptual diagram and facies models for different deep marine deposits (from Rebesco et al., 2014; Rodríguez-Tovar, 2022).

1.3.2 Epicontinental seas: eastern/backarc domain/basin

Epicontinental, intracontinental, shallow or epeiric sea develops when cratons or stable continental zones are flooded during sea-level rise (Johnson and Baldwin, 1996; Pratt and Holmden, 2008). They may show different sizes and shapes according to the geographic and tectonic context (Reading, 1996). Because sedimentary deposits associated with these depositional settings host important portions of the world`s fossil fuel reserves, including coal, gas and oil, there is a broad stratigraphic understanding of them (Schieber et al., 2016).

These depositional environments, widely documented in the geologic past, present great variability due to the diversity of processes and factors involved in their origin, evolution, and filling, including tectonic setting, connection to adjacent oceans, sediment composition, water-column fluctuations, and hydrological configuration (Fig. 1.7; Schwarz et al., 2022; Ferreira et al., 2025). The infilling and architectural evolution of these shallow basins also depend on the balance between accommodation space and sediment input. However, one of the most important factors to consider within these systems is the arrival and subsequent distribution of sediments within the basin (e.g., Orton and Reading, 1993; Nittrouer and Wright, 1994; Wright and Nittrouer, 1995; Walsh and Nittrouer, 2009; Schwarz et al., 2022). Arrival depends on the distribution of source areas, associated with local and regional tectonism, erosion rates, climatic factors, and transport mechanisms. Internal distribution is controlled by physical ocean parameters such as waves, storms, tides, bottom and longshore currents, hypopycnal river plumes and submarine gravity flows (Johnson and Baldwin, 1996; Schieber, 2016). Moreover, together with the physical factors, parameters including salinity, productivity, oxygenation and food supply, can determine the existence, evolution, and distribution of macrobenthic tracemaker communities in these shallow marine environments.

The ichnological record of these depositional settings has been extensively studied due to their wide distribution, especially in the Cretaceous. *Scoyenia*, *Trypanites*, *Glossifungites*, *Skolithos*, *Cruziana* and *Zoophycos* ichnofacies have been reported in deposits associated with these environments (Lazo et al., 2005; Pazos et al., 2009; Schwarz and Buatois, 2012; Varejão et al., 2021; Schwarz et al., 2022; Paz et al., 2023; Ferreira et al., 2025).

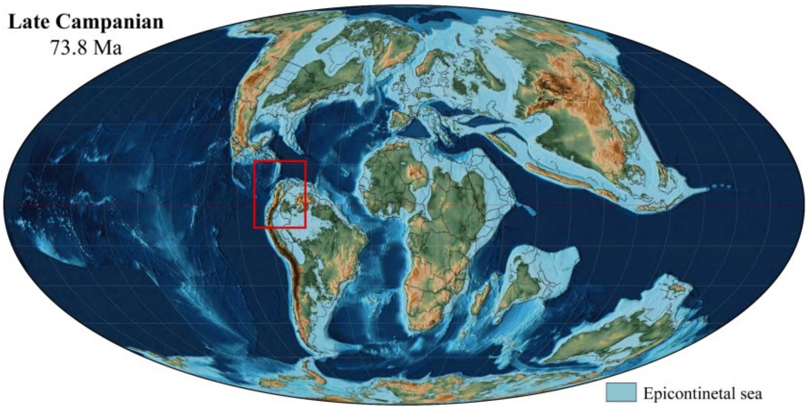
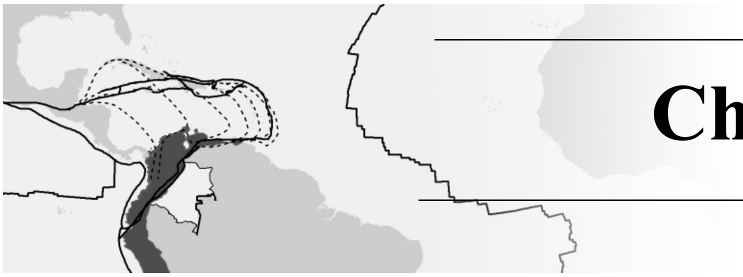


Figure 1.7. Distribution of epicontinental, intracontinental or epeiric seas during the late Campanian, highlighting those by the NW margin of South America (red polygon. From Scotese Paleomap Project).



Chapter 2

GEOLOGICAL FRAMEWORK

2.1 Regional tectonic configuration

The current geological configuration of the NW margin of South America is complex, and includes rocks of different ages, from Precambrian to the Recent, associated with different tectonic accretion events throughout its assembly history (Cediel et al., 2003; Restrepo and Toussaint, 2020; Toussaint and Restrepo, 2020). In general, the Andes, a mountain range that extends along the entire western margin of South America, were generated as a consequence of subduction between the Farallones/Nazca and South American plates. Yet during the Cretaceous in the septentrional part of the Andes, the Caribbean Plate was involved in the geological history, determining a differentiation with respect to the rest of the Andes.

The Mesozoic and Cenozoic geological evolution of the NW of South America is marked by the interaction between the Caribbean (also called as Caribbean Large Igneous Province-CLIP), South American, and Farallones/Nazca plates, shaping the actual landscape (Pindell and Kennan, 2009; Montes et al., 2019; Mann et al., 2021) (Fig. 2.1). Within this complex interaction, the collision of the Caribbean Plate with the South America Plate during the Late Cretaceous, was perhaps the most important tectonic event during the Mesozoic Era of this region. Migration of the oceanic Caribbean Plate from southern regions (4 – 20º south, Hincapié-Gómez et al., 2018), between North and South America, caused the accretion of oceanic plateau and island arc rocks to the South American Margin (Moreno-Sánchez and Pardo-Trujillo, 2003; Pindell and Kennan, 2009). This accretion controlled —and still controls— the filling of sedimentary basins, the creation of mountain massifs, magmatism and volcanism, and the seismicity of this margin (Mora-Páez et al., 2019).

The current landscape of Colombia consists of two major physiographic regions, such as a mountainous western zone corresponding to the Andes, represented by three mountain ranges (Western, Central and Eastern Cordilleras), separated by two fluvial valleys, the Cauca and the Magdalena, and a relatively flat eastern area corresponding to the Amazon Craton, representing the Precambrian to Phanerozoic geological history. The Western Cordillera, composed of igneous, metamorphic and sedimentary rocks, is directly related to the origin, migration, and accretion of the Caribbean Plate, being considered rock of allochthonous origin (Kerr et al., 1996a; Moreno-Sánchez and Pardo-Trujillo, 2003; Weber et al., 2015; Pardo-Trujillo et al., 2020). The Central Cordillera has a much older geological history, and consists of a Paleozoic basement, with Permian and Jurassic metamorphism, which is intruded by Permian to Miocene-Pliocene igneous bodies (Villagómez et al., 2011; Cochrane et al., 2014; Leal-Mejía et al., 2019; Spikings and Paul, 2019). After of the collision of the Caribbean Plate with the South American Plate in the Late Cretaceous, the rocks of the Western Cordillera represented the deposits of the forearc basin, and the Central Cordillera represented the arc formed by the subduction between the two plates. The Upper and Middle Magdalena Valley, Eastern Cordillera, Cesar-Ranchería, Catatumbo, Caguán-Putumayo, and Eastern Llanos basins represented a backarc basin developed by extensional processes related to the Pangea separation and/or backarc extension during the Triassic-early Cretaceous and filled by marine deposits during most of the Cretaceous (Cooper, 1995; Sarmiento-Rojas, 2019). At the end of the Cretaceous, associated with the Caribbean Plate collision, the backarc basin became a basin with a continental fill, owing

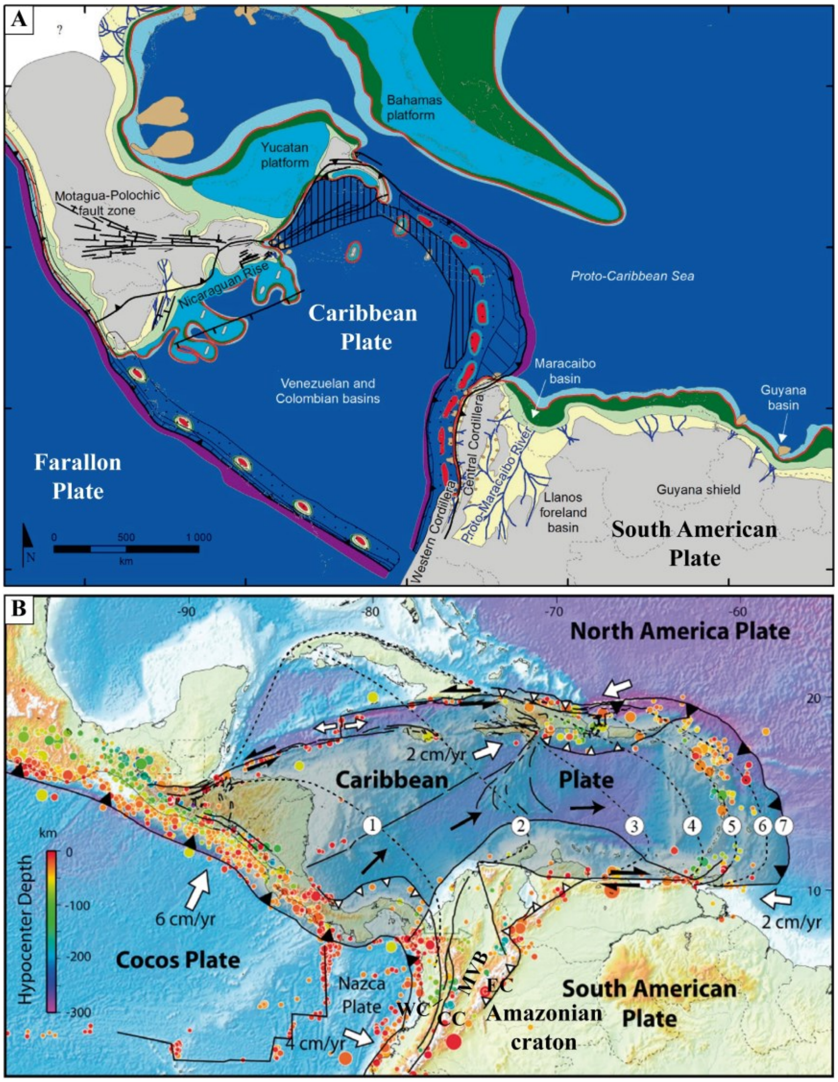


Figure 2.1. A. Late Cretaceous tectonic configuration of the NW margin of South America (from Mann et al., 2021). **B.** Current tectonic configuration. CC: Central Cordillera, EC: Eastern Cordillera, MVB: Magdalena Valley Basins (Middle and Upper), WC: Western Cordillera (modified from Harbitz et al., 2012). The dotted line represents the positions of the frontal volcanic arc, associated with the migration of the Caribbean Plate: 1: Late Cretaceous, 2: middle Paleocene, 3: middle Eocene, 4: middle Oligocene, 5: Middle Miocene, 6: Pliocene, 7: Recent (from Escalona and Mann, 2011).

to the inversion tectonic processes that occurred during the Cenozoic, which caused that today a part of this basin constitutes a mountain range (Etayo-Serna et al., 1983; Maze, 1984; Cooper et al., 1995; Sarmiento-Rojas, 2001, 2019; Cediel et al., 2003; Gómez et al., 2003, 2005a; Sarmiento-Rojas et al., 2006; Spikings et al., 2015; Leal-Mejía et al., 2019; Guerrero et al., 2020; Bayona et al., 2021). The Amazonian Craton constitutes the most stable geological zone within this dynamic and complex context, being directly associated with the South American Plate evolution, and considered for this period as the autochthonous domain.

2.2 Regional geologic and stratigraphic setting of the Late Cretaceous

Since the Late Cretaceous, Colombia can be divided into two distinct geological domains. An allochthonous or western domain is associated with the Caribbean Plate, while an autochthonous or eastern domain is related to the South American Plate, separated by the Romeral Fault system-RFS (Moreno-Sánchez and Pardo-Trujillo, 2002; Vinasco, 2019) (Fig. 2.2). The western domain includes rocks now at the west of the Romeral Fault System, between the western flank of the Central Cordillera and the Pacific coast. This domain consists of a basement of Lower Cretaceous mafic and ultramafic volcanic rocks, intruded by gabbros and tonalites, and covered by Upper Cretaceous sedimentary and low-grade metamorphic (with sedimentary protolith) rocks (Pardo-Trujillo et al., 2020). Conglomerates, sandstones, mudrocks, and in minor proportion limestones and phyllites of Campanian-Maastrichtian ages, accumulated in a forearc context, directly related to the proto-Pacific Ocean, constitutes the sedimentary cover (León et al., 2018; Pardo-Trujillo et al., 2020).

The eastern domain is represented by rocks today located at the east of RFS. However, the major sedimentary record is documented at the east of the Central Cordillera, and includes Magdalena Valley (Upper and Middle), Eastern Cordillera, Cesar-Ranchería, Catatumbo, Caguán-Putumayo and Eastern Llanos basins. This domain has a marine sedimentary record, associated with a backarc context and with the establishment of an epeiric sea connected with the proto-Atlantic Ocean from the Early to the Late Cretaceous, which later became a continental basin during the Cenozoic (Cooper et al., 1995; Villamil and Pindell, 1998; Sarmiento-Rojas, 2001, 2019; Gómez et al., 2003; Sarmiento et al., 2015; Paez-Reyes et al., 2021).

Thus, the eastern and western domains share a Late Cretaceous sedimentary history, specifically Campanian-Maastrichtian, in a backarc and forearc context, and linked to the pro-Atlantic and proto-Pacific oceans, respectively. The sedimentary record of the western forearc domain is represented by conglomeratic, sandy, muddy, and in less proportion calcareous and siliceous fine-grained deposits —which due to the high deformation, commonly do not preserve the original stratigraphical polarity—

accumulated in deep marine environments (Pardo-Trujillo et al., 2020). The deposits include several lithostratigraphic units defined according to their geographic location, but which are chronologically contemporaneous. In the northern region of Colombia, specifically the Sinú-San Jacinto Basin, these rocks are known as the Cansona Formation, whereas while in the south, specifically in the Western Cordillera, they are known as the Penderisco Formation, divided into the Urrao and Nutibara Members. Other names such as Espinal, Cisneros and Nogales formations, also are common for the area. The sedimentary deposits of the eastern backarc domain include mudrocks, sandstones, conglomerates, limestones, coal, and siliceous rocks accumulated in shallow marine and locally fluvio-deltaic environments (Montoya et al., 2016; Bayona, 2018; Sarmiento-Rojas, 2019; Bayona et al., 2021). These deposits show a wide lateral variation of facies, leading to the definition of many lithostratigraphic units, which are shown in Fig. 2.2.

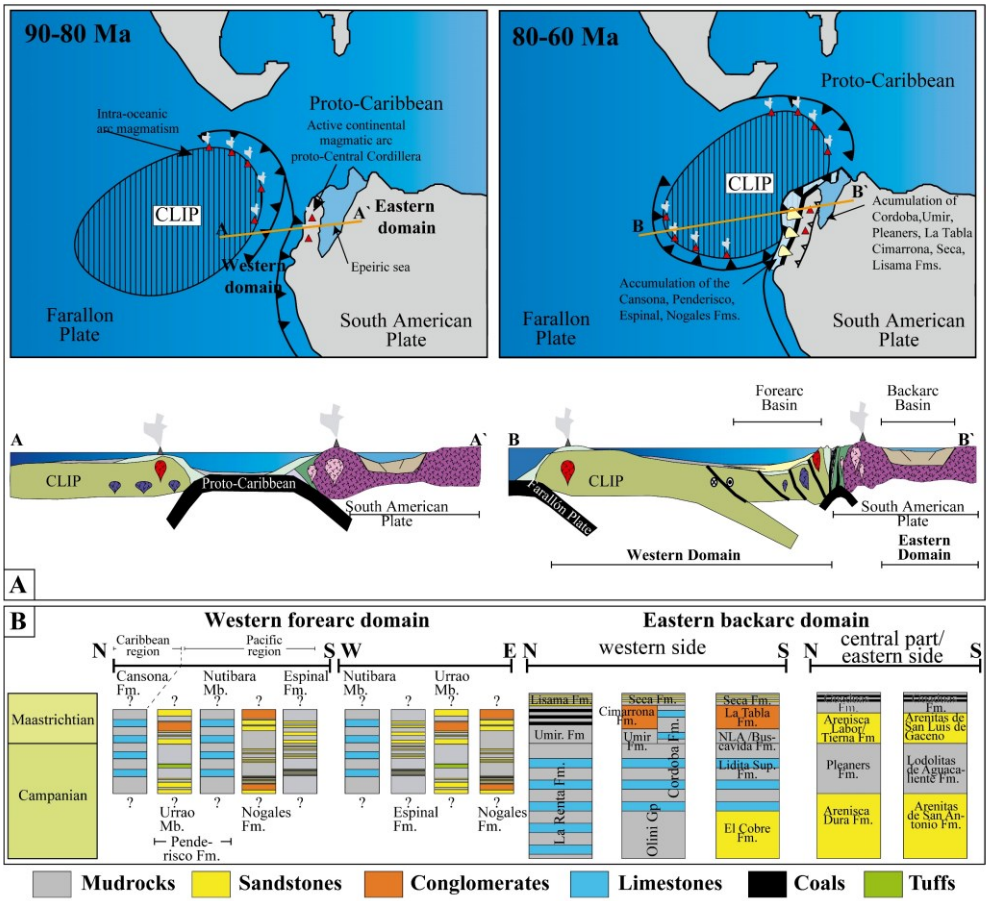
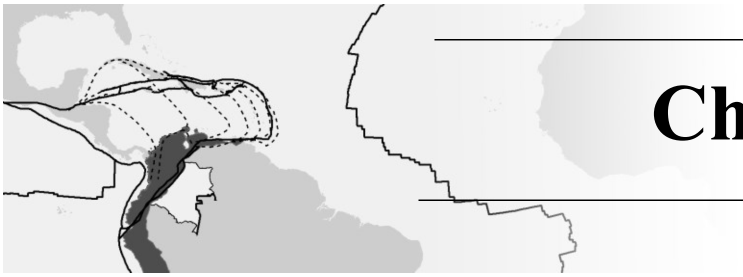


Figure 2.2. A. Paleo-tectonic configuration of NW margin of South America during the Late Cretaceous. Note the tectonic plates involved, the forearc and backarc basins, and the western and eastern domains (modified from Pardo-Trujillo et al., 2020). **B.** Campanian-Maastrichtian stratigraphy of both domains, showing the studied lithostratigraphic units. CLIP: Caribbean Large Igneous Province/Caribbean Plate.



Chapter 3

MATERIALS AND METHODS

3.1 Research basis and approach

This research begins with an extensive bibliographic review, aimed at understanding the spatiotemporal evolution of sedimentary environments during the Late Cretaceous in the NW margin of South America. Thus, literature related to the sedimentary deposits and geological evolution of the Late Cretaceous in Colombia was reviewed. This review began to elucidate the problem established for the development of this thesis (objective section). This led to the bibliographic review of scientific information in the fields of sedimentology, ichnology, sedimentary environments and stratigraphy. Finally, this review culminated in the final definition of the research questions to be solved, the possible hypotheses and the methods to approach them.

3.2 Outcrop selection

The high deformation of the rocks of the western forearc domain, associated with the accretionary phenomena at the NW margin of South America and the subsequent uplift phase, represented a great challenge for the study of these rocks. Therefore, before selecting the outcrops for this study, it was necessary to carry out regional cartographic studies in order to avoid misunderstanding. This was accompanied by sampling for biostratigraphic analysis to confirm the stratigraphic position of the units of interest.

This thesis includes the field-based study of 17 new stratigraphic sections that reach a total of ~1966.5 m nets of logs (Table 3.1), added to 35 sections previously reported (Fig. 3.1). Eight new Campanian-Maastrichtian stratigraphic successions correspond to the western forearc domain, belonging to Cansona, Penderisco (Nutibara and Urrao Members), Espinal and Cisneros formations. These are added to 26 sections described previously. The eastern backarc domain includes nine new Campanian-Maastrichtian stratigraphic successions, together with nine previously reported ones. The lithostratigraphic units covered correspond to La Luna, El Cobre, Arenisca Dura, Arenitas de San Antonio, Lidita Superior, Cordoba, La Renta, Pleaners, Lodolitas de Aguacaliente, Buscavida, Umir, Arenisca Labor/Tierna, Arenitas de San Luis de Gaceno, La Tabla, Cimarrona, Seca, Guaduas and Lisama formations.

Outcrop-based facies analysis was conducted in each new stratigraphic section, and lithological features such as bed thickness and shapes, color, grain size, sedimentary structures, sorting, roundness and sphericity were systematically described. Paleontological features (fossils and trace fossils) were also included in the facies analysis. The fossils were described and classified. Special attention was paid to the ichnological analysis, carried out in two stages, one in the field and the other in the office/laboratory. In the field, the spatial distribution of trace fossils within the beds and along the section, was studied, focusing on relationships with facies and bed contacts.

With respect to trace fossil features, ichnodiversity, cross-cutting relationship between traces, size, and abundance (measured as bioturbation index-BI *sensu* Taylor and Goldring, 1993 and as ichnofabric index *sensu* Droser and Bottjer, 1986) were evaluated. Thus, preliminary taxonomic assignments were made, and detailed photographs were taken. Subsequently, the laboratory work focused on a detailed review of the photographs, analyzing each of the characteristics of the traces (especially ichnotaxobases *sensu* Bromley, 1996; Bertling et al., 2006, 2022), aided by specialized monographs, including outcrop and core examples (e.g., Gerard and Bromley, 2008; Knaust, 2017). Then, the taxonomic assignments were confirmed or redefined as appropriate. In some cases, polished field samples were studied for ichnotaxonomic analysis.

Sedimentary facies were defined based on the integration of lithological and paleontological characteristics. The depositional/hydrodynamic processes related to their origin were interpreted for each of them. Subsequently, sedimentary facies were grouped in facies associations based on their relationships, vertical and spatial distribution, and stacking patterns. Facies associations allowed interpretation of depositional settings, and paleoenvironmental (physical and ecological) parameters.

Previously studied stratigraphic sections were reviewed in detail, with special attention to the biostratigraphic framework and paleoenvironmental interpretations. In some cases, micropaleontological biostratigraphic information was reviewed and updated following actual biostratigraphic databases and zonations (e.g., Koutsoukos and Klasz, 1999; Kaminski and Gradstein, 2005; Holbourn et al., 2013; Young et al., 2017).

Finally, regional stratigraphic correlations encompassing both the new and previously reported sedimentary successions were used for a regional-scale paleogeographic interpretation encompassing the entire time interval studied.

Table 3.1. Information of the new outcrops studied in this research.

Domain	Section	Coordinates		Thickness (m)	Name
		Latitude	Longitude		
Western forearc domain	1	9.242857	-75.787206	22	San Carlos
	2	8.695184	-75.833858	11	Chicoral
	3	6.915067	-76.235543	3.5	Dabeiba
	4	6.069577	-75.950374	Deformed	Concordia
	5	5.872623	-76.065326	Deformed	Ciudad Bolivar
	6	5.616689	-75.922006	33	Andes
	7	3.878525	-76.555222	182	Calima
	8	3.788496	-76.766746	Deformed	El Naranjo
Eastern backarc domain	9	4.419927	-74.830783	57.5	Guataquí-Nariño
	10	4.535538	-74.852005	430	Quebrada Talora
	11	5.185338	-74.669007	264	Honda-Guaduas
	12	5.192436	-74.556512	186	Río Negro
	13	5.366227	-74.570388	150	Túnel Las Lajas
	14	6.216434	-73.832993	21	Quebrada Providencia
	15	6.218782	-73.821154	100	Landazuri-Cimitarra
	16	6.284013	-73.845356	186.5	Quebrada La Armera
	17	4.836900	-73.206604	320	Quebrada San Antonio
			Total	**1966.5**	

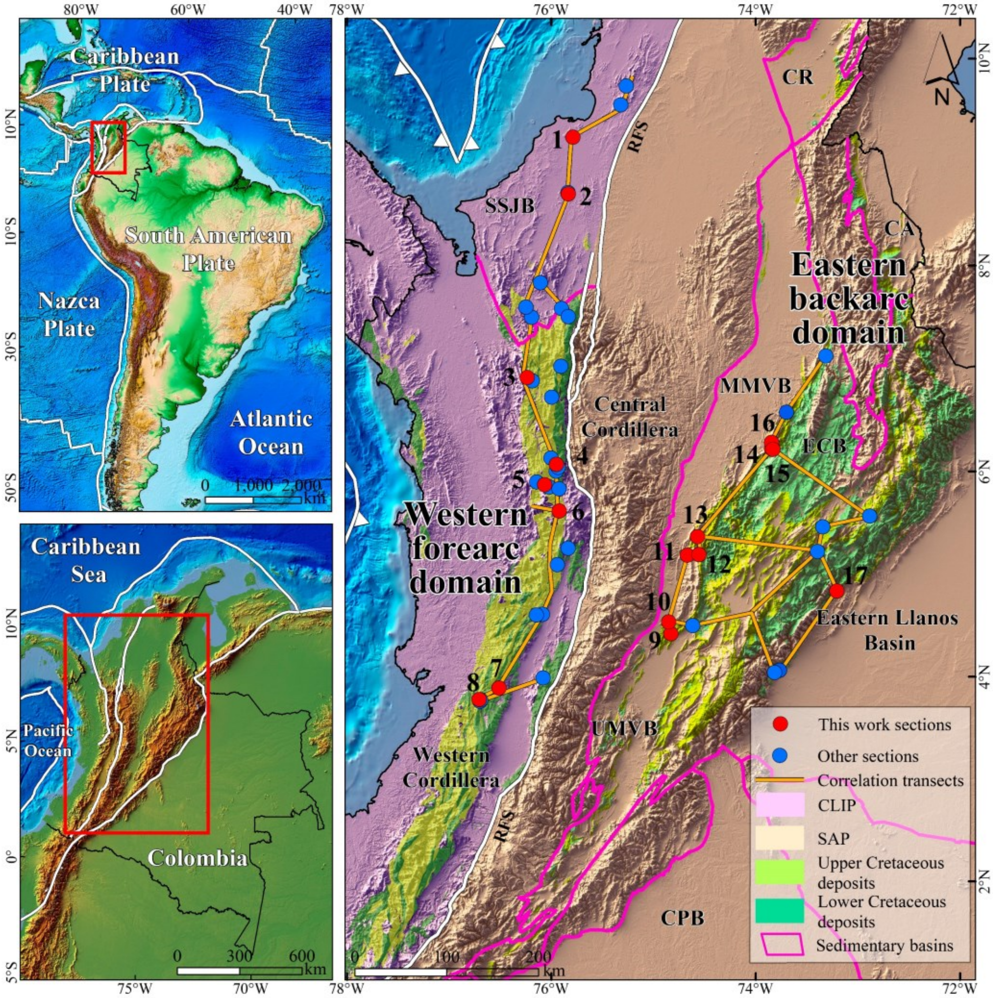
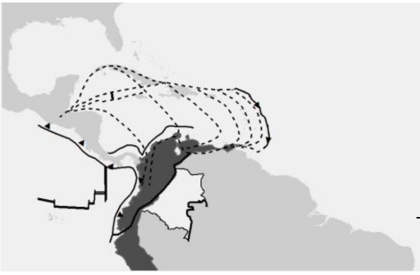


Figure 3.1. Location map of the new stratigraphic sections from this study (1 to 17) together with those from previous works for regional correlation and integration. CA: Catatumbo Basin, CPB: Caguán-Putumayo Basin, CLIP: Caribbean Plate, CA: Catatumbo Basin, CR: Cesar-Ranchería Basin, MMVB: Middle Magdalena Valley Basin, RFS: Romeral Fault System, SAP: South American Plate, SSJB: Sinú-San Jacinto Basin, UMVB: Upper Magdalena Valley Basin.

Part II RESULTS



Chapter 4

WESTERN FOREARC GEOLOGICAL DOMAIN: PALEOENVIRONMENTS AND DEPOSITIONAL CONTROLS

PALEOENVIRONMENTAL CONDITIONS OVER THE CARIBBEAN LARGE IGNEOUS PROVINCE DURING THE LATE CRETACEOUS IN NW OF SOUTH AMERICAN MARGIN: A SEDIMENTOLOGICAL AND ICHNOLOGICAL APPROACH

Carlos A. Giraldo-Villegas [a,b] , Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a,b], Andrés Pardo-Trujillo [b,c], Mónica L. Duque-Castaño b

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain

[b] Instituto de Investigaciones en Estratigrafía-IIES, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

[c] Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia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Paleoenvironmental conditions over the Caribbean Large Igneous Province during the Late Cretaceous in NW of South American Margin: A sedimentological and ichnological approach

Carlos A. Giraldo-Villegas [a, b, *], Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a, b], Andrés Pardo-Trujillo [b, c], Mónica L. Duque-Castaño [b]

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain
[b] Instituto de Investigaciones en Estratigrafía-IIES, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia
[c] Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

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Abstract

The Late Cretaceous in northwest South America was a period marked by synchronous regional geological processes (e.g., accretion of oceanic terranes, arc magmatism, sea-level fluctuations, oceanographic dynamics), related to the interaction of the Caribbean Large Igneous Province (CLIP) with the NW margin of South America. This synchroneity makes it difficult to reconstruct the complex geological evolution of this region. In Colombia, Upper Cretaceous marine sedimentary and low-grade metamorphic rocks are commonly exposed in both the Western Cordillera and the Sinú-San Jacinto Basin in the Pacific and Caribbean regions respectively. Significant deformation and structural complexity are the main limiting factors for sedimentological and paleontological studies of these deposits.

Detailed sedimentological and ichnological analyses were carried out in eight sections, two in the Caribbean region and six in the Pacific region. The Caribbean sections are composed of limestones, mudrocks, siliceous and calcareous mudrocks, and cherts, associated with pelagic and hemipelagic deposits (E2.2 and G2.1 facies). The Pacific sections are characterized by two facies associations, one composed of mudrocks, limestones, as well as chert associated with pelagic and hemipelagic deposits (E2.2 and G2.1 facies) and the other of interlayered siliceous mudrocks and sandstones associated with turbiditic systems (C2 facies). Upper Cretaceous deposits in both regions are characterized by relatively low to moderate abundant and diverse trace fossils assemblages, consisting of *Chondrites*, *Planolites*, and *Zoophycos* in the Caribbean region and *Chondrites*, ?*Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Thalassinoides*, and *Zoophycos* in the Pacific region, assigned to the *Zoophycos* ichnofacies. Sedimentological and ichnological features suggest deposition in deep-marine environments characterized by pelagic, hemipelagic, and turbiditic sedimentation. Integrated with the biostratigraphical framework, this allows us to establish a regional correlation between both regions. High nutrient supply, poor oxygenation, and low hydrodynamic energy and sedimentation rates interrupted by episodic increases associated with turbiditic deposits are main paleoenvironmental factors controlling the sedimentation over the CLIP during Late Cretaceous.

Keywords: Trace fossils, sedimentary environments, ecological and depositional conditions, Western Colombia

4.1 Introduction

The Meso-Cenozoic geological evolution of NW South America was marked by the interaction between the South American, Nazca/Farallon, and Caribbean plates (Pindell and Kennan, 2009; Villagómez et al., 2011; Spikings et al., 2015; Montes et al., 2019; Mora-Páez et al., 2019; Romito and Mann, 2020) (Fig. 4.1). During the Late Cretaceous, the northeastward migration of the Caribbean Large Igneous Province (CLIP) between North and South America caused the accretion of oceanic plateau and island arcs rocks, and its related sedimentary cover to the NW of South America (Colombian-Ecuadorian margin) (Restrepo and Toussaint, 1988; Kerr et al., 1997a; Villagómez et al., 2011; Spikings et al., 2015; Weber et al., 2015; Zapata Villada et al., 2017, 2021; Hincapié-Gómez et al., 2018). In addition to accretion processes, Cretaceous oceanographic events, such as eustatic changes and Oceanic Anoxic Events (OAEs), controlled the infill and sedimentary evolution of adjacent basins (Villamil, 1998; Villamil et al., 1999; Haq, 2014; Bayona, 2018; Pardo-Trujillo et al., 2020; Paez-Reyes et al., 2021). This complex interaction of different geological processes have made it difficult to reconstruct the geological evolution of the NW margin of South America during this period.

In Colombia, these accretionary deposits are exposed in so-called "Western Colombia", which defines the area to the west of the Romeral Fault System (RFS) (*sensu* Moreno-Sánchez and Pardo-Trujillo, 2002), between the western flank of the Central Cordillera, and the Pacific coast of Colombia. The stratigraphical and chronological framework of these rocks is not yet well defined due to the low recovery and preservation of both macro and microfossils, together with outcrop limitations due to dense vegetation, few access roads, and structural complexity, have led to relatively scarce geological and stratigraphical knowledge of these units, suggesting the need for further chronological investigations. However, at least two major assemblages of rocks have been recognized with the available information. An ~Albian to Coniacian? assemblage, corresponding to the CLIP basement associated with oceanic plateau and island arc rocks interbedded with sedimentary deposits, and an ~Santonian-Maastrichtian assemblage, related to the sedimentary cover directly linked to the interaction between the CLIP and the South America Plate (Etayo-Serna et al., 1980; Pardo-Trujillo et al., 2020 and references therein).

In this work, western Colombia is divided into two regions: the Caribbean in the Sinú-San Jacinto Basin (SSJB) and the Pacific in the Andean mountains of the Western Cordillera (Fig. 4.1), in which the sedimentary cover is partially preserved. Although the rocks of both regions share some geological characteristics (e.g., basement, structural position), only few studies have attempted to compare them or comprehend their general relationships (Duque-Caro, 1972a; SGC, 2019a).

Geological mapping as well as stratigraphical (Álvarez and González. 1978; Barrero, 1979; Etayo-Serna et al., 1982; González, 2001; Nivia, 2001; Montoya, 2003; Moreno-Sánchez and Pardo-Trujillo, 2003) and detailed sedimentological studies (Pardo-Trujillo et al., 2020) have suggested mostly deep-marine, turbiditic environments in the Pacific region. Nonetheless, detailed paleoenvironmental interpretations have not been performed.

In the Caribbean region, there is currently a debate about the depositional settings of the Upper Cretaceous deposits. Based on their marine calcareous and siliceous microfossils, some authors have interpreted the environment as deep-marine (Duque-Caro, 1967; Duque-Caro and Dueñas, 1987; Guzmán et al., 2004; Guzmán, 2007). In contrast, other researches indicate that the deposits were formed in shallow-marine environments, mainly based on sedimentological and palynological information (Bermúdez et al., 2009; Herrera et al., 2009; Dueñas and Gómez, 2013; Bermúdez, 2016; Juliao-Lemus et al., 2016). This variable interpretation highlights the lack of detailed and integrated works that include new and precise tools to evaluate depositional environments.

Trace fossils have been previously reported in some of the deposits exposed in western Colombia (e.g., Etayo-Serna et al., 1982; Parra, 1984; Etayo-Serna, 1986; Moreno-Sánchez and Pardo-Trujillo 2002; Pardo-Trujillo et al., 2020), but no detailed ichnological analyses have been conducted. In this sense, the ichnological approach can be a tool to refine paleoenvironmental conditions during the deposition of these sedimentary units, considering the usefulness of trace fossils in sedimentary basin research (Buatois and Mángano, 2011; Knaust and Bromley, 2012).

In this research, a detailed sedimentological and ichnological analysis of several stratigraphical sections from the Caribbean and Pacific regions of western Colombia has been conducted, providing new constraints on the sedimentary environments that existed over the CLIP near the NW margin of Colombia during the Late Cretaceous, focusing on main depositional and ecological factors controlling the sedimentation. This research is based on an exhaustive review of the biostratigraphical data, to establish the temporal framework of the deposits. The integration of obtained sedimentological and ichnological data with the previous data (Supplementary file 1) and the biostratigraphical framework, will allow us to propose a distribution and correlation of facies and depositional environments for the NW margin of Colombia. These results will contribute to a better understanding of the sedimentary paleoenvironments over the CLIP during the Late Cretaceous.

4.2 Geological setting

During the Late Cretaceous, the tectonic interaction associated with the northeast migration of the CLIP between North and South America controlled deposition and caused the accretion of rocks that comprise today's western Colombia (Kerr et al., 1997b;

Vallejo et al., 2006; Pindell and Kennan, 2009; Cardona et al., 2011; Rodríguez and Arango, 2013; Spikings et al., 2015; León et al., 2018; Pardo-Trujillo et al., 2020) (Fig. 4.1). In the Western Cordillera, in the Pacific region, Upper Cretaceous marine sedimentary and low-grade metamorphic (with sedimentary protolith) rocks overlay the accreted basement of the CLIP, which due to the high deformation, commonly do not preserve original stratigraphical relationships (Álvarez and González, 1978; Nivia, 2001; Pardo-Trujillo et al., 2002a, 2002b, 2020; Moreno-Sánchez and Pardo-Trujillo, 2003). In the SSJB, in the Caribbean region, a mafic and ultramafic basement is also recorded, considered as belonging to the same volcanic province as the Western Cordillera (Duque-Caro, 1979, 1984; Cediel et al., 2003; Cerón et al., 2007; Villagómez et al., 2011), also overlain by Upper Cretaceous marine deposits (Guzmán, 2007).

The Upper Cretaceous deposits that overlie the CLIP basement, include cherts, siliceous mudrocks, claystones, micritic limestones, and scattered volcanic deposits (“tuffs”) outcropping in the SSJB, known as the Cansona Formation (Guzmán, 2007). The outcrops of this unit are scarce, highlighting those found in the San Carlos quarry east of Lorica city, and the El Purgatorio, Chicoral, and Lomagrande quarries south of Monteria city, in addition to the outcrops found in the Cansona Hills, where the unit was formally defined. In the Pacific region, the Upper Cretaceous sedimentary portion is composed of mudrocks, siliceous and calcareous mudrocks, limestones, cherts, volcanic deposits (“tuffs”), agglomerates, sandstones, conglomerates, and low-grade metamorphic rocks, including such units as the Penderisco, “sedimentitas de Puente Umbría”, Cisneros, Espinal, Consolida and Nogales formations, among others outcropping along the western flank of the Central Cordillera and Western Cordillera (Pardo-Trujillo et al., 2020 and references therein).

The sedimentology and ichnology of these Upper Cretaceous deposits have been studied in eight localities (Fig. 4.1), two sections from the Cansona Formation in the (1) San Carlos, in Lorica region, and (2) Chicoral in Monteria region, located in the SSJB in the Caribbean region, and six between Dabeiba and Buenaventura cities located in the Western Cordillera in the Pacific region. From north to south, the studied Pacific sections are: (3) Dabeiba, located on the Cañasgordas-Dabeiba road, (4) Concordia, in the Comiá creek in Concordia region, (5) Ciudad Bolívar, in the Ciudad Bolivar - Carmen de Atrato road, (6) Andes, in the Santa Rita creek in the Andes region, (7) Calima, in the Calima lake region, and (8) El Naranjo, in the same name quarry in the Buga-Buenaventura road. Sections 3 to 6 are associated with Penderisco Formation, 7 with Espinal Formation, and 8 with Cisneros Formation (Alvarez and González, 1978; Barrero, 1979; González, 2001).

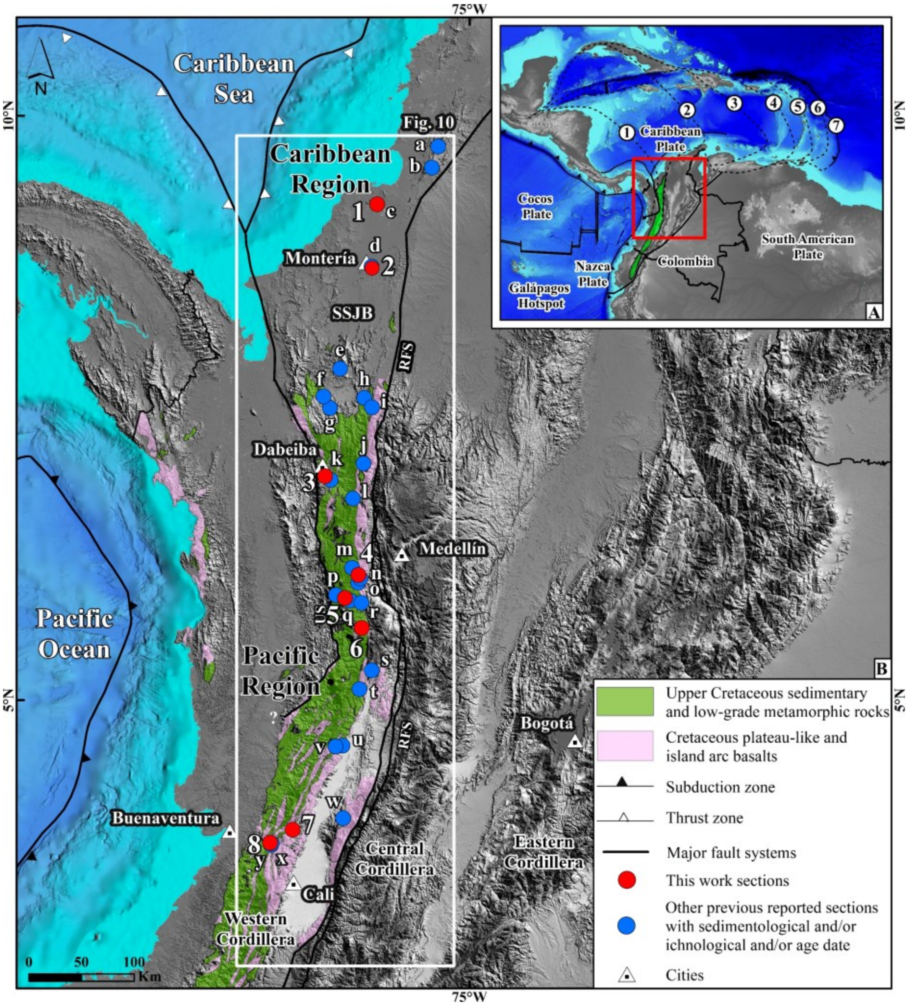

Figure 4.1. A. Tectonic setting of NW of South America. Northeastern margin Caribbean Plate displacement based on Escalona and Mann (2011). 1: Upper Cretaceous; 2: middle Paleocene; 3: middle Eocene; 4: middle Oligocene; 5: middle Miocene; 6: Pliocene; 7: Recent. **B.** Location Map of studied sections (red circles): **1.** San Carlos. **2.** Chicoral. **3.** Dabeiba. **4.** Concordia. **5.** Ciudad Bolivar. **6.** Andes. **7.** Calima. **8.** El Naranjo. Other stratigraphical sections (blue circles): a. Cerro Cansona. b. Chalán Creek (Juliao-Lemus et al., 2016). c. San Carlos quarry (same San Carlos section of this work. Jaramillo et al., 2011). d. El Purgatorio quarry (Jaramillo et al., 2011). e. La Perra section. f. Río Sinú sur section. g. El Limon Creek (SGC, 2019a). h. Chimurrito Creek. i. La Esmeralda Creek (SGC, 2019b). j. Peque area (Etayo-Serna, 1989). k. Río Sucio bridge (Etayo-Serna et al., 1982). l. Giraldo area (Díaz-Cañas and Patarroyo, 2014). m. Betulia section. n. Concordia area. o. Salgar section (Pardo-Trujillo et al., 2020). p. Carmen de Atrato area. q. Ciudad Bolivar area (Rodríguez and Arango, 2013). r. Ciudad Bolivar section (Pardo-Trujillo et al., 2020). s. Puente Umbría area (Moreno-Sánchez et al., 2002). t. Apía area (Pardo-Trujillo et al., 2002a). u. Lázaro Creek (Etayo-Serna, 1986). v. Consólida Creek (Parra, 1984). w. Nogales-Monteloro area (Pardo-Trujillo et al., 2002b). x. Buga-Buenaventura Road (Etayo-Serna, 1985). y. El Naranjo quarry (Barrero, 1979; Etayo-Serna, 1986). For mor details see Supplementary file 1. **SSJB**: Sinú-San Jacinto Basin. **RFS:** Romeral Fault Systems. **US:** Uramite Suture. Geology taken from Gómez et al. (2015).

4.3 Methodology

Given the structural complexity of both study areas, the described stratigraphical sections come from those areas with the lowest identified deformation. In each section, sedimentological (lithology, texture, and sedimentary structures) and ichnological information was systematically obtained. Bed thickness characteristics follows the nomenclature of Ingram (1954): laminae (<1 cm), very thin (133 cm), thin (3-10 cm), medium (10-30 cm), thick (30-100 cm) very thick (>100 cm). Facies analysis follows the nomenclature proposed by Pickering and Hiscott (2016) for deep-marine environments, with differentiation of organized sand-mud couplets, structureless mud, laminated clays and muds, and biogenic muds (Table 4.1). Ichnological features such as shape, wall, lining, branching, filling, and spreite (ichnotaxobases; Bromley, 1996) were analyzed for ichnotaxonomy. Furthermore, quantitative ichnological data, such as dimensions, orientation, abundance, and density, together with lateral and stratigraphical changes, were examined for ichnofacies characterization and distribution and then used for the paleoenvironmental interpretations. Abundance and diversity of trace fossils were semi-quantitatively evaluated as abundant, common, and scarce, and high (>6 ichnogenera), moderate (3-6 ichnogenera), and low (1-2 ichnogenera), respectively.

Moreover, to obtain a biostratigraphical framework, an extensive revision and update of the previous results of the studied area was conducted. Additional data from other localities with deposits coeval with studied sections were included for regional correlation and discussion (blue dots in Fig. 4.1, Supplementary file 1). The foraminiferal associations reported in previous research were duly revised and updated, based on the new biochronological information (Supplementary file 1). Thus, genera and species of foraminifera described in previous regional reports were consulted in WORMS database to validate their current taxonomic status; in some cases, previous assignations were updated. Biostratigraphy of benthic foraminifera was obtained from Bolli et al. (1994), Koutsoukos and Klasz (1999), Kaminski and Gradstein (2005), and Holbourn et al. (2013). For planktonic species, the Mesozoic database of pfmikrotax (Young et al., 2017) was used.

Table 4.1. Description of the facies used in this work based on Pickering and Hiscott (2016).

Facies	Code	Description
Organized sand-mud couplets	C2	Moderately well sorted to poorly sorted sand-mud couplets showing partial or complete Bouma sequences. The distinction between C2.1, C2.2, and C2.3 is based on their thicknesses (facies C2.1: 30–≥ 100 cm, C2.2: 10–30 cm, and C2.3: 3–10 cm).
Structureless mud	E1.1	Structureless muds commonly occur in thick sections, bedding is poorly defined or absent. It is notable the absence of structures, both primary and secondary.
Laminated clays and muds	E2.2	Individual beds or mud-dominated intervals range from 1 cm to decimeters in thickness, commonly with fine parallel lamination.
Biogenic mud	G2.1	Mud with 25-50% of biogenic content, generally associated with microfossils. Muds and biogenic muds may be calcareous or siliceous.

4.4 Results: sedimentological and ichnological features

4.4.1 Caribbean Region

San Carlos and Chicoral sections

The San Carlos section, ~22 m thick, consists of tabular beds of fine-grained limestone interbedded with mudrocks and siliceous mudrocks, through sharp and planar contacts (E1.1, E2.2, G2.1 facies) (Fig. 4.2, Table 4.2). The micritic limestone beds vary between thin and medium, with gray to light-yellow color and are structureless. The mudrocks beds are thin to very thin, brown, and horizontally laminated. At the top of the sequence, thin to medium beds of dark-gray siliceous mudrocks with massive structures dominate. The Chicoral section measures ~11 m, characterized by calcareous mudrocks at the base and interbedded chert and mudrocks toward the top, with sharp planar contacts (E2.2, G2.1 facies) (Fig. 4.2, Table 4.2). The gray yellowish calcareous mudrock beds vary from very thin to thin, with massive structure. Very thin to thin dark-gray chert beds, show massive structure, and conchoidal fracture. The dark-gray mudrocks beds are very thin, and horizontally laminated.

Both sections are characterized by a relatively high abundant and moderately diverse trace fossil assemblage, consisting of *Chondrites*, *Planolites*, and *Zoophycos* (Fig. 4.3, Tables 4.3 and 4.4). *Chondrites* is common in both sections, characterized by its typical tree-like branching morphology and discernible in cross-sections as small circular to elliptical spots, filled with dark material. Tunnels of *Chondrites* are up to 0.2 cm wide and 4 cm long in the San Carlos section and 0.1 cm wide and 1 cm long in the Chicoral section. *Planolites* is scarce in the two sections, observed as flattened circles in cross-section, with

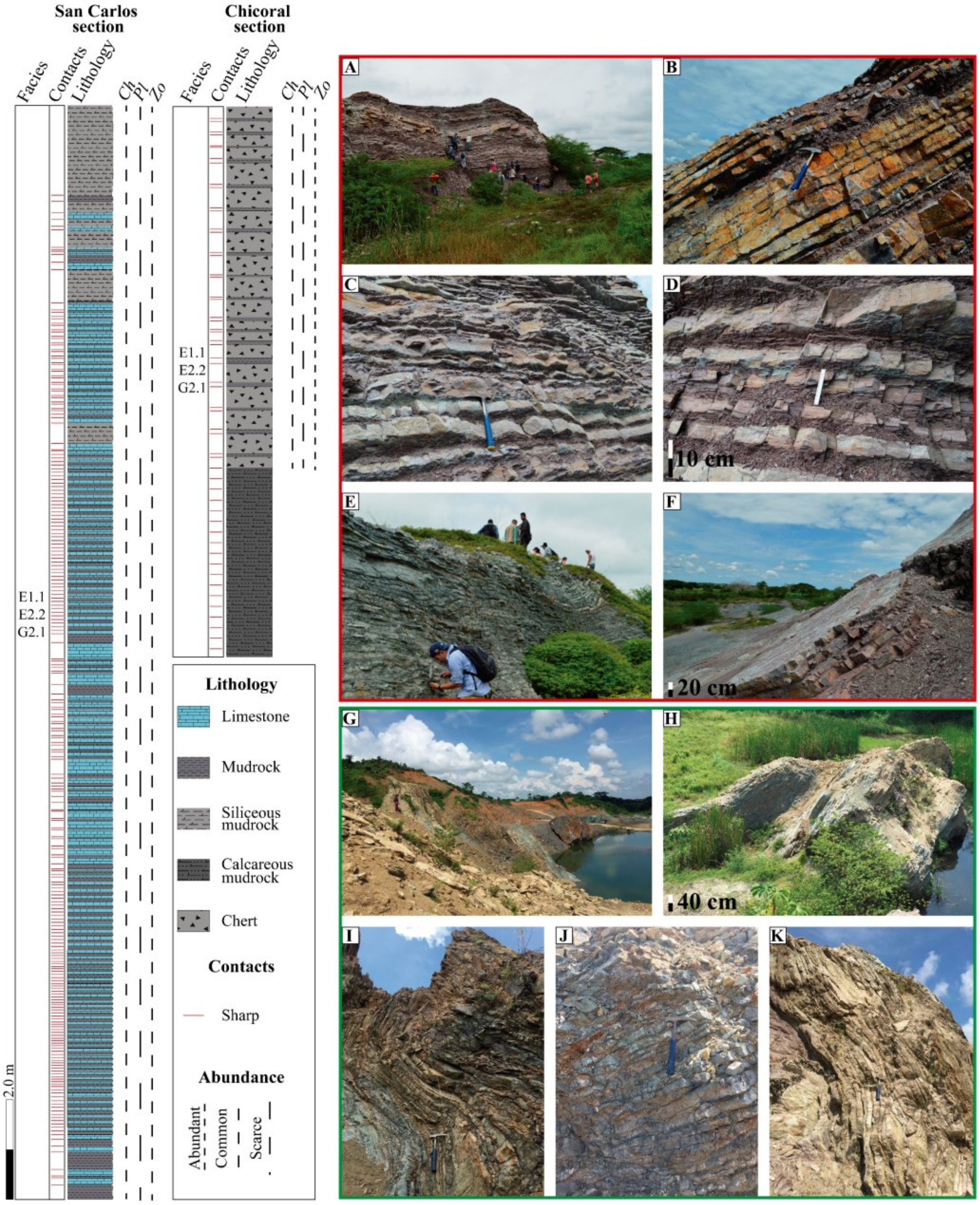

Figure 4.2. Stratigraphical logs, sedimentology, and trace fossils of the San Carlos (A-F) and Chicoral (G-K) sections in the Caribbean region. **A. B.** Outcrop views. **C. D.** Closeup views showing interlayered limestones and mudrocks in the middle part of the sequence. **E.** Siliceous mudrocks at the top of the sequence. **F.** Tabular and continuous beds of limestones and mudrocks. **G. H.** Outcrop overviews. **I.** Contact between calcareous mudrocks and chert-mudrocks interlayered. **J. K.** Detailed chert-mudrocks interlayered. Facies of Pickering and Hiscott (2016): E1.1 structureless mudrocks; E2.2 laminated mudrocks; and G2.1 biogenic mudrocks. *Ch* - *Chondrites*, *Pl* - *Planolites*, *Zo* - *Zoophycos*.

active fill, reaching up to 1 cm and 0.5 cm diameters in San Carlos and Chicoral sections, respectively. *Zoophycos* is common in the San Carlos section and abundant in the Chicoral section, observed as horizontal to sub-horizontal spreiten structures, with widths between ~6 and 25 cm.

4.4.2 Pacific Region

Detailed logs have been carried out in all the selected sections, except on the Concordia, Ciudad Bolivar and El Naranjo sections due to their pronounced deformation (e.g., Supplementary file 2).

Dabeiba section

A partial representative stratigraphical log of 3.5 m of thickness has been carried out, composed of thin and very thin beds of dark-gray siliceous mudrocks with horizontal lamination and occasionally massive structures with sharp and planar contacts (E1.1, E2.2 facies) (Figs. 4.4 and 4.5; Table 4.2). These deposits are bioturbated, showing a low abundant and diverse trace fossil assemblage, composed of scarce *Chondrites*, tunnels of 0.2 cm wide and 5 cm long, and *Zoophycos* up to 5 cm wide (Fig. 4.6, Tables 4.3 and 4.4).

Concordia section

The Concordia section is composed of siliceous mudrocks and interlayered sandstones (C2, E2.2 facies) (Fig. 4.5; Table 4.2). The dark-gray siliceous mudrocks beds are medium to very thin and horizontally laminated. The dark-green, thin- to medium-bedded, sandstone beds, are coarse to fine-grained, moderate to well sorted, normally graded, massive, laminated, and occasionally with ripple lamination. Load and flame structures are common in the contacts between sandstones and mudrocks. This section is characterized by a relatively low abundant and moderately diverse trace fossil assemblage composed of *Chondrites*, *Phycosiphon*, *Planolites*, *Thalassinoides,* and *Zoophycos*, which primarily occur in the mudrocks (Fig. 4.6, Tables 4.3 and 4.4). *Chondrites* is common, with tunnels up to 0.1 cm wide and 1 cm long. *Phycosiphon* is scarce, registered as a core filled with dark material, surrounded by a thin mantle of lighter sediment, being 0.2–0.4 cm wide, showing local concentrations (monospecific association), associated with specific mudrocks horizons. *Planolites* is scarce, reaching up to 0.5 cm in length. *Thalassinoides* is scarce, observed as circular structures in cross-section, with a passive fill, mainly of sandy material, reaching diameters up to 1.5 cm. *Zoophycos* is common, observed as horizontal to sub-horizontal well-developed spreiten structures up to 13 cm wide.

Table 4.2. Summary of the lithology, stratigraphical units, sedimentary structures, facies and trace fossils of the studied sections.

Region	Section	Stratigraphical Unit	Lithology	Sedimentary structures	Facies	Trace fossils
Caribbean	San Carlos	Cansona Formation	Limestones, mudrocks, and siliceous mudrocks	Massive, horizontal lamination	E1.1, E2.2, G2.1	*Chondrites*, *Planolites*, *Zoophycos*
	Chicoral		Chert, mudrocks, and calcareous mudrocks	Massive, horizontal lamination	E2.2 G2.1	*Chondrites*, *Planolites*, *Zoophycos*
Pacific	Dabeiba	Penderisco Formation	Siliceous mudrocks	Massive, horizontal lamination	E1.1, E2.2	*Chondrites*, *Zoophycos*
	Concordia		Siliceous mudrocks and sandstones	Massive, horizontal lamination, current ripples, normal gradation, flame structures	C2.1, C2.2, C2.3, E2.2	*Chondrites*, ?*Nereites*, *Phycosiphon*, *Planolites*, *Thalassinoides*, *Zoophycos*
	Ciudad Bolivar		Siliceous mudrocks	Horizontal lamination	E2.2	*Chondrites*, *Planolites*, *Zoophycos*
	Andes		Siliceous mudrocks and sandstones	Massive, horizontal lamination, normal gradation	C2.1, C2.2, C2.3, E2.2	*Chondrites*, *Planolites*, *Zoophycos*
	Calima	Espinal Formation	Limestones, mudrocks, chert, sandstones	Massive, horizontal lamination	C2.2, C2.3, E1.1, E2.2, G2.1	*Chondrites*, *Phycodes*, *Planolites*, *Thalassinoides*, *Zoophycos*
	El Naranjo	Cisneros Formation	Phyllites			*Chondrites*, *Planolites*, *Thalassinoides, Zoophycos*

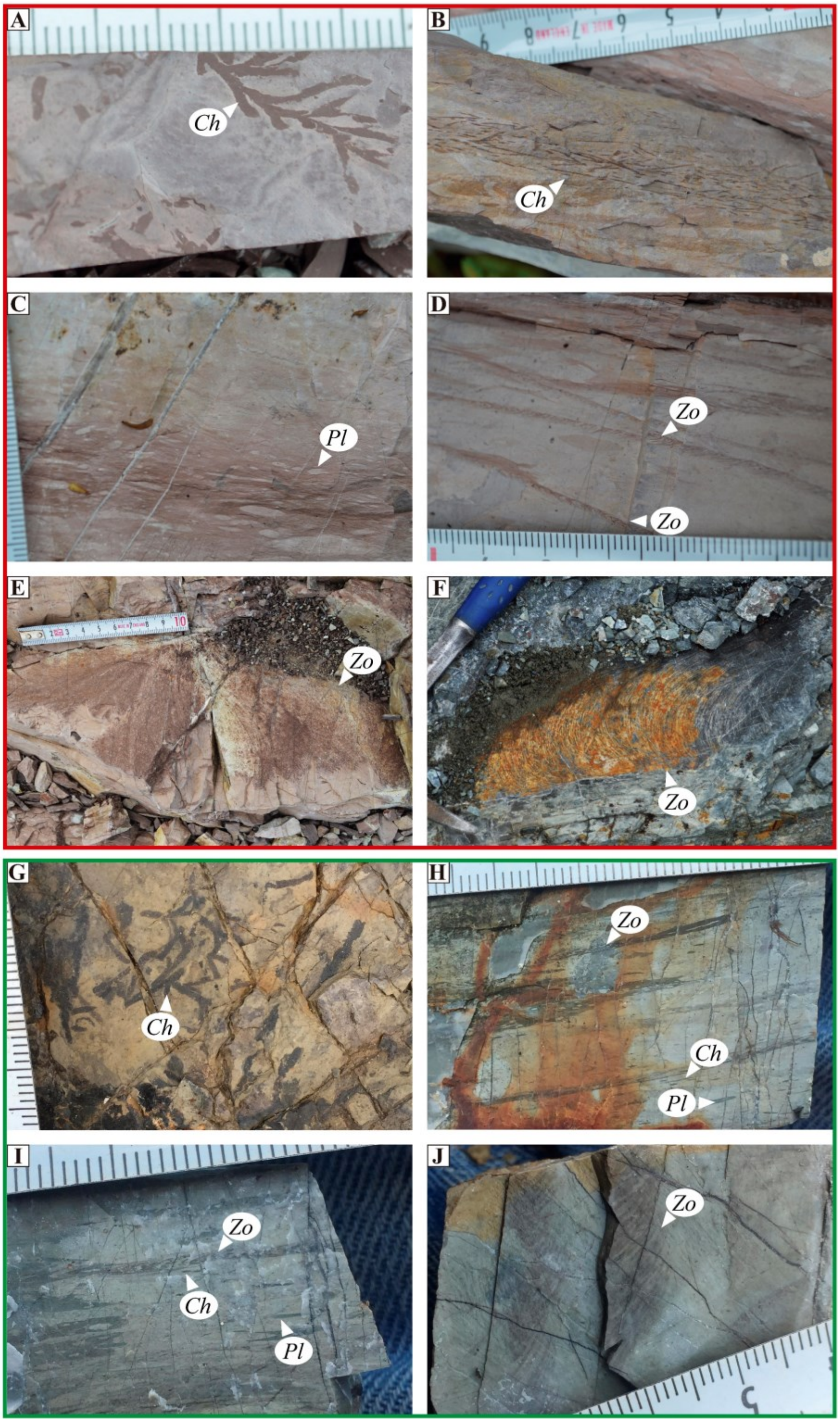

Figure 4.3. Trace fossils of the San Carlos (A-F) and Chicoral (G-J) sections. *Ch* - *Chondrites*, *Pl* - *Planolites*, *Zo* - *Zoophycos*.

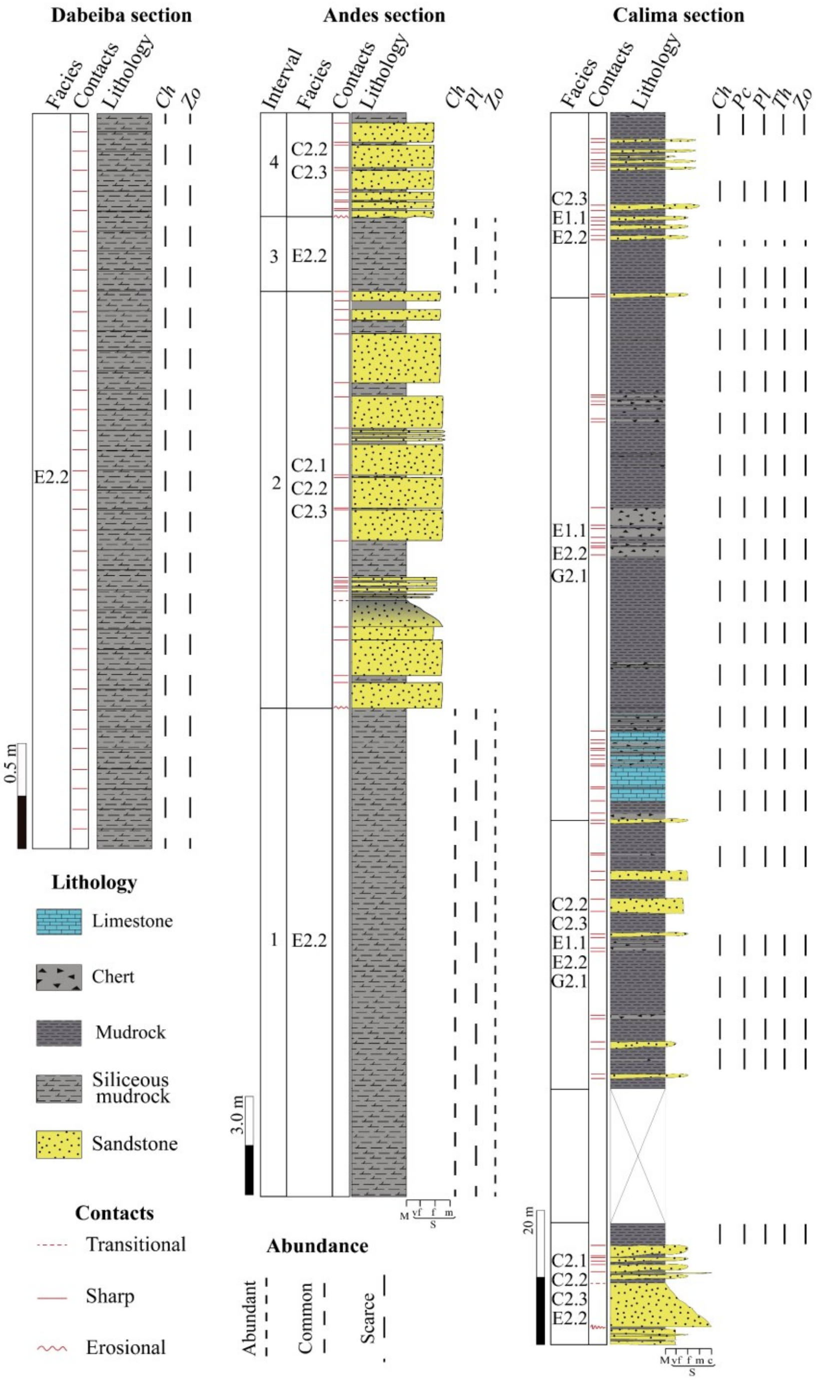

Figure 4.4. Stratigraphical logs, sedimentology, and trace fossils of the Dabeiba, Andes, and Calima sections in the Pacific region. Facies as defined by Pickering and Hiscott (2016): C2.2, C2.2, C2.3 organized sandstones- mudrocks couplets; E1.1 structureless mudrocks; E2.2 laminated mudrocks; and G2.1 biogenic mudrocks. *Ch - Chondrites*, *Pc - Phycodes*, *Pl - Planolites*, *Th - Thalassinoides*, *Zo - Zoophycos*.

Figure 4.5. Sedimentological characteristics of the Dabeiba (A-B) and Concordia sections (C-H). **A. B.** General outcrops views, showing the high deformation of the rocks. **C. D.** Siliceous mudrocks with horizontal lamination. **E.** Contact between sandstone (grayish green) and mudrocks (dark gray) with flame structure development. **F.** Sharp contact between normal graded sandstone and laminated siliceous mudrocks. **G.** Coarse-grained laminated sandstone. **F.** Fine-grained sandstones with ripple lamination.

Ciudad Bolivar section

This section is composed of thin to medium beds of highly deformed siliceous mudrocks (E2.2 facies) (Fig. 4.7, Table 4.2). These rocks are dark-gray with horizontal lamination, and bioturbated by a relatively high abundant and moderately diverse trace fossil assemblage composed of common *Chondrites* and *Zoophycos* and scarce *Planolites*, (Fig. 4.8, Tables 4.3, and 4.4).

Andes section

This ~33 m-thick section has been divided into four intervals according to its sedimentological and ichnological features (Figs. 4.4 and 4.7; Table 4.2). The first and third intervals (I1 and I3; 0–14.8 m and 27.3–29.5 m) consist of a succession of thin to very thin beds of dark-gray, laminated and bioturbated siliceous mudrocks (E2.2 facies). The second and fourth intervals (I2 and I4; 14.8–27.3 m and 29.5–33 m) correspond to interlayered sandstones and siliceous mudrocks beds with sharp, planar and erosional contacts (C2 facies). The yellow-brownish, fine to very fine-grained well-sorted sandstone beds vary between thin and thick, with massive and occasionally normal graded structures. The dark-gray and laminated siliceous mudrocks are thin to medium bedded. This section is characterized by a relatively high abundant and moderately diverse trace fossil assemblage located only in the muddy intervals (first and third), composed of common *Chondrites*, up to 0.3 cm wide, scarce *Planolites*, reaching up to 2.5 cm in length, and abundant *Zoophycos*, up to 10 cm wide, (Figs. 4.4 and 4.8; Tables 4.3and 4.4).

Calima section

This ~182 m-thick section is composed of mudrocks, limestones, chert, and sandstones (Figs. 4.4 and 4.7; Table 4.2). The dark-gray mudrocks are thin to medium bedded, with massive and laminated structures (E1.1, E2.2 facies). The dark-gray, massive micritic limestones are tabular, medium to thin bedded (G2.1 facies). The black, structureless cherts are thin to medium bedded (G2.1 facies). The black-gray sandstones are thin to thick bedded with massive, laminated and normal graded structures, which are interlayered with mudrocks (C2 facies). This section presents a very scarce record of trace fossils, with *Chondrites* up to 0.1 cm wide and 2 cm long, *Phycodes*, *Planolites* up to 0.5 cm long, *Thalassinoides* developed as horizontal tunnels filled by sandy material with 1 cm diameter, and *Zoophycos*, up to 10 cm wide (Fig. 4.9, Tables 4.3, 4.4). *Phycodes* is observed as horizontal to sub-horizontal curved tubes with two-three branches originating from the same point, filled by light material. The tubes are 0.3 cm wide and 2 cm long.

El Naranjo section

This section is composed mainly of phyllites (Fig. 4.9, Table 4.2), with a well-preserved, abundant and moderately diverse trace fossil assemblage. The recognized ichnogenera correspond to common *Chondrites*, as tunnels of 0.1 cm wide and 2 cm long, *Planolites*, with tunnels up to 2 cm diameter, and *Thalassinoides*, reaching up to 2 cm in diameter, and abundant *Zoophycos*, up to 30 cm wide (Fig. 4.9, Tables 4.3 and 4.4).

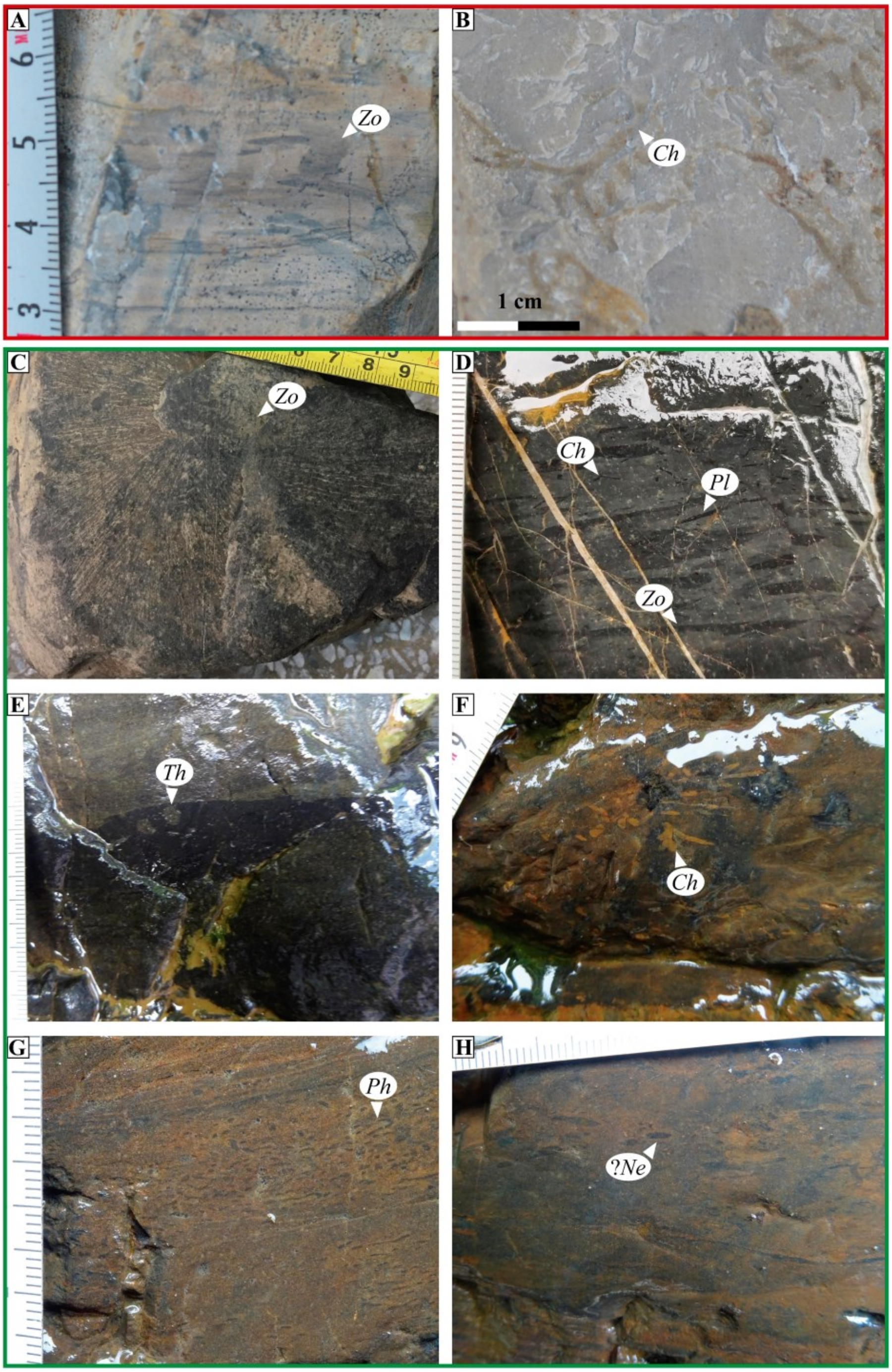

Figure 4.6. Trace fossils of the Dabeiba (A-B) and Concordia (C-H) sections. *Ch* - *Chondrites*, ?*Ne* - ?*Nereites*, *Ph* - *Phycosiphon*, *Pl* - *Planolites*, *Th* - *Thalassinoides*, *Zo* - *Zoophycos*.

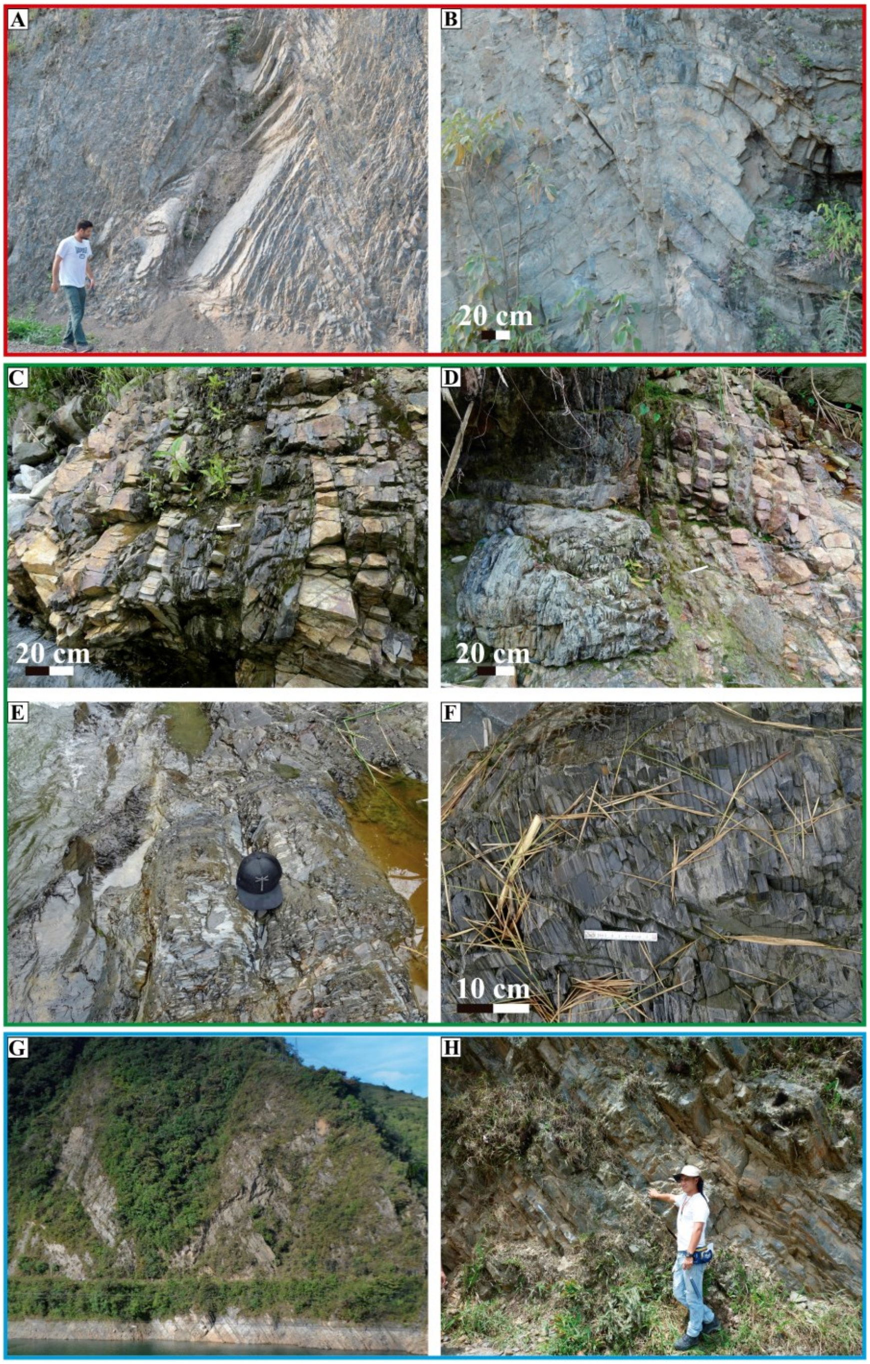

Figure 4.7. Sedimentological characteristics of Ciudad Bolivar (A-B), Andes (C-F), and Calima (G-H) sections. **A.** General outcrop views, showing the high deformation of the rocks. **B.** Deformed laminated siliceous mudrocks. **C. D.** Contact between laminated mudrocks and massive sandstone beds at the middle and upper part of the section. **E. F.** Detail of laminated siliceous mudrocks at the base of the section. **G.** General outcrop views where the stratification can be observed. **H.** Laminated mudrocks beds.

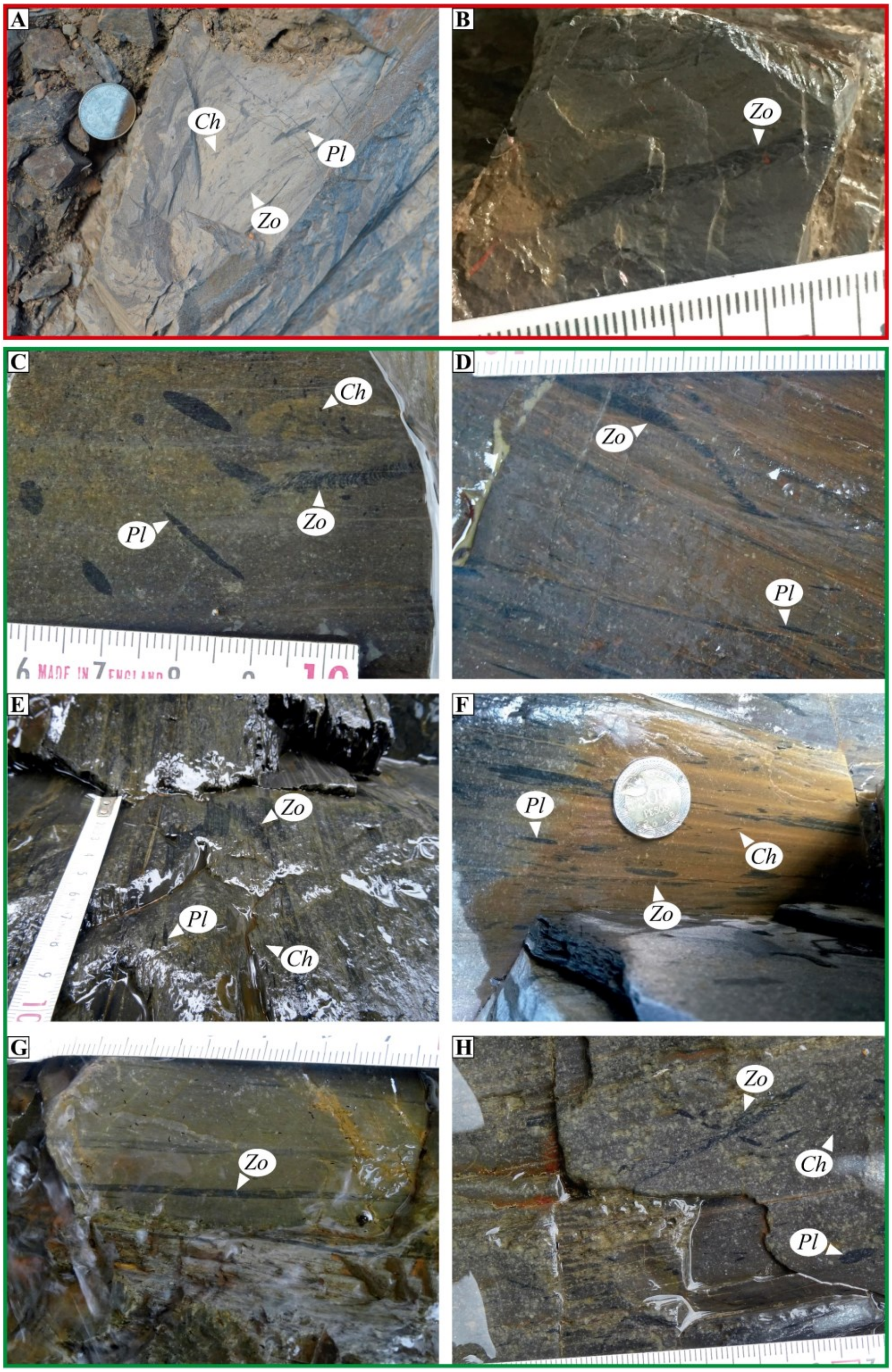

Figure 4.8. Trace fossils of the Ciudad Bolivar (A-B) and Andes (C-H) sections. *Ch* - *Chondrites*, *Pl* - *Planolites*, *Zo* - *Zoophycos*.

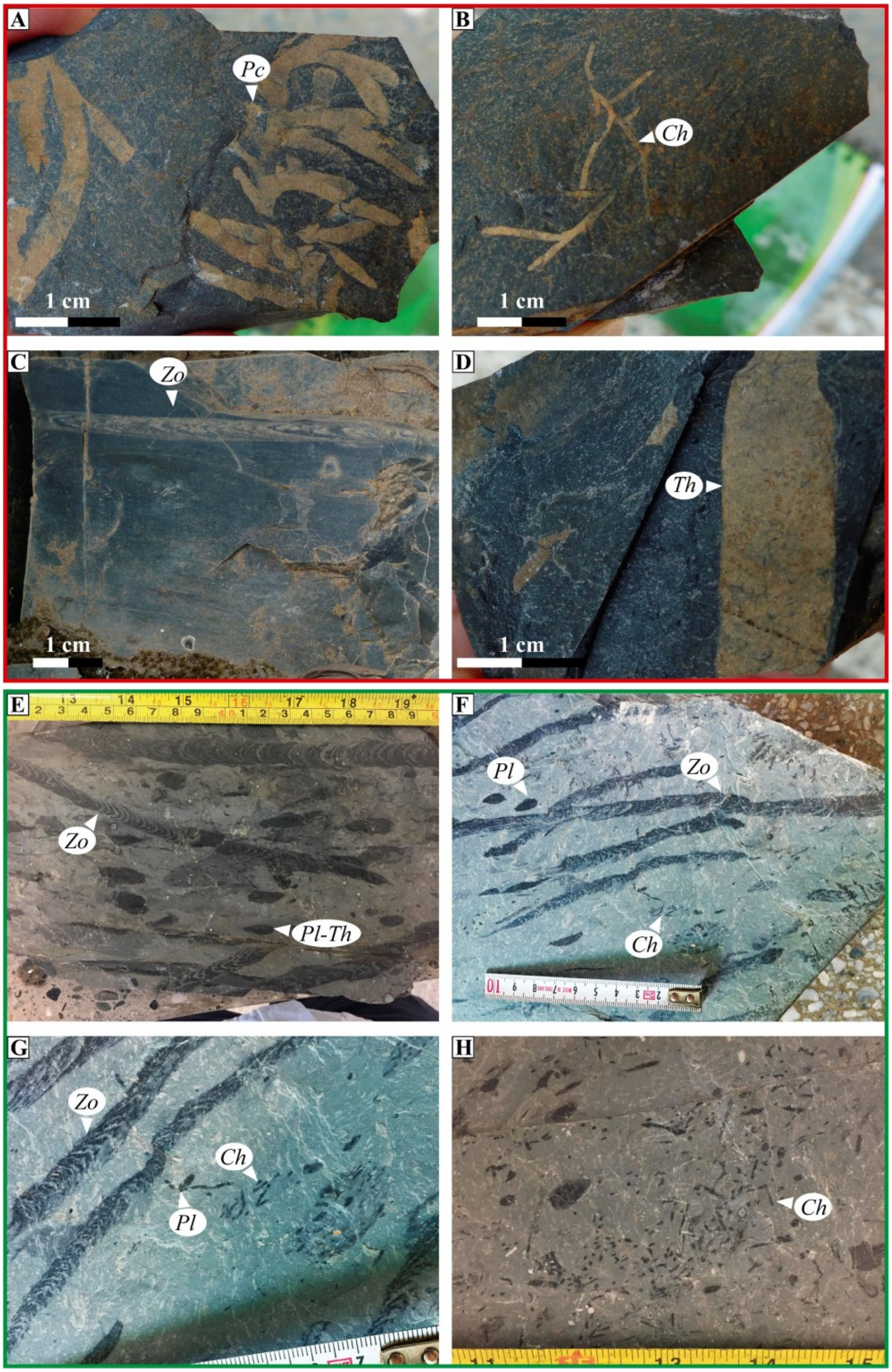

Figure 4.9. Trace fossils of the Calima (A-D) and El Naranjo (E-H) sections. *Ch* - *Chondrites*, *Pc* - *Phycodes*, *Pl* - *Planolites*, *Th* - *Thalassinoides*, *Zo* - *Zoophycos*.

Table 4.3. Distribution and abundance of trace fossils in the studied sections.

Region	Section	Traces						
		Chondrites	*?Nereites*	*Phycodes*	*Phycosiphon*	*Planolites*	*Thalassinoides*	*Zoophycos*
Caribbean	San Carlos	Common				Scarce		Common
	Chicoral	Common				Scarce		Abundant
Pacific	Dabeiba	Scarce						Scarce
	Concordia	Common	Scarce		Scarce	Scarce	Scarce	Common
	Ciudad Bolivar	Common				Scarce		Common
	Andes	Common				Scarce		Abundant
	Calima	Scarce		Scarce		Scarce	Scarce	Scarce
	El Naranjo	Common				Common	Common	Abundant

Abundant — Common — Scarce

Table 4.4. Table summarizing the ichnological features of the studied ichnotaxa. **D:** Diversity (H: high, L: low, M: medium), **Dm:** diameter.

Section	D	*Chondrites*		*?Nereites*	*Phycodes*		*Phycosiphon*	*Planolites*		*Thalassinoides*	*Zoophycos*
		Width (cm)	**Length (cm)**	**Width (cm)**	**Width (cm)**	**Length (cm)**	**Width (cm)**	**Dm (cm)**	**Length (cm)**	**Dm (cm)**	**Length (cm)**
San Carlos	M	0.2	4					1			25
Chicoral	M	0.1	1					0.5			6
Dabeiba	L	0.2	5								5
Concordia	M	0.1	1	0.5			0.4		0.5	1.5	13

Ciudad Bolivar	M	0.1	0.4					0.3	1.8		5
Andes	M	0.3						1	2.5		10
Calima	M	0.1	2		0.3	2			0.5	1	10
El Naranjo	M	0.3						2		1	30

4.5 Interpretation and discussion

4.5.1 Biostratigraphical framework

The geological complexity of the study area is reflected in the diverse biostratigraphical assignation of the deposits. However, a detailed revision of previous works allows the development of a general biostratigraphical framework involving the studied localities (Supplementary file 1, Fig. 4.10, red dots). In the Caribbean region, the San Carlos section (1, c in Fig. 4.10) was dated as Santonian-Maastrichtian by Jaramillo et al. (2011) based on calcareous nannofossils. Near Chicoral section (~ 0.7 km to the SW) in the El Purgatorio quarry (d in Fig. 4.10) consisting of the same lithostratigraphical unit of San Carlos section, Campanian-Maastrichtian ages were reported using calcareous nannofossils (Jaramillo et al., 2011). In the Pacific region, the Dabeiba section (3 in Fig. 4.10) was dated with calcareous nannofossils as Santonian-Maastrichtian (Pardo-Trujillo et al., 2020). Moreover, in this area, in the Rio Sucio bridge (k in Fig. 4.10), ~2.3 km to the SE of the Dabeiba section, Etayo-Serna et al. (1982) dated Santonian-Maastrichtian based on foraminifera, which according to the new update here performed can be assigned to Campanian-Maastrichtian (Supplementary file 1). Théry (1980) reports Coniacian-Maastrichtian foraminifera in the Dabeiba region (not indicates localities). Close to the Concordia section (~ 3.6 km to SE) (4, n in Fig. 4.10), Pardo-Trujillo et al. (2020) identified Coniacian and Coniacian-Maastrichtian bivalves and calcareous nannofossils. Close to the Ciudad Bolivar section, Rodríguez and Arango (2013) recovered Turonian and Campanian-Maastrichtian ammonites (p, q in Fig. 4.10). In the Calima section, CPC (2013) reported Campanian-Maastrichtian deposits dated by means of calcareous nannofossils and foraminifera, and Etayo-Serna (1985) also assigned Campanian-Maastrichtian ages to strata exposed in the Buga-Buenaventura road (x in Fig. 4.10) based on the occurrence of bivalves in the same lithostratigraphical unit (Espinal Formation) outcropping in the Calima section. Barrero (1979) reported foraminifera not older than Aptian from the Cisneros Formation in Buga-Buenaventura road (y in Fig. 4.10), near to El Naranjo section; the new revision allows assignation to Campanian-Maastrichtian and Cenozoic (Supplementary file 1).

Other correlated sections with similar biostratigraphical assignations have been previously reported in western Colombia (Fig. 4.10, blue dots). In the Cansona Hills and Chalan areas (a, b in Fig. 4.10), and other localities in the Caribbean region, different studies using ammonites (Camacho, 1967) and foraminifera, calcareous nannofossils and palynology (Chenevart, 1963; Duque-Caro, 1967, 1972b; Dueñas and Duque, 1981; Guzmán et al., 1994, Guzmán, 2007; Geotec, 1997; Herrera et al., 2009; Jaramillo et al., 2011; Dueñas and Gómez, 2013) assigned Coniacian and Campanian-Maastrichtian ages respectively for the Cansona Formation. Recently SGC (2019a) recovered Santonian-Maastrichtian calcareous nannofossils in the Limon Creek section (g in Fig. 4.10), in the south of the SSJB for the Penderisco Formation.

In the Western Cordillera, in the Pacific region, there also have been reported Campanian-Maastrichtian dates in the sedimentary cover. From north to south, Etayo-Serna (1989), and Díaz-Cañas and Patarroyo (2014) found Campanian-Maastrichtian ammonites and bivalves in turbidites of the Penderisco Formation in the Peque and Giraldo regions (Antioquia) (j, l in Fig. 4.10). Pardo-Trujillo et al. (2002a) report Campanian-Maastrichtian foraminifera, bivalves, and ammonites in turbiditic and hemipelagic deposits in the Apia region (t in Fig. 4.10). Moreno-Sanchez et al. (2002) report Campanian-Maastrichtian in shallow-marine deposits in the Puente Umbria (s in Fig. 4.10) region based on ammonites. In the Toro region (u, v in Fig. 4.10) (Valle del Cauca), Etayo-Serna et al. (1982) report Albian-Maastrichtian and Campanian-Maastrichtian in the same sample using bivalves and algae respectively, which allows us to conclude that the sample would be assigned to Campanian-Maastrichtian. In the Nogales-Monteloro (w in Fig. 4.10) region (Valle del Cauca), Pardo-Trujillo et al. (2002b) report Campanian-Maastrichtian ammonites and bivalves in fan delta deposits of the Nogales Formation.

According to the aforementioned, a biostratigraphical range spanning from the Turonian to the Maastrichtian can be assigned for the deposits in studied sections from western Colombia, with the Campanian-Maastrichtian as the most commonly designated interval (Fig. 4.10). Previous works realized on other stratigraphical sections have also considered this interval as the main period for the deposition of the sedimentary cover of the CLIP in western Colombia (Etayo-Serna. 1989; Pardo-Trujillo et al., 2020), considering that in some cases the oldest reported fossils are reworked (Etayo-Serna. 1989). However, it is important to indicate that local Paleogene ages has also been reported in the north of Western Cordillera (Bourgois et al., 1983; León et al., 2018), which according to Pardo-Trujillo et al., (2020), could be related to a younger unit that overlies the described Upper Cretaceous units.

4.5.2 Depositional processes and paleoenvironmental reconstruction: sedimentological and ichnofacies analysis

The sedimentary rocks of Caribbean and Pacific can be clustered into two regionally differentiated lithologic associations. The first, fine-grained lithologic association, is found in all studied sections and is characterized by cherts, fine-grained limestones, mudrocks, and calcareous and siliceous mudrocks. These lithologies show an ichnoassemblage composed of *Chondrites*, *Planolites*, *Zoophycos* in Caribbean region and *Chondrites*, ?*Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Thalassinoides*, and *Zoophycos* in Pacific regions. In general, the bioturbation is dominated by *Chondrites*, *Planolites* and *Zoophycos*, allow assignation to the *Zoophycos* ichnofacies in both regions. Low-grade metamorphic rocks corresponding to highly bioturbated phyllites observed in the El Naranjo section are also included.

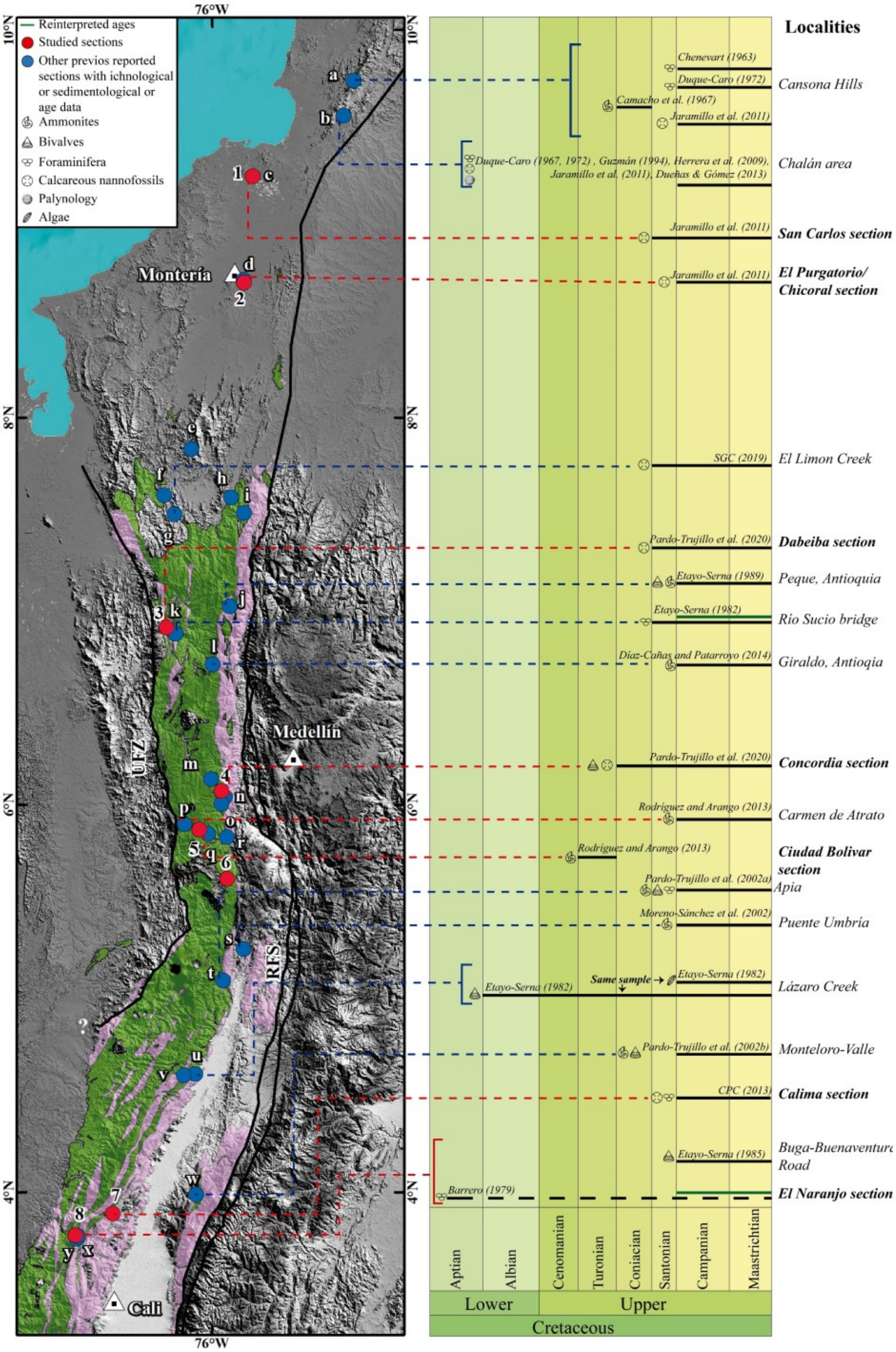

Figure 4.10. Summary of the available biostratigraphical information for the studied and correlated sections of sedimentary cover from western Colombia. Note that most of the localities are assigned to the Late Cretaceous (Campanian-Maastrichtian). The red dotted lines correspond to information reported in the studied section or in close proximity. In bold the sections considered in this work. For more details see Fig. 4.1. For the reinterpreted ages see Supplementary file 1. Geology taken from Gómez et al. (2015).

These facies associations and the ichnological content allow us to assign these deposits to E1.1, E2.2, and G2 facies, mainly associated to settling of pelagic-hemipelagic sediments from suspension, without the influence of other depositional processes as tides, waves or storms, typical of sediments deposited in shelf or basin plain environments (Stow and Tabrez, 1998; Potter et al., 2005; Nichols, 2009; Pickering and Hiscott, 2016; Stow and Smillie, 2020) (Figs. 4.11 and 4.12A). This interpretation is also supported by other features, such as bed-thickness, the continuity and tabular geometry of strata and fine-grained aggradational patterns.

The archetypal *Zoophycos* ichnofacies occurs between the *Cruziana* and *Nereites* ichnofacies, and it is associated with quiet-water settings below storm wave base, particularly in shelf to slope settings (Seilacher, 1964; MacEachern et al., 2007; 2012; Buatois and Mángano, 2011; Uchman and Wetzel, 2011). Furthermore, it is also typical in fine-grained, deep-sea deposits that characterize interturbidite phases (Wetzel, 1984, 2010; Uchman, 2007; Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar, 2022). The ichnological assemblage, mainly consisting of *Chondrites*, *Planolites*, and *Zoophycos*, registered in almost all sections, suggest basin plain environments for the studied deposits (Fig. 4.12A), and allows us to differentiate them from more proximal shelf environments, which are characterized by a higher abundance of *Thalassinoides* belonging to the *Cruziana* ichnofacies (Ekdale and Bromley, 1984; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011; Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar, 2022).

The second lithological association, observed in the Concordia, Andes, and Calima sections (Pacific region) is composed of locally bioturbated siliceous mudrocks, interlayered with sandstones assigned to C2 facies. The sedimentological features of this lithofacies association suggest turbiditic deposits (Figs. 4.11 and 4.12A). These are similar to Ta-e and Tb-e turbidites (Bouma, 1962; Walker, 1967, 1976; Mutti and Ricci Lucchi, 1972; Nichols, 2009; Pickering and Hiscott, 2016; Stow and Smillie, 2020) registered in the distal or lower fans resulting from low-density turbidity currents. The turbiditic origin for other correlative deposits, also located in the Western Cordillera, has been recently proposed based on sedimentological analysis (Pardo-Trujillo et al., 2020). These turbidite successions have no record of pre-depositional and post-depositional traces fossils.

Trace fossil assemblages from turbidite deposits are mostly assigned to the *Nereites* ichnofacies, which typically include trace fossils forming diverse meanders, spirals, and nets pertaining mostly to graphoglyptids group and others post-depositional traces such as *Chondrites*, *Nereites*, *Ophiomorpha*, *Zoophycos* (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar, 2022). Only scarce ?*Nereites* have been observed and then the archetypal *Nereites* ichnofacies could be discarded. However, the record of pre-depositional graphoglytids is not ruled out, because outcrop limitations can prevent the recognition of these traces. Therefore, we suggest that the scarcity or absence of both pre-depositional graphoglytids and post-depositional trace fossils in turbidite beds could be due to physical factors (e.g., high energy determining (i) the complete erosion of the pre-depositional structures, and (ii) inhibiting the development of post-depositional traces, e.g., *Ophiomorpha*), low frequency of sediment gravity flows, paleoecological parameters (e.g., high amount of nutrients), and/or taphonomical factors, which may have influenced or controlled the generation and/or preservation of trace fossils (Buatois et al., 2019).

Variation of depositional environments: stratigraphical distribution of facies and trace fossils

The sedimentological and ichnological record of the Andes section of the Western Cordillera in the Pacific region (Figs. 4.4, 4.7 and 4.8), allows us to interpret the possible relationship and variation of depositional environments over the CLIP during the Late Cretaceous. In this section, four sedimentation phases can be proposed according to the stratigraphical distribution of facies and trace fossils (Fig. 4.11). The first phase (interval 1) is characterized by laminated mudrocks associated with E2.2 and G2.1 facies, deposited in a basin plain environment. In this context, depositional (low sedimentation rate, low energy) and ecological (food supply) conditions were favorable for macrobenthic habitat, allowing the development of a multi-tiered tracemaker community, which is represented by *Planolites* in the shallow tiers and *Chondrites* and *Zoophycos* in the deep tiers. The second phase (interval 2), is characterized by sandy beds, interlayered with some thin mudrocks, which are associated with C2 (C2.1, C2.2, and C2.3) facies, whose genesis is related to episodic sedimentation (turbiditic deposits) in distal fan environments, disturbing background hemipelagic-pelagic sedimentation. In this context, for the studied case, colonization of the substrate diminished (disappeared?), probably due to unfavorable physical and ecological conditions (mainly high energy and sedimentation rates and low oxygen content). Then, the third (interval 3) and fourth (interval 4, T4) phases reveal the repetition of phases 1 and 2, respectively.

4.5.3 Dominant paleoecological conditions: the role of ichnological data

In deep-sea environments the main paleoenvironmental factors affecting the tracemaker communities and resulting trace fossil assemblages are sedimentation rate, organic-matter supply, and oxygenation, in most cases interrelated (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar and Dorador, 2014; Rodríguez-Tovar, 2022). Obtained ichnological information allows us to assess these factors during the sedimentation in western Colombia during the Late Cretaceous.

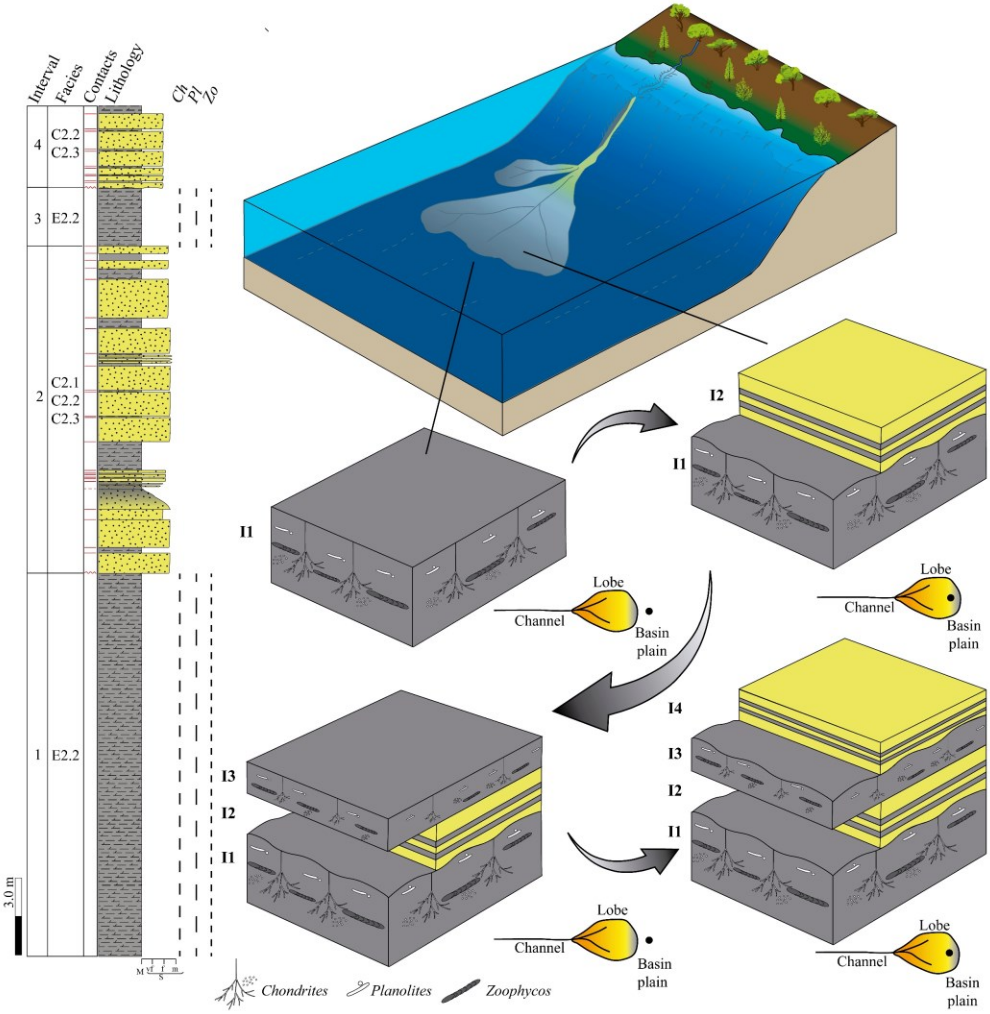

Figure 4.11. Paleoenvironmental interpretation and relationship between the depositional environments of the Western Cordillera (note relative position in respect of the lobe-basin plain and erosion in I1 and I3 intervals). I1, I2, I3, and I4 correspond to the differentiated phases and intervals in the Andes section.

Hydrodynamic energy and sedimentation rate

Hydrodynamic energy in deep-marine environments is generally very low and the sedimentation is mainly controlled by vertical settling of particles and very slow lateral advection (Stow and Tabrez, 1998; Einsele, 2000) as evidenced by the sedimentary record of the interpreted basin plain deposits. At the ichnological level, these deposits show the preservation of upper tiers traces, reflecting the activity of tracemaker just below the sediment-water interface, such as ?*Nereites*, *Phycosiphon*, and *Planolites*, revealing the absence of significant erosional processes at the seafloor surface. However, this general low-energy environmental conditions were interrupted by episodic increases in energy associated with turbiditic processes, causing erosion of the seafloor and rapid deposition of turbidites, preventing preservation of shallower tiers traces (e.g., graphoglytids) and bioturbation in the turbidite beds.

One of the main physical factors affecting *Zoophycos* distribution is sedimentation rate (Wetzel and Werner. 1981; Gaillard and Olivero, 1993; Olivero, 1996; Olivero and Gaillard, 1996; Löwemark et al., 2006; Kotake, 2014; Löwemark, 2015; Richiano, 2015; Dorador et al., 2016). The abundance and large-sized Zoophycos observed in all sections (Table 4), associated with mudrocks and limestones of basin plain environments, support very low sedimentation rates, mainly by vertical settling processes. Premoli-Silva and Bolli (1973) and Sigurdsson et al. (1997) report values between 0.4-1.5 cm/ka and 1.1-1.4cm/ka in correlated Campanian-Maastrichtian deposits in the Caribbean Sea, based on biostratigraphical data. These values are also similar to those (<1-20 cm/ka) indicated by Stow and Smillie (2020) for sedimentation rates in pelagic/hemipelagic environments.

Oxygenation

Zoophycos ichnofacies have been associated, among other parameters with low/poor oxygen conditions (Rhoads, 1975; Frey and Seilacher, 1980; Frey and Pemberton, 1984; MacEachern et al., 2007, 2012; Buatois and Mángano, 2011). In the studied sections, this is also supported by the general low to moderate ichnodiversity and the continuous record of *Chondrites* and *Zoophycos* traces, which are representative of low oxygen environments (Bromley and Ekdale, 1984; Savrda and Bottjer, 1986; Ekdale and Mason, 1988; Rodríguez-Tovar et al., 2015). According to Ekdale and Mason (1988) and Buatois and Mángano (2011), dominance of the fodinichnia behavior (e.g., *Chondrites* and *Zoophycos* traces) is indicative of anoxic conditions in interstitial waters, but dysoxic conditions on bottom waters. This is because *Chondrites* and *Zoophycos* maintain open connections to the seafloor. Furthermore, *Chondrites* producer is linked to poorly oxygenated bottom or pore waters capable of living in dysaerobic conditions, at the aerobic-anoxic interface, as a chemosymbiotic organism (Seilacher, 1990; Fu, 1991; Rodríguez-Tovar et al., 2015). Our interpretations are different from previous proposals, which relate the bioturbation to aerobic conditions based also in *Zoophycos* ichnofacies (called as *Zoophycos*-*Chondrites* ichnofacies) (Etayo-Serna, 1986). The low oxygenation could have favored the preservation of hydrocarbon source rocks as has been demonstrated for the Cansona Formation in the Caribbean region (Osorno and Rangel, 2015).

Although it has commonly been considered that turbiditic processes carry oxygen and nutrients deep into the basin, favoring the establishment of an abundant and diverse macrobenthic tracemaker community, some works have shown that not all turbidites carry oxygen enough to the sea-bottom (Leszczyński, 1991; Uchman, 1991, 1992; Wetzel and Uchman, 2012). This fact could be considered to interpret the low to medium diversity and abundance of traces, mainly associated with muddy deposits of western Colombia.

Nutrient availability

Wetzel and Uchman (1998) indicated several lithological and ichnological features associated with high nutrients availability in deep-marine environments. Some of these features such as dark-colored sediments, deep tiers bioturbated by feeding traces with connection to the sea-bottom surface (e.g., *Chondrites* and *Zoophycos*), and the absence of graphoglyptids are observed in our study sections. The high food supply could be related to the high productivity generated by contemporary volcanism (Frogner et al., 2001; Hamme et al., 2010; Langmann et al., 2010). The studied sections with the highest diversity, abundance, and size of traces, and therefore with the best environmental conditions for the macrobenthic habitat, are associated with the units in which the volcanic material input has been reported (Cansona Formation/San Carlos section, Penderisco Formation/Concordia section, Espinal Formation/Calima section, Cisneros Formation/El Naranjo section) (Barrero, 1979; Guzmán, 2007; Villagómez et al., 2011; Pardo-Trujillo et al., 2020). This allows us to infer that perhaps the input of volcanic material and its associated nutrients were other important factors that controlled the colonization of the sea-bottoms.

4.5.4 Regional implications: Upper Cretaceous deposits over the CLIP in western Colombia

To reinforce and discuss the conducted paleoenvironmental analysis in a regional context, previously published sedimentological, micropaleontological and ichnological information has been considered (e.g., Etayo-Serna et al., 1982, Etayo-Serna, 1986; Juliao-Lemus et al., 2016; SGC, 2019a. 2019b; Pardo-Trujillo et al., 2020).

Juliao-Lemus et al. (2016) from palynofacies analysis suggest lateral changes and hence different depositional environments for the Cansona Formation. Based on lithological features they describe pelagic, hemipelagic, and turbiditic deposits from the analyzed sections, and conclude proximal or onshore environments in the north in Cansona Hills and offshore or distal environments to the south in Lorica (San Carlos section in the present research) and Monteria at El Purgatorio quarry, close to the Chicoral section of this work. In contrast, our suggest basin plain environments for the San Carlos and Chicoral sections. Although Juliao-Lemus et al. (2016) suggest a paleobathymetric variation based on palynological data, it is important to highlight that given the turbiditic origin of some of these deposits, this material may come from shallow or terrestrial environments and could be carried into the basin by turbiditic currents or hyperpycnal flows, and not necessarily be associated with shallower or more proximal depositional environments (e.g., Zavala, 2020).

Previous researches have also reported *Chondrites* and *Zoophycos* in Upper Cretaceous units related to deep-marine environments of the Pacific region, at the Western Cordillera and western flank of the Central Cordillera to the west of RFS, which are correlated with the studied successions (Fig. 4.1). Etayo-Serna et al. (1982) and Etayo-Serna (1986) presented three sections (Figs. 4.1 and 4.10), indicating that the optimal depths for the distribution of *Zoophycos* is deeper than 1500 m. Nonetheless, it is worth mentioning that the marine ichnofacies must not be considered paleobathymeters (Frey et al., 1990; Buatois and Mángano, 2011). Parra (1984) also reports *Chondrites* and *Zoophycos*, associated with the Consólida Formation, and Pardo-Trujillo et al. (2002b) *Chondrites* and *Zoophycos* in Nogales Formation, but without any interpretation. Finally, Pardo-Trujillo et al. (2020), indicated *Nereites*, and *Chondrites*, *Planolites*, *Zoophycos*, associated with *Zoophycos* ichnofacies related to slope settings. Furthermore, lithological and ichnological features described from the studied deposits, have been also found in the Upper Cretaceous deep-sea sedimentary rocks from the Caribbean Sea (Warme et al., 1973; Sigurdsson et al., 1997) and Panamá and Costa Rica (Buchs et al., 2010; 2011), which share the same geological history.

Sedimentological and paleontological studies in both regions (Caribbean and Pacific) also included paleoenvironmental interpretations in correlative Upper Cretaceous strata of western Colombia (Fig. 4.12B). Deep-marine environments (hemipelagic and turbiditic deposits) have been interpreted in the Caribbean region for the Cansona Formation (Duque-Caro, 1972a, 1972b, 1978, 1979, 1984; Duque-Caro and Dueñas, 1987; Guzmán et al., 1994, 2004; Clavijo and Barrera, 2001; Caro and Spratt, 2003; Guzmán, 2007) and Penderisco Formation (SGC, 2019a). In contrast, other studies interpreted shallow-marine environments for these deposits (Herrera et al., 2009; Dueñas and Gómez, 2013; Bermúdez, 2016; SGC, 2019b). In the Western Cordillera in the Pacific region, deep marine settings have been proposed by Barrero (1979) for the Espinal and Cisneros formations, and by González, (2001) and Pardo-Trujillo et al. (2020) for the Penderisco Formation, and by Parra (1984) and Pardo-Trujillo et al. (2002a) for other correlative units. Shallow marine environments (shelf, prodelta, fan delta, and coastal) have been also proposed by Pardo-Trujillo et al. (2002b) for the Nogales Formation, and Moreno-Sanchez et al. (2002) for the “Sedimentitas de Puente Umbria”. This evidence a typical development of marine sedimentary environments from the shallowest to the deepest over the CLIP in the northwestern South American corner (~700 km). However, from the integration of this research and previous date, it is possible to recognize a clear predominance of deposits associated with deep-marine environments. This could evidence that these settings were more extensively developed, as opposed to the shallow-marine environments, which could have been restricted to a few kilometers of extension (Fig. 4.12A), possibly associated with the constant tectonic activity of the margin, as is the case today. However, the influence of erosional processes removing the shallow marine record is not discarded (Pardo-Trujillo et al., 2020).

Integration of all this previously mentioned ichnological and paleoenvironmental information, together with our interpretations, the chronological framework, and other geological characteristics (e.g., basement, structural position), allows us to establish a regional correlation and facies/deposits/environments distribution for the Upper Cretaceous units deposited over the CLIP outcropping to the further west of Colombia (Fig. 4.12B). This correlation shows that the western South American margin during the Late Cretaceous was dominated by deep marine settings, mainly basin plain environments, characterized by pelagic/hemipelagic sedimentation, which were affected by turbiditic flows at the westernmost part, toward the proto–Pacific Ocean. In the east, toward the proto–Central Cordillera, shallow-marine settings such as shelf, prodelta, coastal, and fan delta environments were dominant (Fig. 4.12B). Regionally, these deep-marine environments were inhabited by a similar macrobenthic tracemaker community, associated with a relatively homogeneous depositional and ecological conditions.

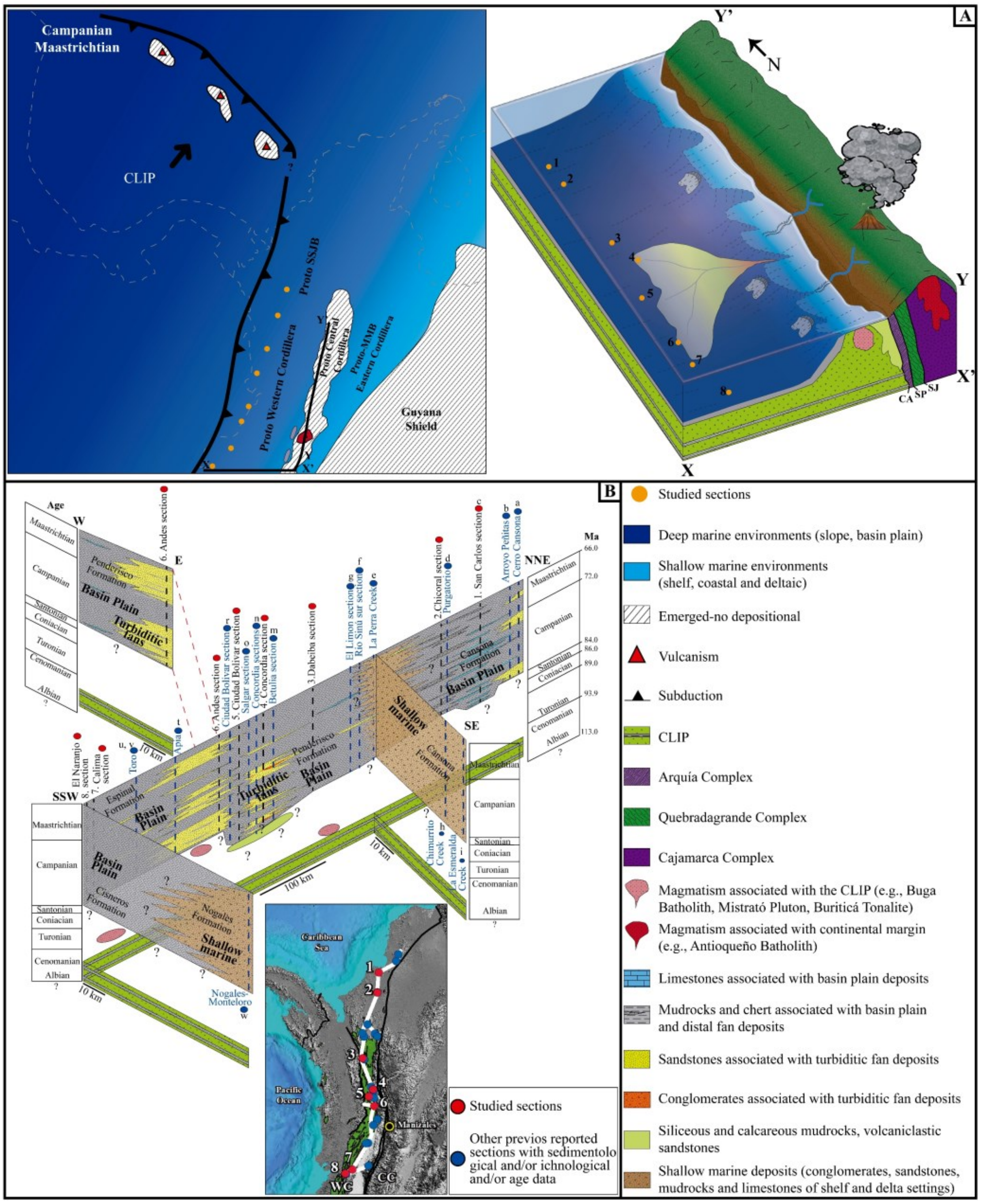

Figure 4.12. A. Paleogeography and paleoenvironmental interpretation of the studied sections. **B.** Stratigraphical correlation between Upper Cretaceous units outcropping in western Colombia. Black lines and red circles correspond to studied sections. Blue lines and circles correspond to sections studied by Juliao-Lemus et al. (2016) and SGC (2019) in the Caribbean region, and Pardo-Trujillo et al. (2002a, 2002b; 2020) and SGC (2019a, b) in the Pacific region. Paleogeography based on Moreno-Sánchez and Pardo-Trujillo (2003), Pindell and Kennan (2009), Buchs et al. (2010), Escalona and Mann (2011), Montaño et al. (2016), Bayona (2018), Montes et al. (2019), Pardo-Trujillo et al. (2020). **CA.** Cauca-Almaguer Fault. **SP.** Silvia-Pijao Fault. **SJ.** San Jeronimo Fault. See Fig 4.1 for more details of the sections.

4.6 Conclusions

The studied Upper Cretaceous marine rocks deposited over the Caribbean Large Igneous Province (CLIP) of western Colombia are characterized by successions of limestones, chert, mudrocks, and siliceous and calcareous mudrocks in the Caribbean region at the Sinú-San Jacinto Basin (SSJB), and by mudrocks, sandstones, siliceous mudrocks, and occasionally low-grade metamorphic rocks in the Pacific region, at the Western Cordillera. These deposits are partially bioturbated, showing ichnoassemblages with relatively low to moderate diversity and variable abundance, consisting of *Chondrites*, *Planolites*, and *Zoophycos* in the Caribbean region, and of *Chondrites*, ?*Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Thalassinoides*, and *Zoophycos* in the Pacific region, assigned to the *Zoophycos* ichnofacies. Lithological and ichnological features, allow us to interpret the deposits as formed in basin plain environments dominated by pelagic/hemipelagic sedimentation, affected by turbidity currents. Sea-bottom was mainly characterized by poor oxygen conditions and high benthic food availability. Low hydrodynamic energy conditions and low sedimentation rates, interrupted by episodic increases in energy associated with turbiditic processes characterized the depositional environment. Over the CLIP in the NW South American corner during the Late Cretaceous deep marine environments were development to the westernmost and shallow-marine settings to the easternmost. We suggest that possibly the deep-marine environments were more extensively developed than the shallow-marine ones, which were inhabited by a similar macrobenthic tracemaker community pointing to relatively homogeneous depositional and ecological conditions.

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Supplementary material

Supplementary file 1. Correlated sections and reinterpreted paleontological ages of some studied sections and lithostratigraphic units.

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Supplementary file 2. Deformational evidence of the Western Cordillera. A. Tight folds in the Dabeiba area (the red dotted line shows the fold axis and the white dotted lines the fold flanks). B–G. Different types of folds in the Concordia area.

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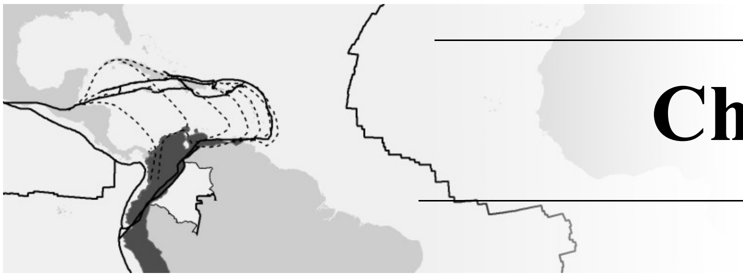


Chapter 5

EASTERN BACKARC GEOLOGICAL DOMAIN: PALEOENVIRONMENTS AND DEPOSITIONAL CONTROLS

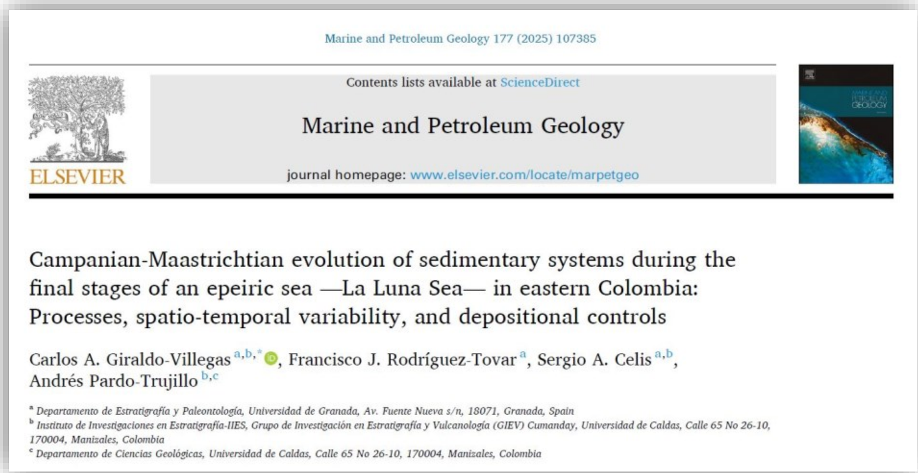
CAMPANIAN-MAASTRICHTIAN EVOLUTION OF SEDIMENTARY SYSTEMS DURING THE FINAL STAGES OF AN EPEIRIC SEA —LA LUNA SEA— IN EASTERN COLOMBIA: PROCESSES, SPATIO-TEMPORAL VARIABILITY, AND DEPOSITIONAL CONTROLS

Carlos A. Giraldo-Villegas [a,b] , Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a,b], Andrés Pardo-Trujillo [b,c]

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain

[b] Instituto de Investigaciones en Estratigrafía-IIES, Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

[c] Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia



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Campanian-Maastrichtian evolution of sedimentary systems during the final stages of an epeiric sea —La Luna Sea— in eastern Colombia: Processes, spatio-temporal variability, and depositional controls

Carlos A. Giraldo-Villegas [a,b,*], Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a,b], Andrés Pardo-Trujillo [b,c]

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain
[b] Instituto de Investigaciones en Estratigrafía-IIES, Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia
[c] Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

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Abstract

Epeiric seas were widespread during the Cretaceous, associated with global sea-level rise. Their stratigraphic record, controlled mainly by eustasy, tectonic and climatic factors, resulted in the accumulation of important hydrocarbon source and reservoir rocks. In the NW of South America-Colombia, an epeiric sea established in the Early Cretaceous—knows as La Luna Sea in the Late Cretaceous—, bounded by a volcanic arc to the western side and by the Amazonian Craton to the east, was progressively filled during the Campanian-Maastrichtian, being these latest Cretaceous deposits important hydrocarbon reservoirs for conventional petroleum systems. In the Campanian-early Maastrichtian period the western side and the central part of the basin had a normal shoreface profile, dominated by pelagic and wave sedimentation processes, while a delta profile dominated by fluvial processes characterized the eastern side. During the late Maastrichtian, directly related to the accretion of western Caribbean terranes, transitional and continental environments dominated by fluvial processes were established on both sides of the basin, suggesting changes in geomorphological-topographic and drainage system characteristics of the emerged areas, leading to the filling of the epeiric basin. The distribution of the deposits was controlled by allogenic processes: tectonism associated with the growth of the proto-Central Cordillera, the global eustatic level, and in minor degree by autogenic processes such as channel avulsion, bottom and longshore currents, and high productivity events. These processes and their variable temporal and spatial influence were responsible for the different types of deposits on either side of the basin, which had a direct impact on the establishment of macrobenthic communities, also providing new exploration ideas related to the reservoirs.

Comparisons suggest that the size of the receiving and emerged zones plays an important role in the distribution and arrangement of deposits along and across the basin, related to the nature of the internal processes involved in sediment redistribution.

Keywords: Lua Luna Sea, Cretaceous, sedimentary parameters, depositional settings, macrobenthic communities, allogenic and autogenic controls, South America.

5.1 Introduction

An epeiric sea develops when cratons are flooded during sea-level rise (Johnson and Baldwin, 1996; Pratt and Holmden, 2008). This type of sea has been widely documented in the geologic past, showing great variability due to the diversity of processes and factors involved in its origin, evolution and filling —e.g., tectonic setting, connection to adjacent oceans, sediment composition, water-column fluctuations, hydrological configuration, climatic and oceanographic variables— (Erlich et al., 2003; Schwarz et al., 2022; Ferreira et al., 2025). In these shallow seas, important factors and/or processes to estimate are how the siliciclastic material arrived and was distributed in the basin (e.g., Orton and Reading, 1993; Nittrouer and Wright, 1994; Wright and Nittrouer, 1995; Walsh and Nittrouer, 2009; Schwarz et al., 2022). Arrival depends on external basin factors that include the distribution, extent and topography of emerged areas, erosion rate, transport mechanism, and sediment paths. Distribution is controlled by internal basin factors, including waves, storms, tides, bottom and longshore currents, hypopycnal river plumes, paleobathymetric barriers and submarine gravity flows (Johnson and Baldwin, 1996; Erlich et al., 2000; Schieber, 2016). These processes and factors behind sediment arrival and its subsequent distribution in the epeiric basin affect parameters such as salinity, productivity, oxygenation and food supply, hence determining the existence, evolution, and distribution of macrobenthic communities in the depositional setting. The combination of external and internal factors, as well as physical and biological parameters, would therefore condition the origin, development, and subsequent evolution of elements of the petroleum system in hydrocarbon-producing basins.

The Cretaceous was a highly dynamic period in which diverse geologic and biologic processes occurred: important eustatic changes generating epicontinental seas, the formation of large igneous provinces (LIPs), the occurrence of Oceanic Anoxic Events (OAEs), a geographic expansion of carbonate platforms, collision of terrains, global warming and cooling, and mass extinctions (Scotese et al., 2024 and references therein). Although the imprint of all these events is recorded in the sedimentary deposits, their detection and differentiation is not an easy task and requires very detailed work that integrates different analytical tools.

In the northwestern margin of South America, especially in Colombia and Ecuador, the Cretaceous was characterized by a simultaneous occurrence of several of the aforementioned complex geologic processes (e.g., accretion of oceanic terranes, vulcanism, magmatism, eustatic sea-level fluctuations, rifting, OAEs), making it challenging to understand the geologic evolution of this region (Villamil, 1998; Villamil et al., 1999; Pindell and Kennan, 2009; Zapata et al., 2019; Paez-Reyes et al., 2021; Zapata-Villada et al., 2021). The rocks that preserve the record of these processes currently crop out in the western and eastern domains of Colombia, separated by the Romeral Fault System (RFS) acting as the tectonic boundary between these domains

(Moreno-Sánchez and Pardo-Trujillo, 2002; Vinasco, 2019; Restrepo and Toussaint, 2020; Toussaint and Restrepo 2020; Fig. 5.1). The co-existence during the Late Cretaceous of contractional processes in the western allochthonous margin related to the Caribbean Plate evolution, and extensional processes in the eastern autochthonous margin related to the South American Plate, were the dominant tectonic processes that controlled sedimentary dynamics and basin evolution of this region (Bayona, 2018; Sarmiento-Rojas, 2019; Pardo-Trujillo et al., 2020; Botero-Garcia et al., 2023; León et al., 2023). The western domain exhibits a discontinuous Cretaceous sedimentary record, with mainly Santonian-Maastrichtian deposits accumulated in deep marine environments associated with the proto-Pacific Ocean (Pardo-Trujillo et al., 2020; Giraldo-Villegas et al. 2023 and references therein), while the eastern domain has a record of shallow marine deposits associated with the development of an epeiric sea connected to the proto-Atlantic Ocean during most of the Cretaceous, and finally filled during the Campanian-Maastrichtian (Villamil et al., 1999; Erlich et al., 2000, 2003; Sarmiento-Rojas et al., 2006; Bayona, 2018; Sarmiento-Rojas, 2019; Bayona et al., 2021; Paez-Reyes et al., 2021).

The sedimentary basins associated with the eastern domain have been extensively studied due to their hydrocarbon potential, as they host significant global oil source rocks, commonly known as the La Luna Fm, now Salada, Pujamana, Galembo and La Renta formations (Terraza, 2019; Pastor-Chacón et al., 2023; De la Parra et al., 2024) and the Campanian-Maastrichtian reservoirs that are the focus of this work. The fine-grained source rocks were deposited during the Cenomanian-Campanian in an epeiric sea called the La Luna Sea (Erlich et al., 2000; Paez-Reyes et al., 2021), dominated by oxygen-deficient and highly productive environments that allowed the accumulation of large amounts of organic carbon (Villamil et al., 1999; Erlich et al., 2003; Terraza, 2019). Posteriorly, during the Campanian-Maastrichtian the uplift of the proto-Central Cordillera driven by the collision of the Caribbean Plate with the NW margin of South America, led to the deposition of coarse-grained deposits (Guadalupe Group, La Tabla Fm, Cimarrona Fm; Guerrero, 2002; Gómez et al., 2003, 2005; Sarmiento-Rojas, 2019; Giraldo-Villegas et al., 2024), which constitute important producing reservoirs in the basin (e.g., Guando, Guaduas, Colon, Cusiana oil fields). Since the Campanian-Maastrichtian deposits were also accumulated under marine influence and mark the final stages of the epeiric sea before it became a continental basin, we use the term La Luna Sea to refer to the epeiric basin developed in the northwestern of South America from the Cenomanian to the Maastrichtian.

Despite extensive research on the Cretaceous sedimentary basins of the eastern domain in Colombia, significant gaps remain in understanding of the depositional processes (physical and ecological) and spatio-temporal variability of sedimentary environments associated with the depositional controls (autogenic and allogenic) that governed the final stages of the La Luna Sea. Previous studies have primarily focused on broader stratigraphic, paleontologic and tectono-structural aspects, often emphasizing the Cenozoic, rather than Mesozoic deposits (e.g., Bayona et al., 2006, 2008, 2013, 2021; Parra et al., 2010; Mora et al., 2013, 2015a, 2015b; Bayona, 2018; Caballero et al., 2020), and recently, important works have focused on the study of the change from calcareous to siliciclastic sedimentation that occurred during the Late Campanian (Patarroyo et al., 2017; Bayona, 2018; Etayo-Serna, 2019; Patarroyo et al., 2022).

Our research, therefore, provides a detailed process-based sedimentologic and ichnologic analysis of the Campanian-Maastrichtian deposits. By integrating depositional environments and their spatio-temporal variability, this study provides for a comprehensive understanding of the physical and ecological processes involved in the sediment accumulation, controlling factors and the regional distribution of hydrocarbon reservoirs. This contribution is essential for refining regional geological models and enhancing our knowledge of the sedimentary dynamics in this region, thus offering valuable insights for future explorations and study of similar epeiric systems.

This work aims to understand the evolution of sedimentary systems during the final stages of the central part of the Late Cretaceous La Luna epeiric sea in Colombia, specifically seeking to elucidate the processes and factors that controlled the spatial and stratigraphic distribution of deposits and influenced the evolution of the macrobenthic fauna on the seafloor. Through sedimentologic, ichnologic, and paleogeographic evidence, this research furthermore provides a comprehensive understanding of the regional stratigraphic architecture and sedimentary dynamics, offering valuable insights into basin evolution, reservoir potential, and paleoenvironmental conditions in hydrocarbon-producing epeiric basins.

5.2 Geological setting and stratigraphic framework

The Cretaceous geologic evolution of the NW corner of South America was controlled by the interaction among the Caribbean, Nazca-Farallon, and South American plates (Pindell and Kennan, 2009; Montes et al., 2019; Mora-Paez et al., 2019; González et al., 2023). This interplay during the Cretaceous divided the region into two distinct geologic domains separated by the RFS —a western allochthonous domain and an eastern autochthonous domain (Moreno-Sánchez and Pardo-Trujillo, 2002; Vinasco, 2019; Toussaint and Restrepo, 2020). This plate interaction has likewise controlled the development of orogens and sedimentary basins from Mesozoic to recent times (Fig. 5.1). Several sedimentary basins linked to this interaction developed in the eastern domain of Colombia, over the South American Plate, during the Cretaceous. Today, remnants of this basins in Colombia are mainly found in outcrops of the Upper Magdalena Valley (UMVB), Middle Magdalena Valley (MMVB), Eastern Cordillera (ECB), Cesar-Ranchería (CR) and Catatumbo (CA) basins, and wells of the Eastern Llanos Basin,

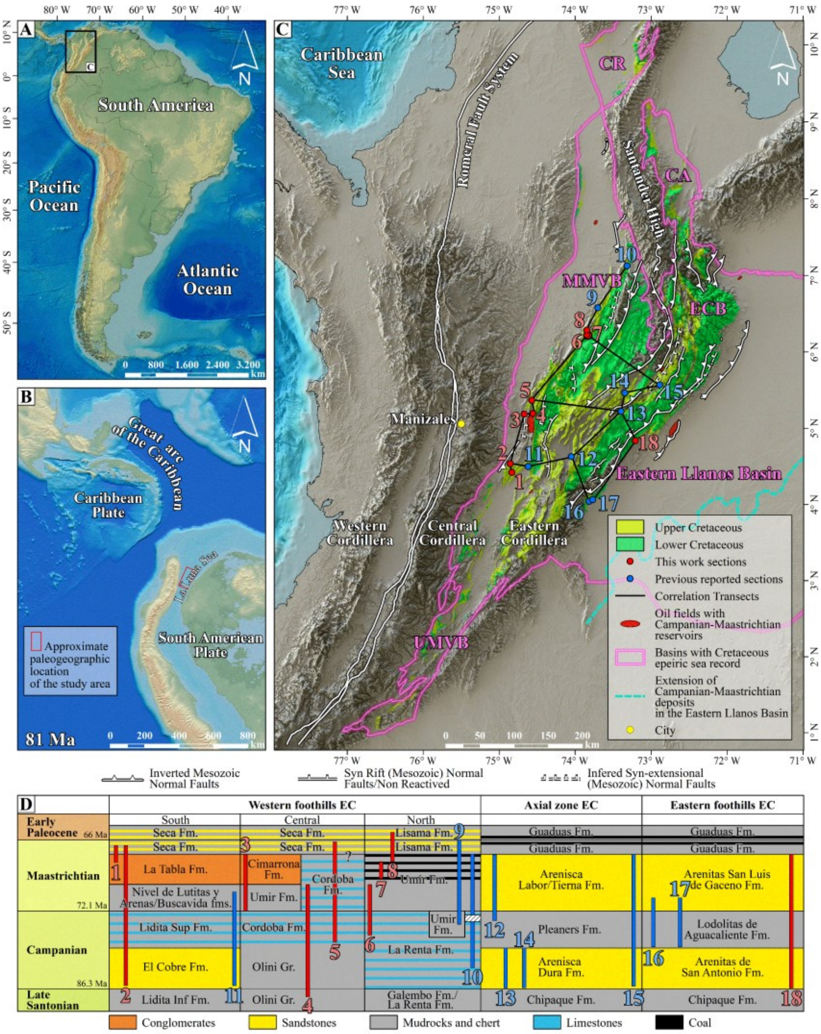

Figure 5.1. A-C. Location maps. Green marks the remnant surface outcrops of Cretaceous epeiric sea deposits in different sedimentary basins (pink polygon). CA: Catatumbo Basin; CR: Cesar-Ranchería Basin; ECB: Eastern Cordillera Basin; MMVB: Middle Magdalena Valley Basin; UMVB: Upper Magdalena Valley Basin. In red are the stratigraphic sections of this work and in blue the stratigraphic sections of Vergara and Rodriguez (1997), Garzón et al. (2012), Montaño et al. (2016), Terraza (2019), and Carvajal-Torres et al. (2022). The black lines correspond to stratigraphic correlation transects. **B.** Paleogeographic map of the northwestern corner of South America at 81 Ma, showing the La Luna epeiric sea and the approximate location of the study area (from Salles et al., 2022). **D.** Lithostratigraphic nomenclature for the Campanian-Maastrichtian deposits according to their position in the sedimentary basins and the corresponding studied sections (red bars for this study and blue bars for previously reported sections) with the age interval according to Petters (1955), De Porta (1966), Pérez and Salazar (1978). Föllmi et al. (1992), Tchegliakova (1993, 1995, 1996), Rodríguez and Ulloa (1994), Guerrero and Sarmiento (1996), Tchegliakova et al. (1997), Vergara (1997a), Vergara and Rodriguez (1997), Guerrero et al. (2000), Sarmiento and Guerrero (2000), Tchegliakova and Mojica (2001), Montaño et al. (2016), Etayo-Serna (2019), Terraza (2019), Patarroyo et al. (2022, 2023), De la Parra et al. (2024). Faults taken from Tesón et al. (2013).

UMVB and MMVB (Villamil et al., 1999; Gómez et al., 2003, 2005; Sarmiento-Rojas, 2019), all currently significant hydrocarbon-producing basins (Cediel et al., 2011). This study focuses on the central part of the epeiric basin, encompassing the UMVB, MMVB and ECB (Fig. 5.1).

These present-day sedimentary basins formed a single one during the Jurassic-Cretaceous and part of the Cenozoic (Fig. 5.1). It was an elongated NNE-SSW basin, with maximum widths of ~ 400 to 500 km, bounded by a volcanic arc (proto-Central Cordillera) to the west which was partially flooded during the Turonian-Santonian and later reemerged during the Campanian-Maastrichtian, and the Amazonian Craton to the east, as indicated by the compositional provenance of the deposits in both the eastern and western domains (Guerrero et al., 2000, 2020; Sarmiento-Rojas et al., 2006; Horton et al., 2010, 2015, 2020; Bayona, 2018; Zapata et al., 2019; Pardo-Trujillo et al., 2020; Valencia-Gómez et al., 2020; Botero-Garcia et al., 2023; Reyes et al., 2024). The origin of the former Early Cretaceous extensional basins has been linked to a rifting phase associated with the breakup of Pangaea and/or backarc extension between the Triassic and Early Cretaceous (Etayo-Serna et al., 1983; Maze, 1984; Cooper et al., 1995; Sarmiento-Rojas, 2001, 2019; Cediel et al., 2003; Gómez et al., 2003, 2005; Sarmiento-Rojas et al., 2006; Spikings et al., 2015; Leal-Mejía et al., 2019; Guerrero et al., 2020; Bayona et al., 2021). The sedimentary fill is a mixture of siliciclastic and carbonate deposits, related to the development of carbonate platforms overlain by mixed and siliciclastic shelves. During the Jurassic-Lower Cretaceous (syn-rift phase), ~3 km thick red beds and pyroclastic deposits were deposited (Etayo-Serna et al., 1983; Sarmiento-Rojas, 2001; Gómez et al., 2005; Bayona et al., 2020; Jiménez et al., 2021; Osorio-Afanador and Velandia, 2021). Subsequently, an Early Cretaceous marine transgression allowed the development of an interior sea connected with the proto-Atlantic Ocean, depositing marine rocks ~7 km thick (Cooper et al., 1995; Villamil and Pindell, 1998; Sarmiento-Rojas, 2001, 2019; Gómez et al., 2003; Sarmiento et al., 2015; Paez-Reyes et al., 2021). Variations in deposit thicknesses along the basin suggest tectonic activity during deposition. At the end of the Cretaceous, the focus of this study, the collision of allochthonous terrains in western Colombia, combined with a global sea-level fall, led to the retreat of the sea, and the accumulation of fine- and coarse-grained deposits, that now constitute important hydrocarbon sources and reservoirs in the basin. This event marked a shift in depositional systems, transitioning from marine deposition during the Latest Cretaceous to continental accumulation during the early Paleocene (Cooper et al., 1995; Sarmiento-Rojas et al., 2006; Bayona, 2018; Sarmiento-Rojas, 2019). The terrain collision is evidenced in the sedimentary record by the local deposition of coarse-grained clastic wedges near the uplifted mountain ranges (Gómez et al., 2003; Bayona et al., 2021; Giraldo-Villegas et al., 2024).

The current structural configuration of the UMVB, MMVB and ECB basins is related to a Cenozoic double vergent orogen caused by tectonic inversion processes (Cooper et al., 1995; Mora et al., 2015a; 2015b; Siravo et al., 2019). Tectonic inversion occurred through major faults on the western (La Salina Fault) and eastern (Guaicaramo Fault) boundaries, along with associated transfer faults (e.g., El Carmen, Tesalia, Pajarito; Cooper et al., 1995; Mora et al., 2013; Jiménez et al., 2022); the most positive relief zone roughly coincides with the zone of maximum subsidence during the Early Cretaceous (Casero et al., 1997; Mora et al., 2006, 2013; Sarmiento-Rojas et al., 2006).

The Cretaceous deposits of these basins have different lithostratigraphic nomenclatures owing to their wide and complex lithological variations, both vertically and laterally, in terms of depositional settings, ages and geographic locations. For the Campanian-Maastrichtian deposits in the study area, dividing the basins in three along-strike transects (western, central and eastern), the nomenclature from south to north and from west to east is as shown in Fig. 5.1.

The sedimentary record throughout the epeiric basin is not continuous, and some unevenly distributed unconformities have been identified in the uppermost Cretaceous deposits. North of the MMVB and in the UMVB, late Campanian-early Maastrichtian and Maastrichtian unconformities have been reported, separating La Renta and Umir, and Monserrate and San Francisco formations, respectively (Veloza et al., 2008; Mora et al., 2010; Bayona, 2018; Etayo-Serna, 2019; Guerrero et al., 2021; Carvajal-Torres et al., 2022; Pastor-Chacón et al., 2023; De la Parra et al., 2024).

5.2.1 Biostratigraphic considerations

Various micropaleontological analyses have been conducted on Campanian-Maastrichtian deposits in the UMVB, MMVB and the Eastern Cordillera basins, to study marine (foraminifers, calcareous nannofossils, ostracods) and continental (palynomorphs, ostracods) fossil groups. Recent research (e.g., UCaldas-ANH, 2021; Patarroyo et al., 2023) has focused on establishing a robust biostratigraphic framework for the selected outcrop sections for this work (Fig. 5.1; Supplementary file 1). However, the resolution of these data prevents the recognition of time gaps (unconformities). Our study involved 18 stratigraphic sections. From south to north along the western foothills of the central part of the Eastern Cordillera, Section 1 shows middle Campanian-late Maastrichtian ages between 4.3 and 5.9 m based on the presence of calcareous nannofossils. However, by correlation it is considered late Maastrichtian. In Section 2, ages range from the Campanian-Maastrichtian (109 – 218 m) to Maastrichtian (218 – 363 m) as identified through the integration of palynomorphs, foraminifers, ostracods, and calcareous nannofossils. Previous work reports early to late Campanian ages for this stratigraphic section based on foraminifers and ammonites (Guerrero et al., 2000; Tchegliakova and

Mojica, 2001; Patarroyo et al., 2010). Section 3 reveals a Maastrichtian age based on the integration of palynomorphs, foraminifers, ostracods and calcareous nannofossils. Middle to upper Maastrichtian ages have been previously attributed to this section based on foraminifers (Tchegliakova, 1996). Section 4 has Santonian-Campanian (31.5 – 72 m) and Campanian-Maastrichtian (72 – 185.5 m) ages, while 5 exhibits late Campanian-Maastrichtian (0 – 76 m) and Maastrichtian ages (76 – 150 m) based on the integration of palynomorphs, foraminifers and calcareous nannofossils. Section 6 shows Campanian-Maastrichtian (1.5 – 6 m) and Maastrichtian (6 – 19.5 m) ages derived from the integration of palynomorphs, foraminifers and calcareous nannofossils. Maastrichtian ages are reported for Section 7 based on palynomorphs. Maastrichtian-Paleocene ages are obtained from palynomorphs for Section 8. In Section 9, late Campanian-Maastrichtian ages are reported based on palynomorphs (Montaño et al., 2016). Patarroyo et al. (2023) assign Campanian to late Maastrichtian ages for Section 10 according to the integration of foraminifers and calcareous nannofossils and the Section 11 records deposits accumulated between the Campanian and lower Maastrichtian suggested by the palynomorphs (Garzón et al., 2012).

In the axial zone of the central segment of the Eastern Cordillera, Late Campanian-Maastrichtian ages indicated by palynomorphs are reported for section 12 (Vergara and Rodriguez, 1997). Likewise based on palynomorphs, Vergara and Rodriguez (1997) report Campanian ages for Sections 13 and 14, in agreement with those reported by Pérez and Salazar (1978) and Föllmi et al. (1992). Lower Campanian to upper Maastrichtian deposits are preserved in Section 15, as indicated by the record of palynomorphs (Vergara and Rodriguez, 1997). Along the eastern foothills of the central segment of the Eastern Cordillera, the palynomorphs in Sections 16 and 17 points to the late Campanian-early Maastrichtian (Vergara and Rodriguez, 1997; Carvajal-Torres et al., 2022), while in Section 18, early Campanian-early Maastrichtian ages are suggested by Guerrero and Sarmiento (1996), also derived from the palynomorph record.

5.3 Methodology

An outcrop-based facies analysis was conducted, entailing the description of nine Campanian-Maastrichtian stratigraphic sections situated along the current outcropping eastern and western foothills of the central portion of the Eastern Cordillera Basin, which can be associated paleogeographically with the eastern and western sides of the central part of the La Luna Sea: eight located on the western foothills (Sections 1 to 8) and one on eastern foothills (Section 18). Nine previously studied and well-dated Campanian-Maastrichtian stratigraphic sections were included for comparison, integration, regional stratigraphic correlation and paleogeographic interpretations: three on the western (Sections 9 to 11), two on the eastern (Sections 16 and 17), and four in the axial part

(Sections 12 to 15, Fig. 5.1). The first preliminary field descriptions of the western zone sections were developed under the 220-2021 project contract 220-2021 developed between the ANH and the University of Caldas (UCaldas-ANH, 2021). The same field sections were subsequently revisited to perform and refine the descriptions and interpretations.

Lithological and paleontological features such as bed geometry and thickness, grain size, sorting, sedimentary structures, trace fossils and fossil distribution were recorded in each section. We use the term "mudrock" to refer to lithologies with grain sizes smaller than 63 microns and having similar proportions of silt and clay. Ichnologic analysis encompassed the identification of ichnogenera considering qualitative and quantitative properties (following the ichnotaxobases of Bromley, 1996; Bertling et al., 2006, 2022). The abundance of bioturbation (bioturbation index, BI) was assessed following Taylor and Goldring (1993), ranging from no bioturbation (BI= 0) to complete bioturbation (BI= 6). Bed thickness characterization followed the proposal of Ingram (1954): laminae (<1 cm), very thin (1-3 cm), thin (3-10 cm), medium (10-30 cm), thick (30-100 cm) and very thick (>100 cm). Sedimentary facies were defined according to sedimentologic and ichnologic signatures and grouped in facies associations (FA) based on their relationships, vertical and spatial distribution, and stacking patterns, allowing for the interpretation of depositional settings, specific physical and ecological sedimentary parameters, and the overall paleoenvironmental and paleogeographic evolution.

To assess and understand the evolution of the sedimentary systems over time and space, six correlation transects were performed, including three along-strike and three cross-strike transects of the depositional system. Although paleomagnetic research concludes that the inverted rift shares similar structural trends with the exposed compressional structures (Jiménez et al., 2014), it should be noted that even though these successions are currently located towards the basin sides, their positioning does not always correspond directly to these edges due to the evolution of the basin in its inversion process. In some cases, especially in the north-south transects, different tectonic thrust sheets may be involved.

5.4 Results

5.4.1 Facies and facies associations

The integration of sedimentologic, ichnologic, and paleontologic (micro and macro) data allowed for the definition of seven facies associations (FA) in the western zone (from FA1w to FA7w), two in the central part (FA1c and FA2c), and three in the eastern zone (from FA1e to FA3e). These combinations of facies are genetically related to specific depositional environments (see Table 5.1).

Table 5.1. Description and interpretation of facies associations identified in the last stages of the central part of the La Luna epeiric sea during the Campanian-Maastrichtian.

Region	Facies association	Stratigraphic section	Lithology	Sedimentary structures	Trace fossils and fossils	Thickness	Depositional setting
Western	Mixed shelf (FA1w)	2, 4, 5, 6, 10, 11	Tabular beds of limestones (mudstones, wackestones, packstones), marls, cherts, mudrocks, shales, and bioclastic sandstones.	Fissility, structureless, horizontal lamination, asymmetric ripples.	Barren in trace fossils (BI 0); foraminifers, ammonites, bivalves, fish scraps, mollusk fragments.	~ 200 m thick	Pelagic settling from suspension in low energy, poorly oxygenated environments, with influence of bottom currents and local storms. Mixed shelf.
	Offshore (FA2w)	2, 3, 5	Tabular beds of mudrocks, muddy sandstones, sandstones, and locally marls.	Horizontal lamination, heterolithic bedding (lenticular, wavy, flaser), symmetric ripples, structureless	*Asterosoma*, *Chondrites*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Schaubcylindrichnus*, *Scolicia*, *Taenidium*, *Teichichnus*, *Thalassinoides* (BI 3 to 4); ammonites, fish scraps, inoceramids, mollusk fragments.	~ 80 m thick	Alternation of settling from suspension and high energy storm events in well-oxygenated settings. *Cruziana* ichnofacies. Offshore.
	Shoreface (FA3w)	2	Amalgamated tabular beds of very fine- to fine-grained sandstones and sandy siltstones. Locally mudrocks.	Ripple lamination, heterolithic bedding (flaser, wavy), horizontal lamination.	*Thalassinoides* (BI 1); foraminifers, carbonized wood fragments.	~ 120 m thick	High-energy environments controlled by wave oscillatory processes and storms. Shoreface.
	Fan delta (FA4w)	1, 2, 3	Amalgamated cuneiform- lenticular- and tabular-shape	Structureless, planar and trough cross-bedding,	*Arenicolites*, *Dactyloidites*, *Ophiomorpha*,	~ 100 m thick	High-energy environments and sediment source relatively close to the receiving basin. Subaerial

		medium to very thick beds of clast- and matrix-supported granule- to cobble-size conglomerates, pebble- and granule-size conglomeratic sandstones, fine- to very coarse-grained sandstones, mudrocks.	horizontal bedding, normal grading, heterolithic bedding (wavy).	*Taenidium*, *Thalassinoides* (BI= 2); bivalves, gastropods, carbonized wood fragments.		cohesionless debris and sheet flow deposits typical of alluvial fan environments. Intervals with fining- and thinning-upward trends are interpreted as channel filling, which would be arriving at the coast. The occasional presence of marine fossils and trace fossils is indicative of marine influence in the system. Fan delta complex.
Tidal flat (FA5w)	1, 2, 8	Irregular concave-up and tabular beds of very fine- to medium-grained sandstones interbedded with mudrocks. Very thin beds of mudrocks follow the tangential cross-strata foresets.	Macro-heterolithic bedding, symmetric and asymmetric ripples, flaser and wavy bedding, trough cross-bedding, bi-directional cross-bedding reactivation surfaces, structureless.	*Arenicolites*, *Rhizocorallium*, *Thalassinoides* (BI 1).	~ 50 m thick	The physical sedimentary structures (heterolithic bedding) reflect increase and decrease in the speed and energy of flows, sandy material deposited during high-energy episodes (tidal flood) and muddy material in low-energy periods (tidal ebb). Bidirectional trough cross-bedding and mud drapes associated with trough cross-bedding, forming bundled cross-bedding, are clearly indicative of tidal processes. Tidal flat.
Swamp-lagoon (FA6w)	7, 9	Tabular beds of mudrocks, carbonaceous mudrocks and coal, and tabular to lenticular beds of very fine- to medium-grained sandstones.	Structureless, horizontal lamination, symmetric and combined-flow ripples, flaser and wavy bedding.	?*Gyrolithes*, *Taenidium*, *Thalassinoides* (BI 0 to 1); mangrove palynomorphs.	~ 450 m thick	High amount of organic matter linked to mudrocks and coals is indicative of large accumulations of organic matter and areas near the continent. The dominant fine-grained lithologies are indicative of low-energy settings, e.g., lagoon or protected coastal plains.
Fluvial (FA7w)	3, 5	Amalgamated tabular to cuneiform-shaped beds of fine- to medium-grained sandstones, and tabular beds of siltstones and mudrocks.	Structureless, horizontal lamination, trough and planar cross-bedding, scour marks.	?*Taenidium* (BI 1); agglutinated foraminifers.	~ 40 m thick	Fining upward trends from erosional-base sandstones to mudrocks are characteristic of channel-floodplain deposits. Mixed- or suspended-load anastomosing river systems

Central	Offshore (FA1c)	12, 15	Tabular beds of cherts, shales, siltstones, claystones, very fine- to fine-grained sandstones.	Horizontal lamination, wavy and lenticular bedding, ripples, convolute lamination.	Indeterminate bioturbation (BI not reported); foraminifers, fish scraps.	~ 60 m thick	Offshore.
	Shoreface (FA2c)	12, 13, 14, 15	Tabular beds of medium- to very fine-grained sandstones, mudrocks, cherts.	Horizontal lamination, heterolithic bedding (flaser and wavy), planar and trough cross-bedding, hummocky and swaley cross-bedding, ripples.	Indeterminate bioturbation (BI not reported); fish scraps, foraminifers, bivalves.	~ 200 m thick	Shoreface.
Eastern	Fluvial-dominated prodelta (FA1e)	18	Tabular beds of mudrocks, siltstones, very fine-to fine-grained sandstones.	Structureless, horizontal lamination, flaser, wavy and lenticular bedding, scour marks.	*Thalassinoides* (BI 0 to 1); carbonaceous sheets.	~ 100 m thick	High amounts of carbonaceous material indicate significant terrestrial supply. This, combined with features such as internal scours, tractive and massive structures related fine-grained lithologies, may suggest traction transport or fall-out processes from turbulent flows associated with hyperpycnal and hypopycnal flows in prodelta settings.
	Fluvial-dominated delta front (FA2e)	17, 18	Tabular and lenticular beds of fine- to coarse-grained sandstones, tabular beds of mudrocks and lenticular beds or pockets of granule- to pebble-size conglomerates.	Discontinuous horizontal lamination, structureless, symmetric and combined flow ripples, trough cross-bedding, convolute lamination, normal grading.	*Conichnus*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Skolithos*, *Taenidium*, *Teichichnus* and *Thalassinoides* (BI 2 to 4); bivalves. Carbonaceous sheets.	~ 250 m thick	This facies association shows products related to high energy settings linked to oscillatory and combined flows, like those recorded in shoreface-foreshore environments. However, in contrast to shoreface settings, these successions are regarded as delta front deposits based on the abundant amount of carbonaceous material, suggesting phytodetrital pulses from fluvial discharges.

Shoreface (FA3e)	16	Tabular beds of fine- to medium-grained sandstones and mudrocks, with phosphahtic peloids and mud intraclasts.	Structureless, horizontal lamination, wavy and lenticular bedding.	Indeterminate bioturbation (BI no reported), plant remains.	~ 260 m thick	Shoreface.

The FA are organized by location related to the Eastern Cordillera Basin (western foothills, axial zone, and eastern foothills), thus by regional location within the sedimentary epeiric basin (western side, central part, and eastern side) and arranged from the most distal (deeper) to the most proximal (shallower) with respect to the coastline. Shallow marine sedimentary environments dominated by pelagic settling, waves and local tides were interpreted for the western and central parts, along with a fan delta complex and fluvial deposits. In contrast, deltaic environments dominated by hyperpycnal processes were interpreted along the eastern side.

Western foothills

This western side of the basin includes Sections 1, 2, 3, 4, 5, 6, 7 and 8. Integrated additionally are Sections 9 of Montaño et al. (2016), 10 of Terraza (2019), and 11 of Garzón et al. (2012).

FA1w: mixed to carbonate shelf

Description: FA1w is recorded in the Campanian and Maastrichtian deposits of Sections 2, 4, 5, 6, 10 and 11, being predominant in the Campanian. It shows aggradational trends (up to ~ 200 m thick; Fig. 5.2A) of thin to thick tabular beds of limestones (mainly mudstones, occasionally wackestones and packstones, according to Dunham, 1962) in some cases silicified, with horizontal lamination and occasional asymmetric ripple cross-lamination, both highlighted by foraminifers alignment (Fig. 5.2B-C), as well as structureless chert with concoid fracture (Fig. 5.2D). The lamination in limestones is laterally continuous, with lenticular sheets of segregated grains (foraminifers). In addition, thick tabular beds of horizontally laminated marls and mudrocks are observed, interbedded with black shales (Fig. 5.2E-F). Thin to very thin beds of phosphorites are also recorded separating the limestones layers. These lithologies sporadically show macro- and microfossils such as ammonites, bivalves, foraminifers, fish scraps, and indeterminate mollusk fragments. Scattered medium to thin tabular beds of fine- to very fine-grained bioclastic sandstones with horizontal lamination are seen. Bioturbation is not observed in these lithologies (BI= 0). Some levels with calcareous concretions up to 1.5 m in diameter are locally recorded. Layers of granular phosphorites are also reported by Terraza (2019) in Section 10. These successions are underlain by shoreface deposits (FA3w) and overlain by offshore deposits (FA2w).

Interpretation: The domain of mixed fine-grained lithologies (mudrocks and limestones) with foraminifers suggests pelagic settling from suspension in low-energy environments below the storm-wave base in a mixed shelf environment (Reading, 1996; Nichols, 2009; Flügel, 2010). The horizontal and asymmetric ripple cross-lamination indicates weak suspension currents (Potter et al., 2005; Stow and Smillie, 2020) or bedload transport re-

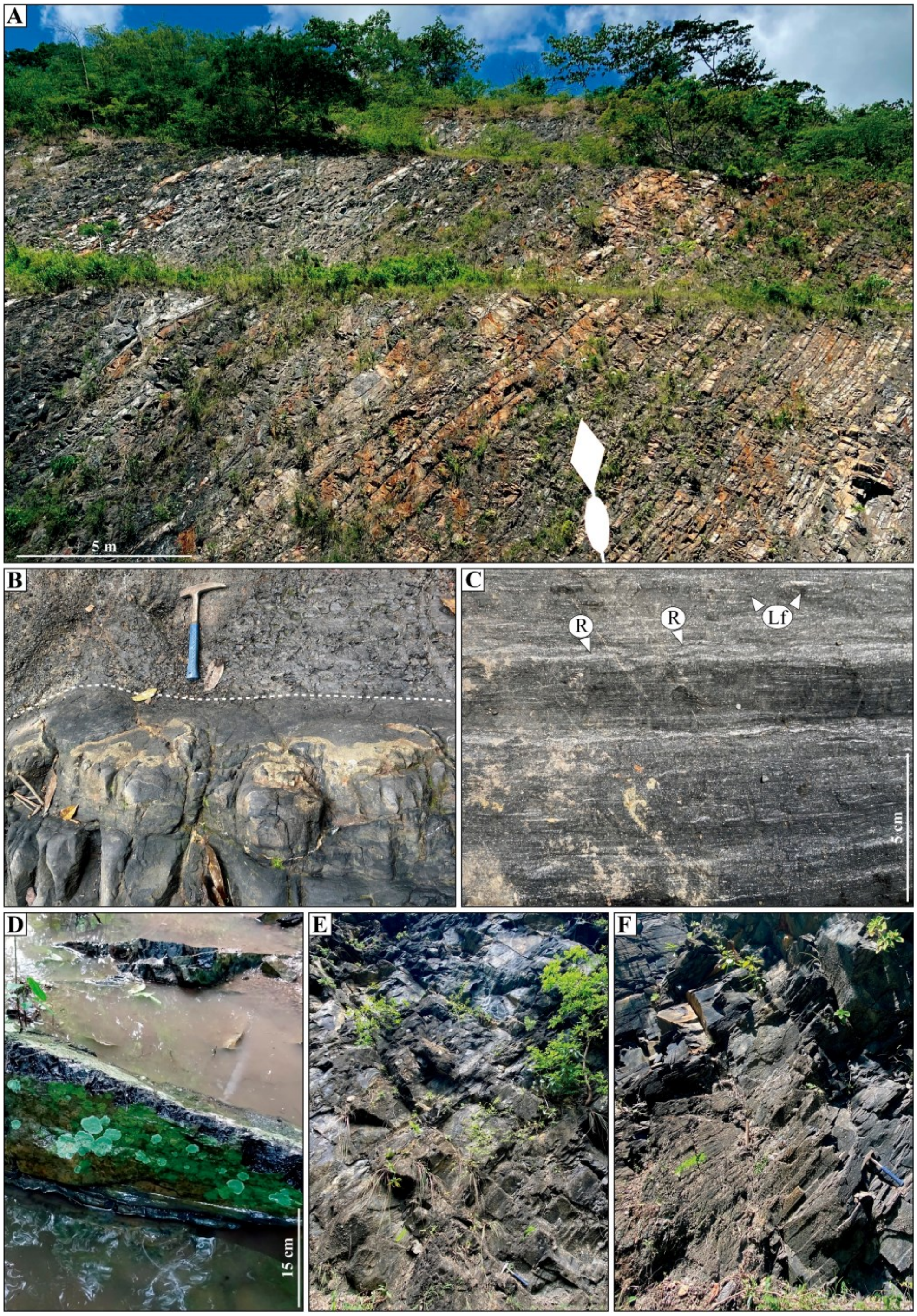

Figure 5.2. Mixed to carbonate shelf FA1w. **A.** General outcrop view of Section 5. **B.** Sharp contact between limestones (base) and mudrocks (top) in Section 6. **C.** Detail of horizontal and ripple (R) lamination, and lenticular sheets of foraminifers (Lf) in wackestones and packstones of section 6. **D.** Lenticular chert bed in Section 2. **E, F.** Mudrocks-shales interlayered in Section 4.

lated to weak bottom currents (Schieber et al., 2007; Yawar and Schieber, 2017). The bioclastic sandstones and granular phosphorites may be considered as distal tempestites linked to storm events that caused sediment remobilization (Kidwell, 1991; Glenn et al., 1994; Myrow and Southard, 1996). The high abundance of organic matter reflected in the dark colors of the rock, and the lack of bioturbation indicate high productivity and a poorly oxygenated seafloors (Ekdale and Mason, 1988; Savrdra and Bottjer, 1991; Tyson and Pearson, 1991), which could be linked to upwelling (Föllmi et al., 1992; Villamil et al., 1999; Spalletti et al., 2001). However, the discrete level with fossils suggests a macrobenthic community tolerant of oxygen-deficient environments. The origin of the chert is considered diagenetic in other parts of the basin, such as the Upper Magdalena Valley Basin, where it was derived from mudstones and wackestones that were later intensely silicified (Terraza, 2003). These silicified beds, also called "liditas", are considered regional lithological markers (Mora et al., 2010).

FA2w: offshore

Description: FA2w is observed in the Maastrichtian of Sections 2, 3 and 5. It is characterized by mudrocks, and discrete marls, sandstones and muddy sandstones, interbedded in an aggradational arrangement, resulting in successions up to ~ 80 m thick (Fig. 5.3A-C). The mudrock beds are medium to very thick, with tabular geometry, showing horizontal and lenticular (heterolithic) bedding. The sandstones and muddy sandstones beds are sharp-based, medium to very thick, tabular in geometry, fine- to very fine-grained, with horizontal lamination, symmetric ripple cross-lamination (Fig. 5.3D), flaser and wavy bedding, and locally structureless (Fig. 5.3B-E). The thick to very thick tabular beds of marls show horizontal lamination. Occasionally, intervals up to 2 m thick of amalgamated massive sandstones are present (Fig. 5.3A-B). Ammonites, fish remains, inoceramids and mollusk fragments are recorded mainly in the sandy beds. Fallen blocks exposed at the base of the some of these exposed outcrops exhibit a moderate to abundant (BI= 3, 4) and diverse ichnoassemblage composed of *Asterosoma*, *Chondrites*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Schaubcylindrichnus*, *Scolicia*, *Taenidium*, *Teichichnus*, and *Thalassinoides* (Figs. 5.3F-H). These successions are underlain and overlain by mixed shelf (FA1w) and fan delta/fluvial deposits (FA4w and FA7w), respectively.

Interpretation: The high occurrence of mudrocks represents suspended fall-out deposition in low-energy offshore environments (Stow, 1985; Stow and Tabrez, 1998). Sandstones bearing broken fossils and horizontal lamination and subordinate amalgamated massive beds may be the response to high-energy storm-related events (Walker and Plint, 1992; Myrow and Southard, 1996), whereas the symmetric ripple cross-lamination and heterolithic bedding probably formed by the action of oscillatory

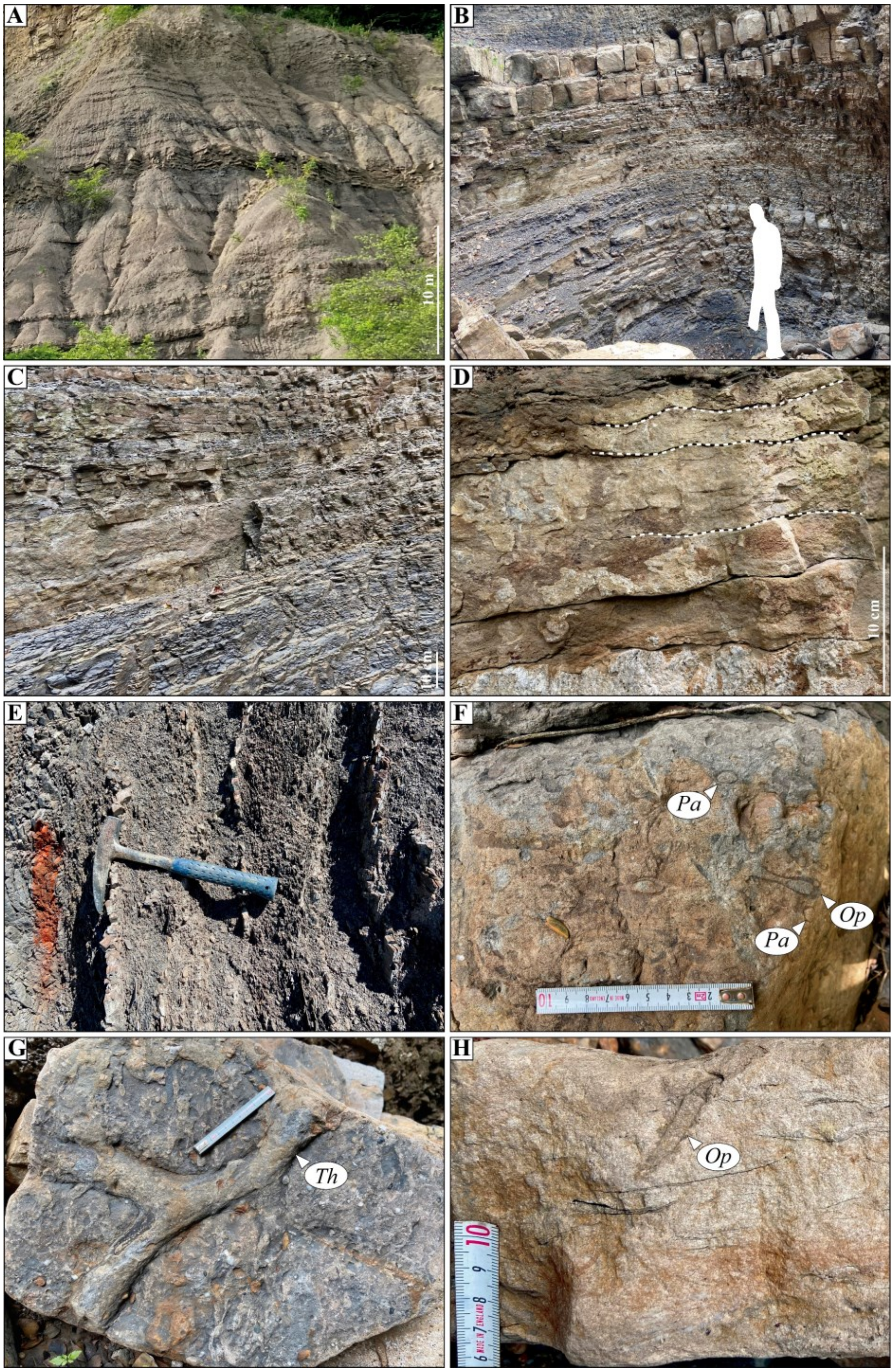

Figure 5.3. Offshore FA2w. **A, B.** General outcrop views of Section 3. **C.** Mudrock-fine-grained sandstone interbedding in Section 3. **D.** Fine-grained sandstone with symmetric ripple cross-lamination in Section 3. **E.** Mudrocks interbedded with fine-grained sandstone in Section 5. **F, G, H.** Trace fossils in fallen blocks of Section 3. *Op*: *Ophiomorpha*, *Pa*: *Palaeophycus*, *Th*: *Thalassinoides*.

flows (Dumas et al., 2005). This is supported by the trace fossil assemblage, interpreted as the *Cruziana* ichnofacies, associated with lower shoreface-offshore environments, between storm-wave base and fair-weather-wave base (MacEachern et al., 2007; MacEachern and Bann, 2008). The abundant and diverse trace fossil assemblage indicates a well-oxygenated seafloor, with benthic food available for a macrobenthic tracemaker community. In this scenario, the siliciclastic supply was high enough to dilute the calcium carbonate, avoiding limestone deposition.

FA3w: shoreface

Description: FA3w is recorded in the Campanian of Section 2. Towards the base of this section, a succession up to ~ 120 m thick comprises amalgamated thick to very thick tabular beds of very fine- to fine-grained sandstones and sandy siltstones, locally fossiliferous (foraminifers), with symmetric ripple and horizontal lamination (Fig. 5.4A-C). Sporadic mudrocks forming heterolithic bedding (flaser and wavy with symmetric and asymmetric ripple cross-lamination) (Fig. 5.4D-E), show aggradational and progradational arrangements. Occasional glauconite grains, foraminifers, charred wood fragments and *Thalassinoides* (BI= 1) are observed. These successions are underlain and overlain by mixed to carbonate shelf deposits (FA1w).

Interpretation: The record of amalgamated sandstone bedsets with ripple cross-lamination, glauconite, and occasional foraminifers suggests a relatively moderate-energy environment controlled by oscillatory wave processes in shoreface and probably some variations to foreshore settings (Reading, 1996; Einsele, 2000). The high energy caused by prolonged wave action removes mud from the seafloor, except where the local occurrence of mudrocks forming heterolites suggests a decrease in energy relative to sandstones-dominated areas (Weimer et al., 1982; Brenchley et al., 1993; Reading, 1996). The horizontal lamination can be linked to high-energy events generated by combined flows, e.g. storms (Arnott, 1993; Perillo et al., 2014). The scarce mudrock record suggests deposition above the fair-weather-wave base. The low bioturbation is indicative of a high-energy unstable environment that inhibits the establishment of a macrobenthic community. Charred wood remains indicate a nearby terrestrial source.

FA4w: fan delta

Description: FA4w occurs in the Maastrichtian of Sections 1, 2 and 3. Successions up to ~ 100 m thick show aggradational, progradational, and retrogradational patterns, characterized by amalgamated cuneiform- lenticular- and tabular-shaped medium to very thick beds of clast- and matrix-supported granule- to cobble-size conglomerates, pebble- and granule-size conglomeratic sandstones, and medium- to very coarse-grained sandstones with irregular and planar sharp bases (Fig. 5.5A). The dominant sedimentary structures of these lithologies are massive, planar and trough cross-, as well as horizontal-bedding, and normal grading. The sedimentary structures in the gravelly sandstones are often highlighted by granule- and pebble-sized clasts (Fig. 5.5B-E). The matrix varies between fine- to coarse-grained sandy material. Lateral outcrop variations in thickness are associated with the cuneiform-lenticular geometry of beds. Some fining- and thinning-

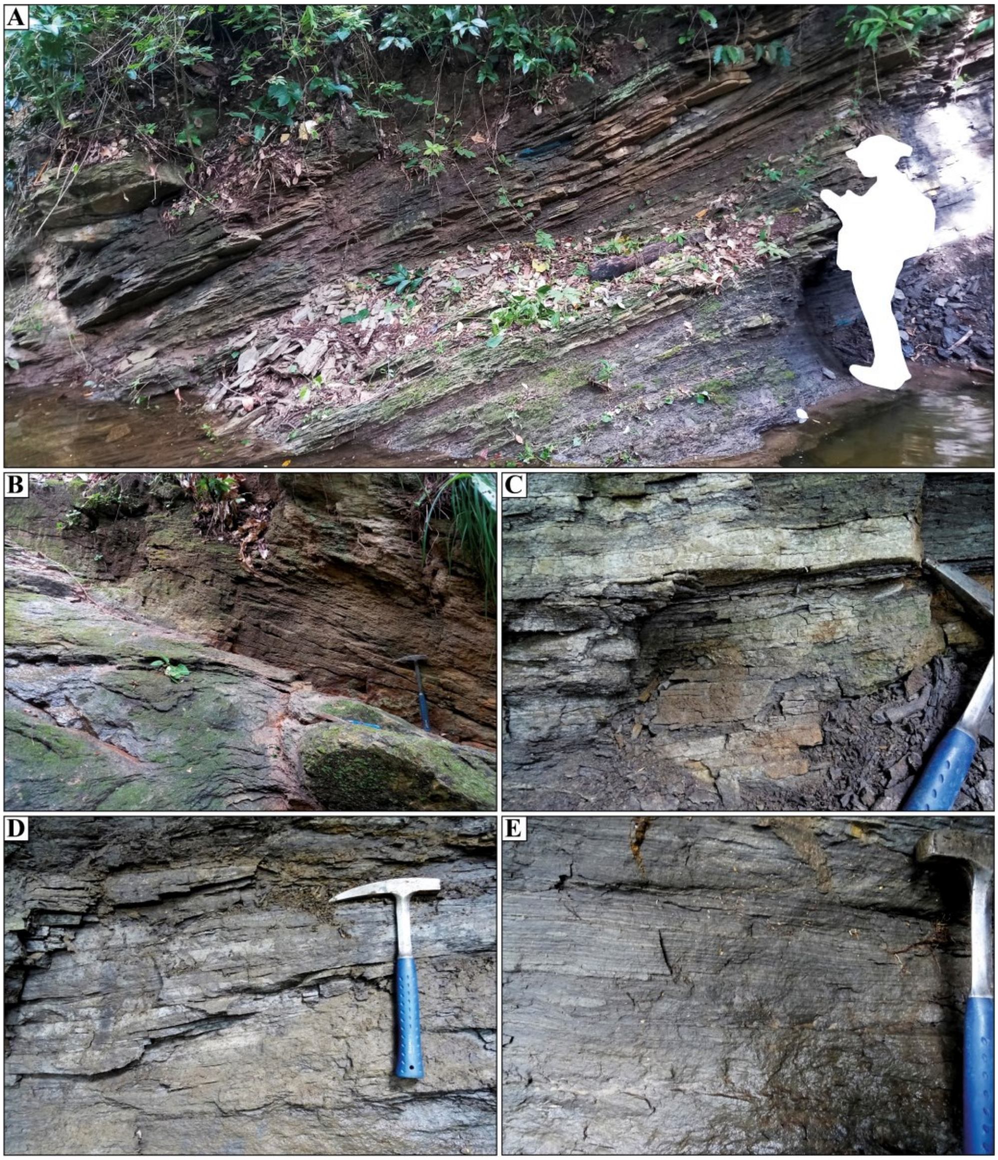

Figure 5.4. Shoreface FA3w in Section 2. **A.** General outcrop view composed of amalgamated sandstones with wavy bedding. **B, C.** Medium-grained sandstone with ripple cross-lamination. **D-E.** General and detailed views of fine- to medium-grained sandstones and sandy siltstones with wavy lamination

upward trends are observed, from cuneiform-shape beds of massive conglomerates to medium-grained sandstones with tractional structures. The clasts are poorly- to well-sorted, showing subangular to rounded and highly spherical morphologies, and mostly quartz composition. Calcareous concretions and muddy intraclasts are common features. Locally, some intercalations of fine-grained sandstones and mudrocks forming heterolithic (wavy) bedding are found overlying gravelly beds with molluscan shell fragments (bivalves and gastropods) (Fig. 5.5F). In addition, charred wood fragments and *Ophiomorpha* occur in in-situ outcrops (Fig. 5.5G), and *Arenicolites*, *Dactyloidites*, *Taenidium* and *Thalassinoides* are recorded in fallen blocks (BI= 2). These successions are underlain and overlain by offshore (FA2w), and tidal (FA5w) and fluvial (FA7w) deposits, respectively.

Interpretation: The dominance of coarse-grained lithologies suggests high-energy environments and a sediment source relatively close to the basin (Nemec and Steel, 1988). The occasional presence of marine fossils and trace fossils is indicative of marine influence in the system (Giraldo-Villegas et al., 2024). Intervals of structureless conglomerates, along with horizontally stratified and normally graded conglomeratic beds, suggest subaerial cohesionless debris and sheet flows deposits typical of alluvial fan environments (Nemec and Steel, 1988; Blair, 1999; Sohn et al., 1999; García-García, 2004; Boggs, 2014). Conglomerates and sandstones with *Ophiomorpha* and mollusk shell fragments are associated with mouth bar deposits reworked by marine processes, representing a seaward migration of the sedimentary system (Lowe, 1982; Kleinspehn et al., 1984; Nemec and Steel, 1984; Ainsworth et al., 2016; van Yperen et al., 2020; Giraldo-Villegas et al., 2024). Intervals with fining- and thinning-upward trends are interpreted as channels that would have reached the coast (Miall, 1996; Einsele, 2000; Longhitano, 2008; Yeste et al., 2020). Structureless conglomerates represent the bedload or channel-floor lag deposits transported by the river during the peak flood, while the cross-bedding features attest to gradual filling of active channels related to the migration of bedforms (2D and 3D dunes or megaripples) (Lowe, 1982; Nemec and Postma, 1993; Miall, 1996; Reading, 1996). The horizontal lamination associated with these successions may reflect the development of longitudinal bar bedforms in the channels (Hein and Walker, 1977; Miall 1996), or else could be related to short-lived increases in channel energy or stream velocity (Flemming, 2000; Yeste et al., 2019). Some thin beds of mudrocks and fine-grained sandstones associated with these channel successions may correspond to floodplains in the fluvial system (Miall, 1996). The amalgamated cuneiform- and lenticular-shaped beds of coarse-grained sandstones and conglomerates are interpreted as multi-storey channels or as the result of rapid runoff during or after sudden rainstorms on the alluvial fans (Siggerud and Steel, 1999; Scherer et al., 2015; Varejão et al., 2021). Furthermore, the heterolithic intervals overlying the coarse-grained marine influenced deposits indicate wave and tidal activity in the more distal parts of the

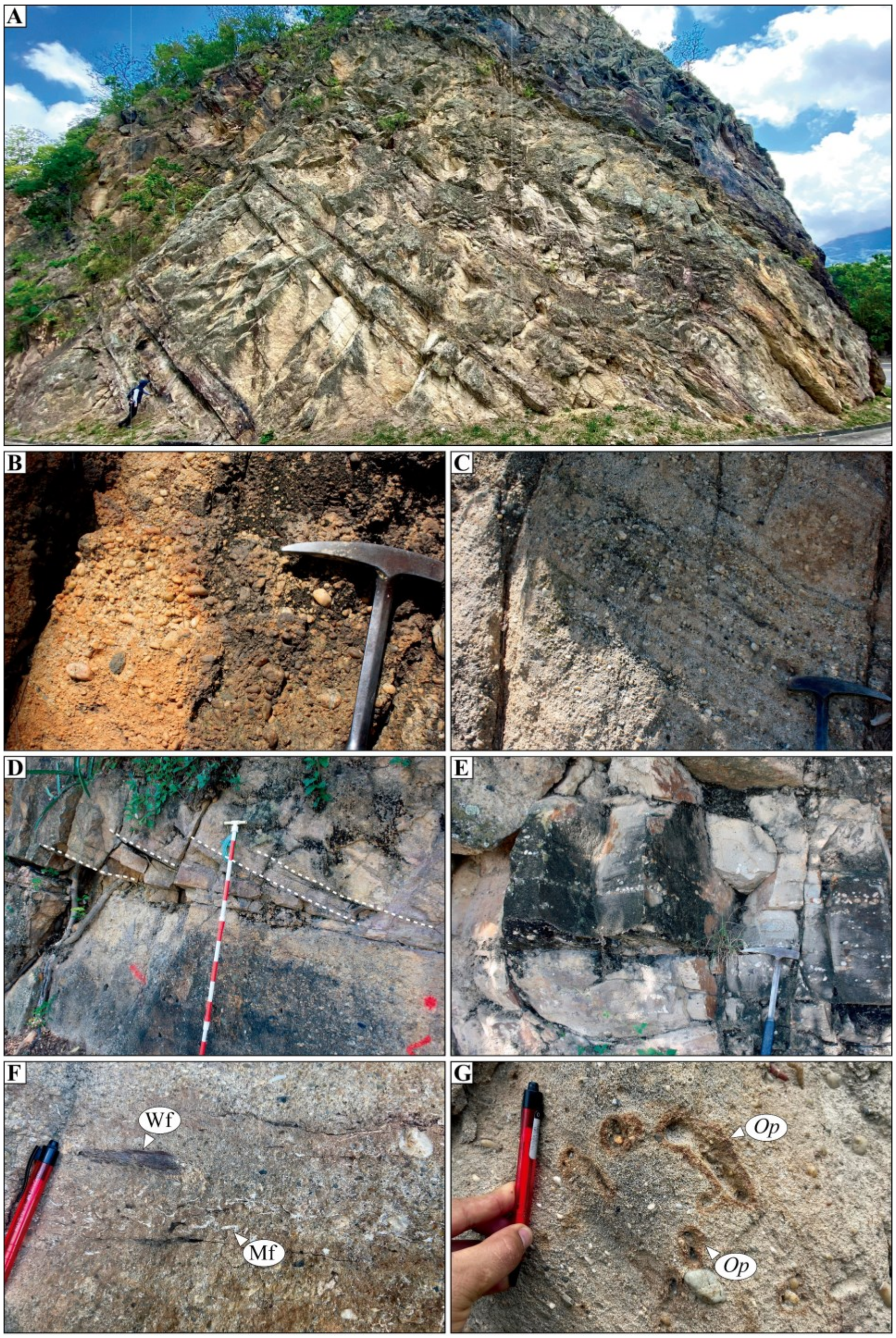

Figure 5.5. Fan delta FA4w in section 3. **A.** General outcrop view. **B.** Massive clast-supported conglomerate dominated by quartz. **C.** Granule-size conglomerate with planar cross-bedding. **D.** Conglomeratic sandstones with trough cross-bedding. **E.** Conglomeratic sandstone with horizontal lamination. **F.** Conglomeratic sandstone with mollusk shell fragments (Mf) and charred wood fragments (Wf). **G.** *Ophiomorpha* (*Op*) in conglomeratic sandstone.

system (e.g., Ainsworth et al., 2016). This relationship between alluvial, fluvial and marine processes and the resulting deposits signals a fan delta complex setting (Gómez and Pedraza, 1994; Nemec and Steel, 1988; Giraldo-Villegas et al., 2024). The establishment of these prevailing marine processes in the fluvial-dominated sedimentary system could indicate upstream avulsion of fluvial channels, or relative sea-level variations.

FA5w: tidal flat

Description: FA5w is recorded in the Maastrichtian of Sections 1, 2 and 8. It occurs as sandstones interbedded with mudrocks (Fig 5.6A), generating in some cases macro-heterolithic bedding (Fig. 5.6B) that forms aggradational trends, resulting in successions up to ~ 50 m thick. Irregular concave-up and tabular beds of sandstones are recorded, ranging from thin- to thick, very fine- to medium-grained, with asymmetric, and locally symmetric ripples, flaser and wavy bedding (Fig. 5.6C-E). Intervals of medium- and fine- to very fine-grained sandstone sheets are interbedded, forming a type of "horizontal lamination" that is locally interrupted by massive sandstones (Fig. 5.6F). Thick stacked sets of trough cross-bedding with reactivation surfaces and locally bidirectional cross-bedding are also present, occasionally with very thin beds of mudrocks following the tangential cross-strata foresets (mud drapes; Fig. 5.6G-H). The mudrock beds are thin to thick, structureless, found filling the concave-up morphology of sandstone beds. Trace fossils such as *Arenicolites*, *Rhizocorallium* and *Thalassinoides* are registered in the sandstone beds (BI= 1). A mixture of marine (dinoflagellates and foraminiferal linings) and continental (pollen and spores) elements are found in these deposits (UCaldas-ANH, 2021). These successions are respectively underlain and overlain by fan delta (FA4w) and fluvial (FA7w) deposits.

Interpretation: Physical sedimentary structures (heterolithic bedding) reflect changes (increase/decrease) in the velocity and energy of flows, sandy material being deposited during high-energy episodes (tidal flood) and muddy material during low-energy periods (tidal ebb) in marine settings, as indicated by the marine trace fossil assemblage (Reineck and Singh, 1973; Allen, 1982; Davis and Dalrymple, 2012). Features such as bidirectional trough cross-bedding and the mud drapes associated with trough cross-bedding, forming bundled cross-bedding, are evidence of tidal processes (Davis and Dalrymple, 2012; Longhitano et al., 2012; Steel et al., 2012). Sandstone beds with sets of trough cross-bedding can be linked to tidal dune bedforms (Longhitano and Nemec, 2005; Davis and Dalrymple, 2012) and the sandstone sheets showing horizontal lamination may indicate the development of tidal rhythmites. Additionally, some thick structureless sandstone layers could potentially reflect the influence of storm events (Archer, 1991, 1995; Dalrymple, 1992; Longhitano et al., 2012). The scarce and scattered bioturbation suggests

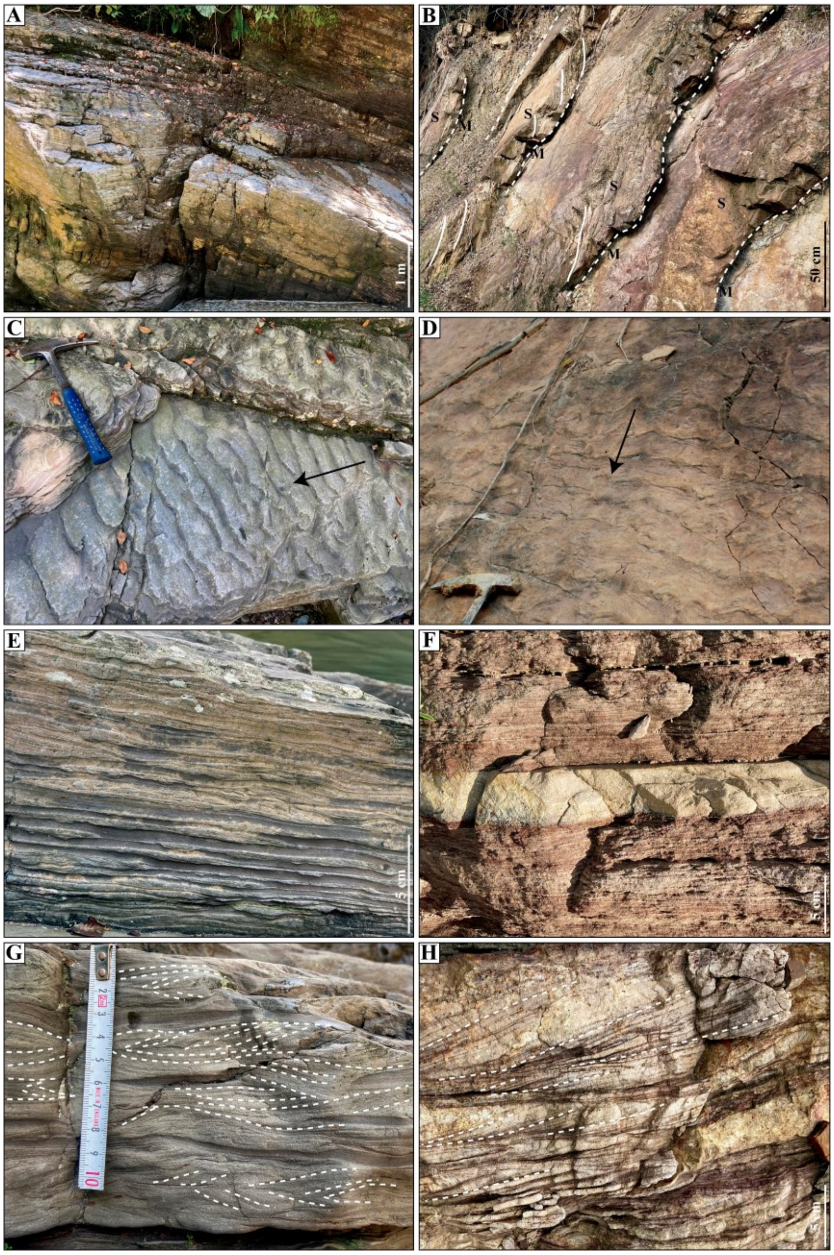

Figure 5.6. Tidal flat FA5w. **A.** General outcrop view of Section 8, with interbedded mudrocks and sandstones forming heterolithic bedding. **B.** Macro-heterolithic flaser bedding in Section 1 (S: sandstone, M: mudrocks). Note the irregularly-shaped beds and the mudrocks filling the concave-up bed morphologies. **C, D.** Asymmetric ripples in Sections 8 and 2, respectively. Arrows indicate flow direction. **E.** Wavy heterolithic bedding in Section 8. **F.** Medium- to very fine-grained sheet sandstones forming horizontal lamination in Section 1. **G.** Fine-grained sandstones with bi-directional trough cross-lamination in Section 8. **H.** Fine-grained sandstone with trough cross-bedding and mud drapes following the foresets in Section 2 (bundled cross-bedding).

unfavorable marine habitats for macrobenthic communities, perhaps related to unstable substrates. Symmetrically-rippled sandstones point to a local influence of wave processes (Dumas et al., 2005).

FA6w: swamp-lagoon

Description: FA6w occurrs in the Maastrichtian of Sections 7 and 9. It is characterized by mudrocks, carbonaceous mudrocks, coals and sandstones in aggradational successions up to ~ 450 m thick (Fig. 5.7A). Thin to medium tabular mudrock beds show horizontal lamination. Coal beds of massive structure and typical concoid fracture show tabular geometries with thicknesses ranging from medium to thick. The sandstone beds range from thin to thick, fine- to medium-grained, featuring tabular and lenticular geometries, and having asymmetric and combined-flow ripples and flaser and wavy bedding (Fig. 5.7B-F). Punctual records of ?*Gyrolithes*, *Taenidium*, and *Thalassinoides* (BI= 1) are observed (Fig. 5.7G-H). These deposits contain low records of marine elements (dinoflagellates and foraminiferal linings) and high abundances of continental palynomorphs (pollen and spores; UCaldas-ANH, 2021). Montaño et al. (2016) report beds with marine and mangrove palynomorphs in Section 9. These successions are underlain and overlain by shelf (FA1w) and tidal deposits (FA5w), respectively.

Interpretation: High amounts of organic matter associated with mudrocks and coals indicate large accumulations of continental origin. However, the weak marine influence evidenced in the record of marine trace fossils and of mangrove and marine palynomorphs (Montaño et al., 2016) suggests that the accumulation occurs in continental areas locally flooded by the sea. The dominant fine-grained deposits suggests low-energy environments, such as lagoons or protected coastal plains. Heterolithic bedding may be related to local tidal and/or wave influence in the system.

FA7w: fluvial

Description: FA 7w is present in the Maastrichtian of Sections 3 and 5. It consists of tabular beds of mudrocks and claystones, either structureless or displaying horizontal lamination (Fig. 5.8A-B). These beds are occasionally interbedded with tabular and cuneiform sandstone beds, which may be structureless or exhibit horizontal lamination, as well as trough and planar cross-bedding, occasionally highlighted by granule-size clasts (Fig. 5.8C-F). The sandy levels show fining-upward trends, transitioning from thick amalgamated medium-grained sandstones to thin fine- to medium-grained beds and mudrocks, forming successions up to ~ 5 m thick, before reverting to a dominance of mudrocks. Scour marks are locally recorded at the mudrock and sandstone contacts (Fig.

Figure 5.7. Swamp-lagoon FA6w in Section 7. **A.** General outcrop view. **B, C, D.** Interbedding of carbonaceous mudrocks and coal beds. **E.** Detail of carbonaceous mudrock with high amount of fossilized organic matter. **F.** Detail of coal with concoid fracture. **G.** *Thalassinoides* (*Th*). **H.** ?*Gyrolites* (?*Gy*).

5.8C). ?*Taenidium* (BI= 1) and oxidized mud intraclasts are rarely observed (Fig. 5.8G-H). Continental palynomorphs (pollen and spores) are abundant in these successions, while discrete agglutinated foraminifers are recorded in the Section 3 (UCaldas-ANH, 2021). These successions reach thicknesses up to 40 m and are underlain by fan delta (FA4w) and tidal (FA5w) deposits.

Interpretation: The domain of mudrocks and claystones suggests relatively low-energy conditions, likely associated with extensive floodplains situated at a considerable distance from the main channel (e.g., Makaske, 2001). The scarce beds of sandstones with fining-upward trends and tractional structures such as planar and trough cross-bedding, would represent the action of unidirectional currents in fluvial channels. The mudrock-sandstone interbedding indicate sedimentation under varying hydrodynamic conditions, marked by periodical channel activity and the deposition of facies associated with small channels or crevasse splay deposits reaching the floodplain, such as those caused by levee breaches or overflows (Einsele, 2000; Yeste et al., 2020; Varejão et al., 2021). The fine-grained nature and the record of deposits associated with floodplains suggest mixed- or suspended-load anastomosing river systems (Reading, 1996; Makaske, 2001). The continental palynomorphs suggest the dominance of terrestrial environments, whereas foraminifers may indicate reworked material or a local rise in relative sea-level, reaching the mouths of river systems in coastal plain settings (e.g., Oboh-Ikuenobe et al., 2008).

Axial zone

This central part of the basin includes from south to north stratigraphic Sections 12, 13, 14 and 15 described by Vergara and Rodriguez (1997) along the axial part of the Eastern Cordillera Basin.

FA1c: offshore

Description: FA1c is recorded in the Campanian of Section 12 and in the Campanian-Maastrichtian of Section 15. It is dominated by aggradational and retrogradational trends forming successions up to ~ 60 m thick of cherts and black shales, locally with nodular phosphates and horizontal lamination (Vergara and Rodriguez, 1997). Siltstones, claystones and subordinate very fine- to fine-grained sandstones are also common, showing horizontal and convolute lamination, wavy and lenticular bedding, normal and inverse grading, and ripples. Foraminifers, fish scraps and indeterminate scarce bioturbation are also recorded. These successions are underlain and overlain by shoreface deposits.

Interpretation: FA1c is interpreted as an offshore marine environment with high primary productivity (Vergara and Rodriguez, 1997).

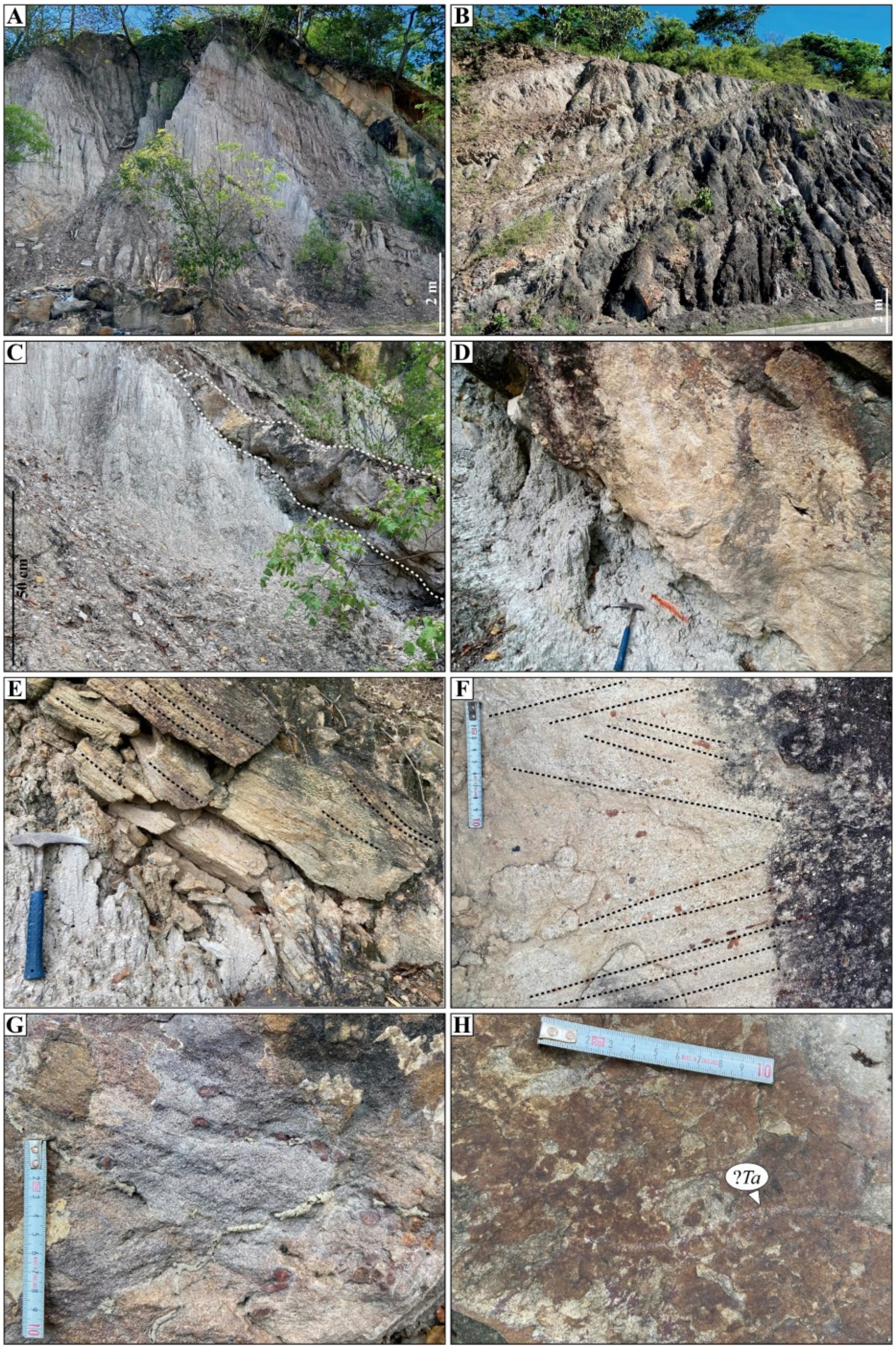

Figure 5.8. Fluvial FA7w. **A, B.** General outcrop views of the Sections 3 and 5. **C.** Cuneiform-shaped bed of fine- to medium grained sandstones interbedded with claystones and mudrocks in Section 3. **D.** Sharp irregular contact between massive mudrocks and medium-grained sandstones with trough cross-bedding in Section 3. Note scour marks at the base of the sandstone. **E, F.** Fine- to medium-grained sandstones with planar and trough cross-bedding in Section 3. **G.** Oxidized mud intraclast in sandstone. **H.** ?*Taenidium* (?*Ta*).

FA2c: shoreface

Description: FA2c is reported in the Campanian of Sections 13, 14 and 15, and in the Maastrichtian of Sections 12 and 15. It is characterized by progradational and aggradational trends in successions up to ~ 200 m thick containing tabular and cuneiform beds of fine- to very fine-grained (mainly in the Campanian) and medium- to very coarse-grained bioturbated sandstones (mainly in the Maastrichtian), and locally mudrocks and diagenetic cherts (only in the Campanian). The sandstone beds show tabular geometry, with horizontal lamination, lenticular and wavy bedding, planar and trough cross-bedding, hummocky and swaley cross-bedding, normal and inverse grading, locally symmetric and asymmetric ripples, and massive structures. In addition, glauconite, fish remains, foraminifers, bivalves, and indeterminate bioturbation are reported. Scattered phosphatic peloids, reactivation surfaces, and mud intraclasts are also recorded. These successions are respectively underlain and overlain by offshore and tidal/marsh deposits.

Interpretation: These deposits have been interpreted as accumulated in shoreface environments (Vergara and Rodriguez, 1997).

Eastern foothills

This eastern side of the basin includes Section 16 of Vergara and Rodriguez (1997), Section 17 of Carvajal-Torres et al. (2022), and Section 18 of this work complemented with information of Guerrero and Sarmiento (1996).

FA1e fluvial-dominated prodelta

Description: FA1e is recorded in the upper Campanian of Section 18. It is mainly characterized by very thin- to medium-thick tabular- and lenticular-shaped beds of mudrocks, siltstones and very fine- to medium-grained sandstones in aggradational trends, resulting in successions up to ~ 100 m thick (Fig. 5.9A-B). The mudrocks exhibit sharp bases, horizontal lamination and massive structures, and high organic matter content. They are interbedded with very thin beds of siltstones and sandstones having internal scours, load and flame structures, lenticular and wavy bedding (with symmetric and asymmetric ripple cross-lamination) (Fig. 5.9C). Predominantly muddy successions (Fig. 5.9A) alternate with intervals dominated by tabular sharp-based very fine- to medium-grained sandstones (Fig. 5.9B) with some phosphatic fragments and showing discontinuous subhorizontal lamination marked by muddy carbonaceous material, asymmetric ripple lamination, and local intercalations of mudrocks forming flaser bedding (Fig. 5.9D-E). These deposits are unbioturbated (BI=0) to slightly bioturbated (BI=1), with some *Thalassinoides* in the muddy beds (Fig. 5.9F). These successions are underlain and overlain by delta front deposits.

Figure 5.9. Fluvial-dominated prodelta FA1e in Section 18. **A, B.** General outcrop views showing muddy- and sandy-dominated intervals, respectively. **C.** Interbedded mudrocks and siltstones. Note the scour marks (yellow arrows) and load structures (white arrows) at the base of the siltstone beds. **D.** Fine-grained sandstone with discontinuous horizontal and asymmetric ripple cross-lamination highlighted by muddy carbonaceous material. **E.** Mudrocks and sandstones interbedded, forming wavy bedding. **F.** Mudrocks bioturbated by *Thalassinoides* (*Th*).

Interpretation: High amounts of carbonaceous material indicate significant terrestrial supply. This, combined with features such as internal scours, tractive and massive structures related fine-grained lithologies, may suggest traction transport or fall-out processes from turbulent flows associated with hyperpycnal currents (Sumner et al., 2008; Zavala et al., 2012; Wilson and Schieber, 2014; Zavala and Pan 2018; Irastorza et al., 2021). The scarce or absent bioturbation may be related to stress conditions, probably salinity fluctuations in response to the freshwater input and water turbidity, or to high sedimentation rates, or soupground substrates having a low preservation potential (MacEachern et al., 2005; Bhattacharya and MacEachern 2009; MacEachern and Bann, 2023). The massive mudrocks may be the result of flocculation processes from hypopycnal plumes, producing fluid mud deposits (MacEachern et al., 2005; Bhattacharya and MacEachern, 2009; Ponce et al., 2022), or could represent low-energy episodes with normal marine suspended sediment fall-out deposition (Potter et al., 2005). Relative variations in pollen vs. dinoflagellate content —with proportions of up to 70% pollen vs. 30% dinoflagellates in some beds— indicate high continental input (Guerrero and Sarmiento, 1996). These processes are interpreted as being responsible for the fluvial-dominated character of this prodelta environment. In addition, some intervals with horizontally laminated sandstones with phosphatic grains are interpreted as deposited from high-energy flows related to combined flows such as storms (Arnott, 1993; Glenn et al., 1994; Perillo et al., 2014). The rare occurrence of *Thalassinoides* suggests episodes of colonization between fluvial-dominated events (Buatois et al., 2011).

FA2e Fluvial-dominated delta front

Description: FA2e occurs in the lower Campanian and Maastrichtian of Sections 17 and 18. It is characterized by progradational arrangements of thin to medium tabular beds of mudrocks interbedded with thin to thick tabular and lenticular beds of amalgamated sandstones, and subordinate lenticular beds or pockets of conglomerates, resulting in successions up to ~ 250 m thick. The sandstones are sharp- and irregular-based, fine- to coarse-grained, with discontinuous horizontal lamination highlighted by muddy carbonaceous material, massive, symmetric and asymmetric ripple cross-lamination, trough cross-bedding, and convolute lamination structures (Fig 5.10A-C). Mud intraclast concentrations and bivalve fragments are rarely observed, while the phosphatic fragments are abundant. The mudrocks show horizontal lamination and are generally associated with sandstones forming heterolithic bedding (flaser and wavy). In some intervals, centimeter-thick beds of highly bioturbated sandstones interbedded with bioturbated carbonaceous mudrocks are evidenced (Fig. 5.10D-E). Load and flame structures are also common in these intervals. The erosional-based conglomerates are granule- to pebble-grained, structureless, with subrounded and poorly sorted muddy clasts (Fig. 5.10F). Normal grading is occasionally observed between pebble-size conglomerates and medium- to coarse-grained sandstones. Toward the top of the succession, carbonaceous muddy and sandy-muddy beds up to 80 cm thick, with high amounts of organic matter, are registered (Fig 5.10A-D). These beds have sharp and erosional bases and transitional irregular tops, horizontal lamination, and exhibit bioturbation represented almost exclusively by *Thalassinoides* and sporadically *Teichichnus* (BI= 2, 4), with diameters up to 6 cm. These levels are overlain by sandy beds that also show a high content of organic matter as sheets, organized forming a subtle horizontal lamination. A diverse and abundant (BI= 2, 4) trace fossil assemblage, composed of *Conichnus*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Skolithos, Taenidium*, *Teichichnus* and *Thalassinoides*, characterizes these beds. A less abundant (BI= 1, 2) and diverse ichnoassemblage composed of *Ophiomorpha*, *Palaeophycus*, *Planolites* and *Thalassinoides* is observed throughout the succession, mainly associated with sandstones. Bed bases colonized exclusively by *Rhizocorallium* and *Thalassinoides* are recorded in the lower part of the succession (BI= 4) (Fig. 5.10G-H). Amalgamated fine-grained sandstone beds forming successions up to 6.5 m thick, colonized almost exclusively by *Ophiomorpha* and in a minor proportion *Palaeophycus* and *Planolites* are also recorded at the base of the section. These successions are underlain and overlain by swamp/coastal lagoons, and marsh/estuarine deposits, respectively.

Interpretation: This facies association may be related in a general context to high-energy environments associated with oscillatory and combined flows, like those recorded in shoreface-foreshore environments, within which some energy fluctuations may also be recorded. Yet in contrast to shoreface settings, these successions are considered as delta front deposits due to the abundance of carbonaceous material, suggesting phytodetrital pulses from fluvial discharges (MacEachern et al., 2005; MacEachern and Bann, 2023). In addition, these deltaic environments feature the occurrence of soft-sediment deformation structures related to sedimentary loading along steep slopes (MacEachern et al., 2005; Buatois et al., 2012). These structures may also be associated with deformation related to external factors such as earthquakes (e.g., seismites; Seilacher, 1969). The erosive conglomerate beds or pockets are interpreted as bedload arriving at the delta front linked to mouth bar deposits (van Yperen et al., 2020; Ponce et al., 2022). Intervals of massive (by bioturbation) sandstones interbedded with carbonaceous bioturbated mudrocks (colonized from the top down; Fig. 5.10E) suggest fluctuations in hydrodyna mic energy; high-energy periods accumulating sandy beds alternate with the fall-out deposition of muddy beds. These muddy beds are considered as mudrock drapes, related to deposition by flocculation from hypopycnal plumes (MacEachern and Bann, 2023). The high bioturbation in sandy layers indicates the establishment of a well-developed macrobenthic tracemaker community between river flood events (mudstone drapes) under normal, favorable marine conditions. Similar interpretations are suggested for the organic-rich muddy and sandy-muddy beds overlain by highly bioturbated sandstones that occur toward the top of the succession. These organic-rich beds would mark hyper-

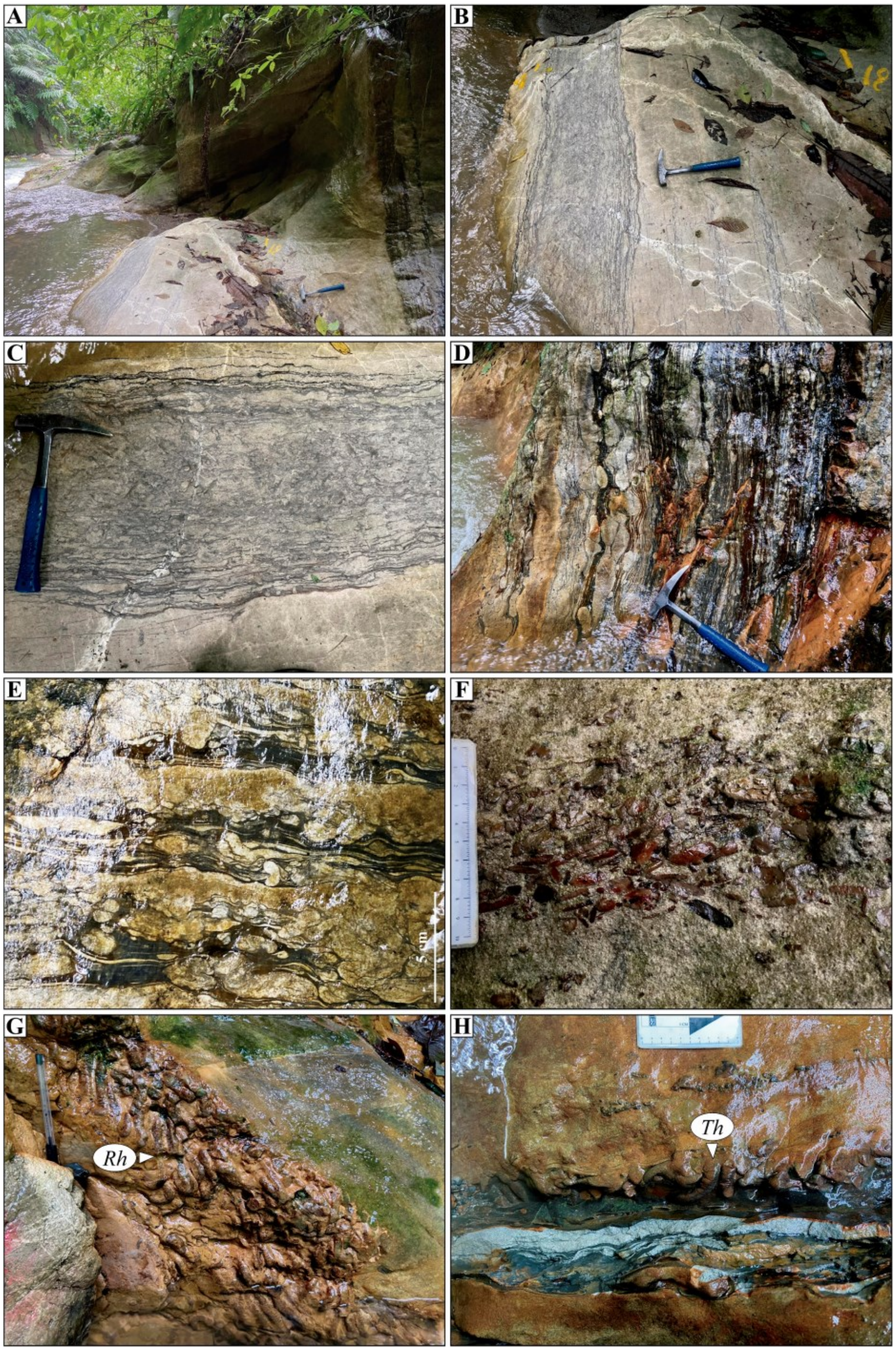

Figure 5.10. Fluvial-dominated delta front FA2e in Section 18. **A.** General outcrop view. **B, C.** Sandy beds with subtle horizontal lamination highlighted by sheets of organic matter. Note abundant bioturbation. **D, E.** Medium-grained sandstones beds alternating with dark mudrocks drapes. Note the bioturbation associated mainly with sandstones. **F.** Pebble-size conglomerates grading into a coarse-grained sandstone. **G, H.** Base of a sandstone bed bioturbated exclusively by *Rhizocorallium* (*Rh*) and *Thalassinoides* (*Th*).

pycnal deposits, linked to sudden fluvial flows arriving at the delta front, supported by the erosive bases and the record of *Thalassinoides* and *Taenidium* alone, possibly linked to brackish, less favorable conditions. The abundant bioturbation assigned to the *Cruziana* ichnofacies in the overlying sandstones could reveal wave-dominated periods, after fluvial discharges. The low record of trace fossils associated with suspension-feeders, as opposed to deposit-feeders, can be interpreted as a scarcity of suspension food, or high turbidity, suggesting that organic matter was transported mainly by hyperpycnal flows (MacEachern et al., 2005; MacEachern and Bann, 2023). The scarce levels with bivalve and phosphate fragments are considered as the result of storm events remobilizing material from distal areas (Glenn et al., 1994; Myrow and Southard, 1996). This difference between marine-dominated and those fluvial-dominated deposits is supported by the pollen vs. dinoflagellate record, which is 95%-5% in some cases and 70%-30% in others (Guerrero and Sarmiento, 1996).

FA3e Shoreface

Description: FA3e is recorded in the Campanian and lower Maastrichtian of Section 16. A succession of ~ 260 m thick of sandstones and subordinate mudrocks arranged in progradational and aggradational trends characterizes these deposits. The tabular beds of fine- to medium-grained sandstones show massive, wavy bedding structures, while the mudrocks form tabular beds having horizontal lamination and lenticular bedding. Plant remains, phosphatic peloids, mud intraclasts and indeterminate bioturbation are common. These successions are respectively underlain and overlain by swamp/coastal lagoons and swamp/estuarine deposits.

Interpretation: Shoreface environments are interpreted for these deposits (Vergara and Rodriguez, 1997).

5.4.2 Depositional model: spatial distribution and stratigraphic evolution of sedimentary deposits and processes

The stratigraphic correlation of well-dated successions allows us to observe the distribution and evolution along-strike (Figs. 5.11 and 5.12) and cross-strike (Fig. 5.13) of depositional sedimentary systems during the Campanian-Maastrichtian. The vertical (stratigraphic) and lateral (spatial) relationship between calcareous, mixed (shelf) and siliciclastic (offshore, shoreface, fan delta, delta front, prodelta, tidal, swamp, fluvial) facies associations and sedimentary environments provide insight into the dominant sedimentary processes and depositional conditions in the final stages of the epeiric La Luna Sea during the Campanian-Maastrichtian. Two distinct phases are recognized in the basin during this period: one characterized by marine processes during the Campanian and early Maastrichtian, the other by marginal/transitional and continental processes during the late Maastrichtian (Figs. 5.14 and 5.15). At the marine phase, two different sedimentary systems are distinguished: a normal shoreface-basin profile that includes shelf, offshore, and shoreface-foreshore environments towards the western and central parts; and a delta profile in the eastern part, consisting of delta front to prodelta settings. These are respectively overlain by fan delta complex, tidal and fluvial deposits, and swamp and estuarine deposits, associated with the marginal-continental phase.

Along- and cross-strike depositional trends and processes

Western zone

In the southwestern area, shoreface deposits overlie Santonian siliciclastic shelf deposits, associated with a progradational trend due to relative sea-level fall (Guerrero et al., 2000; Guerrero, 2002). They represent the onset of Campanian siliciclastic sedimentation in this sector of the basin (Section 2), while towards more northerly sectors (Sections 4 and 10), the deposition continues in carbonate and mixed shelf environments (Fig. 5.11). Thus, lower Campanian sedimentation in this region was dominated by high energy processes related to wave activity in shoreface environments, influenced by sporadic storm events (FA3w) and by suspended fall-out in shelf settings. These environments were unfavorable for the establishment of a macrobenthic tracemaker community, as indicated by the record of scarce or no bioturbation. However, a high abundance of benthic foraminifers has been reported (Guerrero et al., 2000), suggesting favorable habitats for microorganisms.

Above the shoreface deposits, during the late Campanian, shelf environments (FA1w) expanded and were also developed and distributed along the southwestern zone of the basin (Figs. 5.11 and 5.14), associated with a retrogradational trend due to relative sea-level rise (Guerrero et al., 2000, Guerrero, 2002). These shelf deposits, marking the deepest part of the basin for this epoch, were characterized by suspended fall-out deposition of calcareous and siliciclastic material, with a local influence of weak bottom currents, and an absence of significant seafloor colonization by macrobenthic tracemaker organisms, reflected in the rare or absent record of bioturbation. This might suggest depositional settings characterized by low oxygenation or nutrients availability. However, amounts of total organic carbon between 3% and 7% have been reported in these rocks, associated with upwelling processes (Föllmi et al., 1992; Villamil et al., 1999; Martínez, 2003; Patarroyo et al., 2017, 2021), ruling out this possibility. Thus, a low oxygenated environment can be interpreted, as supported by geochemical and micropaleontological analysis (Martínez, 2003; Patarroyo et al., 2023), as the main parameter controlling the colonization by macrobenthic tracemakers.

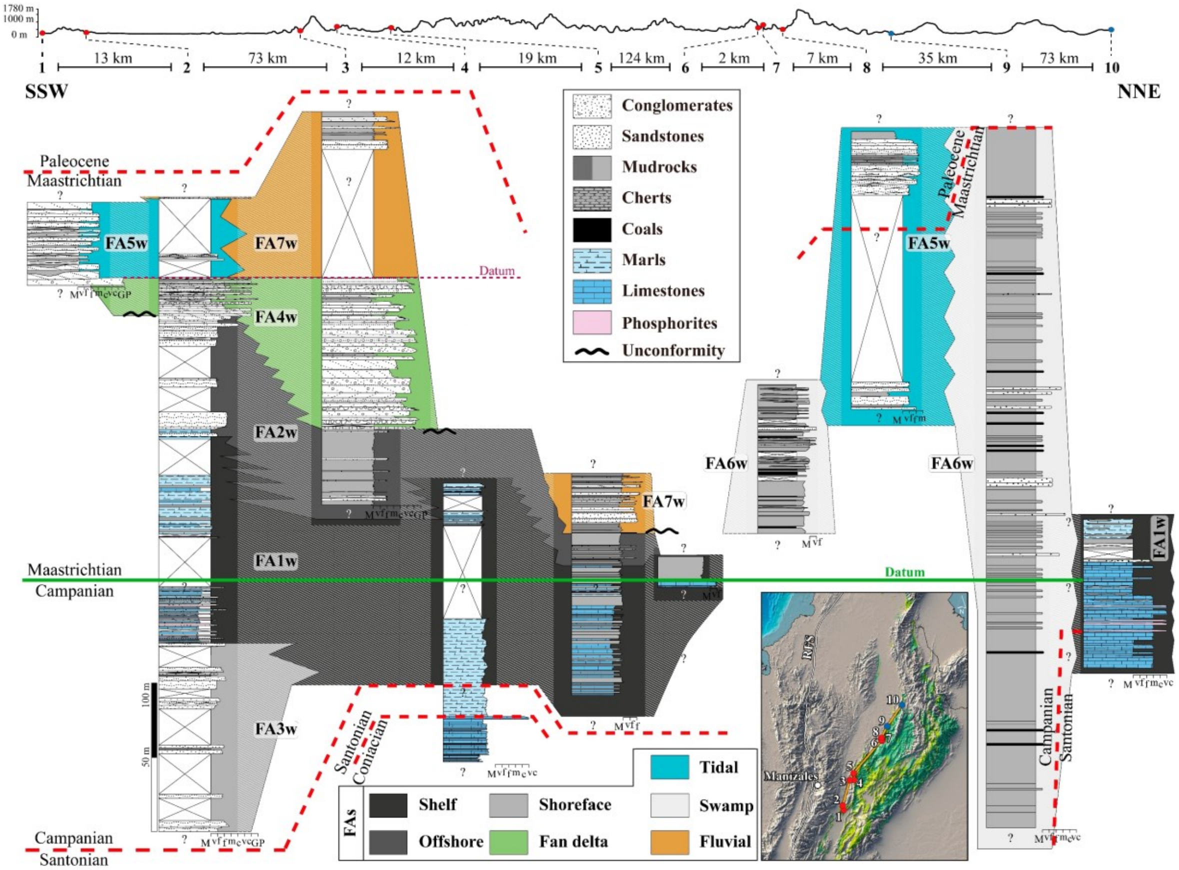

Figure 5.11. Western along-strike correlation transect. The topographic profile shows the current location of the studied sections. Datum: approximate Campanian-Maastrichtian boundary and the top of fan delta deposits. Light areas with steep lines represent uncertainty in the stratigraphic correlation of the depositional settings.

A marked change from calcareous-dominated to mixed- or siliciclastic dominated shelf and offshore deposits is evidenced in this basin area between the late Campanian and early Maastrichtian (Fig. 5.11). This change in mud composition (termed xenoconformity; Carroll, 2017) has been associated with freshwater input and an increase in the terrigenous sediment supply, linked to a regressive phase and tectonic activity generated by the accretion of western allochthonous terranes (Villamil et al., 1999; Guerrero et al., 2000; Guerrero, 2002; Bayona, 2018; Montes et al., 2019; Patarroyo et al., 2017; 2023). Different authors hold that the end of calcareous sedimentation occurred at the end of the Santonian and/or Campanian (Cooper et al., 1995; Ayala-Calvo et al., 2009; Bayona, 2018; Sarmiento-Rojas, 2019; Terraza, 2019, Pastor-Chacón et al., 2023). Section 6 shows the change in the approximate Campanian-Maastrichtian boundary, but Sections 2, 4, 5, and 10 show calcareous and mixed deposits even in the Maastrichtian (Fig. 5.11). The present stratigraphic correlation suggests that this change is diachronic throughout the basin, and its distribution is not only associated with an unconformity in certain areas but could be geographically controlled (location within the basin) in places where the sedimentation is continuous (Figs. 5.11, 5.13 and 5.14). Therefore, it is possible to infer that the areas where the change occurred first were those close to emerged areas or directly connected to the systems that transported the siliciclastic material through continental runoff, while areas where carbonate sedimentation continued were most likely protected areas or distant from continental systems. Intra-basin uplift blocks further to the southeast that occurred in the late Campanian may also have influenced these changes in sediment composition and distribution, and/or be associated with the development of the unconformity (Carvajal-Torres et al., 2022).

The siliciclastic/mixed/carbonate shelf evolved towards the SW part to deposits interpreted as offshore settings in the early Maastrichtian (FA2W; Fig. 5.11). The accumulation of these deposits was dominated by suspension settling and the influence of storms. Benthic conditions improved in these deposits, allowing in some cases the establishment of diverse and abundant macrobenthic tracemaker communities belonging to the *Cruziana* ichnofacies. The favorable conditions are further evidenced by geochemistry and micropaleontology, which indicate eutrophication and better oxygenation of the bottom waters in Section 10 (Patarroyo et al., 2023).

The most important change in deposits, and therefore in the depositional processes, took place in the southwestern zone of the central (this work) and south (Upper Magdalena Valley Basin) parts of the basin during the late Maastrichtian, associated with the transition from marine to marginal-continental phase, indicating rapid and significant changes in sedimentary dynamics (emerged vs catchment areas) (Figs. 5.11 and 5.14). The offshore deposits (FA2w) are overlain by coarse-grained fan delta complex deposits (FA4w) to the south and central parts (Section 1 and 3), and by fluvial deposits (FA7w) to the north (Section 5), representing the progradation of the marginal and continental sedimentary systems (Figs. 5.11 and 5.14). Although micropaleontological studies provide no evidence of missing time, this marked change represents an erosional unconformity in the sedimentary record (e.g., Veloza et al., 2008; Mora et al., 2010).

The conglomerate-dominated deposits —comprising the Cimarrona Formation— indicate very energetic processes during their accumulation, associated with channel deposits whose characteristics suggest a braided fluvial system (Gómez and Pedraza, 1994; Miall, 1996; Einsele, 2000; Giraldo-Villegas et al., 2024). These channels drained alluvial fans coming from the proto-Central Cordillera, according to detrital signals and paleocurrents (Gómez and Pedraza, 1994; Guerrero et al., 2020; Valencia-Gómez et al., 2020), and reached the coastal plain, forming mouth bar deposits and fan delta complexes where a scarce macrobenthic tracemaker community was established, due to the high erosive power and constant supply of fresh water (Giraldo-Villegas et al., 2024). Towards the eastern side, coeval coarse-grained deposits are not reported thus far (see below). The thickness of these deposits increases to the north, reaching up to ~100 m in Section 3 (Fig. 5.11), suggesting the location of a depocenter or arrival of the major channel systems. The fact that lateral expressions are not evidenced in our WSW-ESE correlations (Figs. 5.13 and 5.14), would indicate local extension or strong reworking by waves towards the central part of the basin. Accordingly, this sedimentary record provides direct evidence of the growth of the proto-Central Cordillera, and the development of an important sediment source relief.

Tidal (FA5w) to the south, and fluvial environments in the central part, overlie the coarse-grained sedimentation; again they represent a reaccommodation of sedimentary systems and a decrease in hydrodynamic energy as compared to the underlying deposits. The tidal deposits contain the record of flooding and ebbing. Because these marginal depositional settings are influenced by freshwater input and the arrival of sediments, the resulting environment is unfavorable for colonization by a marine macrobenthic tracemaker community, as reflected by the scattered and sparse bioturbation recorded. The tidal environments change laterally to the north, to fluvial deposits of a fine-grained nature, with associated floodplains and crevasse splays, common features of anastomosed and/or meandering fluvial systems (Miall, 1996). The change in grain size (from the coarse-grained fan delta complex to the fine-grained tidal and fluvial deposits) reflects a marked change in hydrodynamic parameters possibly linked to the geomorphological/topographical configuration or differential erosion of emerged areas. The coarse-grained facies formed relatively close to the coast, implying less transport and considerable relief, associated with the development of alluvial fans in the most proximal parts and fluvial and fan delta deposits in the most distal positions, while still preserving their gravelly nature. In contrast, the fine-grained fluvial successions are associated with extensive, relatively flat areas that transported sediment over long distances. This change in depositional processes occurred over a relatively short period of time and space, suggesting important and rapid topographic or geomorphological changes in the western border. In Section 5, fluvial deposits overlie offshore successions, suggesting an unconformity.

In the northwesternmost part of the basin, the late Campanian is represented by two different depositional systems. One is associated with the calcareous shelf systems (Section 10), similar to those of the SW part, and the other related to marsh (Section 9) (Figs. 5.11 and 5.14). The late Campanian swamp settings (FA6w) are observed only in this area, implying that singular depositional parameters (compared to the general shelf context of most of the basin) prevailed locally during this period. The shallower near-continent areas point to an irregular basin border, providing high amounts of organic matter of terrestrial origin, hence favoring the accumulation of these successions. Moreover, these settings had a direct connection with the sea, evidenced by the presence of ?*Gyrolithes*, and several levels with marine palynomorphs (Montaño et al., 2016).

Swamp sedimentation continued in this area during the Maastrichtian (Sections 7 and 9), with some lateral variation to tidal deposits (Section 8) (Figs. 5.11 and 5.14). Tidal settings are correlated with the SW part (Sections 1 and 2), showing similar features, plus an absence of trace fossils suggesting unfavorable environments for the macrobenthic tracemaker community.

Axial zone

The central part of the basin was dominated by shallower depositional settings than the western zone (Figs. 5.12, 5.13 and 5.14), and environments that were slightly more distal or similar to those at the eastern area suggesting an off-axis basin. The Campanian sedimentation in this sector also overlies fine-grained deposits accumulated in estuarine to shelf environments, dominated by wave and storm processes (Vergara and Rodriguez, 1997). The lower Campanian deposits begin with shoreface successions (FA2c), indicating a regressive event as in the western side of the basin. These environments were dominated by waves and storms, and locally by tidal processes, providing favorable benthic conditions according to bioturbation. An abundant and diverse ichnoassemblage composed of *Arenicolites*, *Arthrophycus*, *Crossopodia*, *Cylindrichnus*, *Gordia*, *Laevicyclus*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Scolicia* and *Thalassinoides* is reported by Pérez and Salazar, (1978) for these deposits, and of *Arenicolites*, *Asterosoma*, *Diplocraterion*, *Helminthopsis*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Skolithos*, *Teichichnus*, *Thalassinoides*, and *Zoophycos* in southern deposits of the Guando oil field (Leckie et al., 2003), reflecting the development of a permanent macrobenthic community, in contrast to the westward coeval deposits. Offshore deposits (FA1c) that overlie these successions evidence a relative deepening of the sedimentary systems during the late Campanian-early Maastrichtian, as seen for the western and eas-

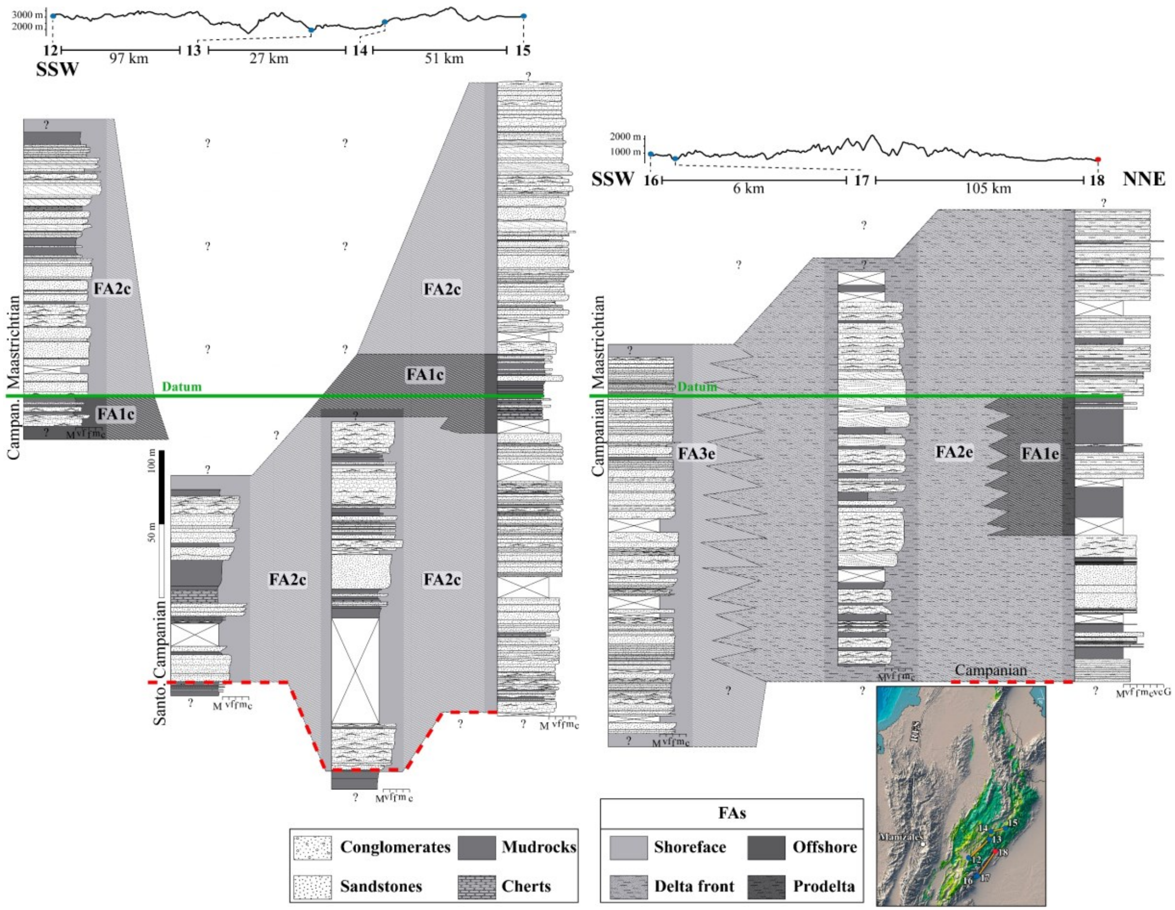

Figure 5.12. Central and eastern along-strike correlation transects. The topographic profile shows the current location of the studied sections. Datum: approximate Campanian-Maastrichtian boundary. Light areas with steep lines represent uncertainty in the stratigraphic correlation of depositional settings.

tern sides (Figs. 5.12 and 5.13). In these environments suspension sedimentation prevailed, with a local influence of storm deposits. Scarce bioturbation suggests unfavorable benthic conditions for the tracemaker community. Overlying these deposits, shoreface environments were reestablished during the early to late Maastrichtian, when wave processes constituted the predominant sedimentation mechanism (Figs. 5.12 and 5.13). The ichnoassemblage composed of *Arenicolites*, *Cylindrichnus*, *Fraena*, *Gordia, Planolites*, *Protovirgularia*, *Rhizocorallium*, *Scolicia*, and *Thalassinoides* (Pérez and Salazar, 1978) indicates a weak influence of stress conditions (i.e., low oxygenation, brackish conditions, high sedimentation rate) during the accumulation of these deposits. This bioturbation is mainly associated with the contacts between shoreface sandy bodies and disappears again when paleoenvironmental conditions change in the overlying units (Pérez and Salazar, 1978; Sarmiento, 1992).

Eastern zone

The eastern segment of the basin is represented by deltaic deposits. As in the western and central parts, they overlie fine-grained deposits accumulated under estuarine to shelf environments, meaning a regressive event occurred at the end of the Santonian (Guerrero and Sarmiento, 1996). The early Campanian sedimentation begins with fluvial-dominated delta front successions (FA2e) having high continental organic content. Still, features such as storm beds and the trace fossil assemblage suggest that these sandy seafloors were locally reworked by wave activity. Similar to the shoreface deposits of the central part, these deltaic successions are bioturbated by an abundant and diverse ichnoassemblage belonging to *Cruziana* ichnofacies, so that habitats were suitable for the tracemaker community during wave-dominated periods of the system. These systems stratigraphically evolve into upper Campanian-lower Maastrichtian prodelta deposits (FA1e) that were dominated by fall-out and tractional transport processes from hyperpycnal flows and hypopycnal plumes, sporadically influenced by storm events. Altogether, the high amount of carbonaceous debris along with sparse bioturbation indicates a significant terrestrial supply through the influence of dominant river-fed hyperpycnal flows (Mulder and Alexander, 2001; Mulder et al., 2003; Zavala and Pan, 2018). The freshwater input —causing salinity fluctuations— carrying the continental sediments, plus the associated turbidity, created an unfavorable environment for the marine macrobenthic community.

Above these fluvial-dominated prodelta deposits, fluvial-dominated delta front environments were reestablished during the early Maastrichtian. Their deposits resemble those accumulated during the early Campanian, but the upper part offers evidence of mouth bars and levels whose high organic debris content signal fluvial flows generated during sudden floods (flood deposits), which are overlain by highly bioturbated deposits

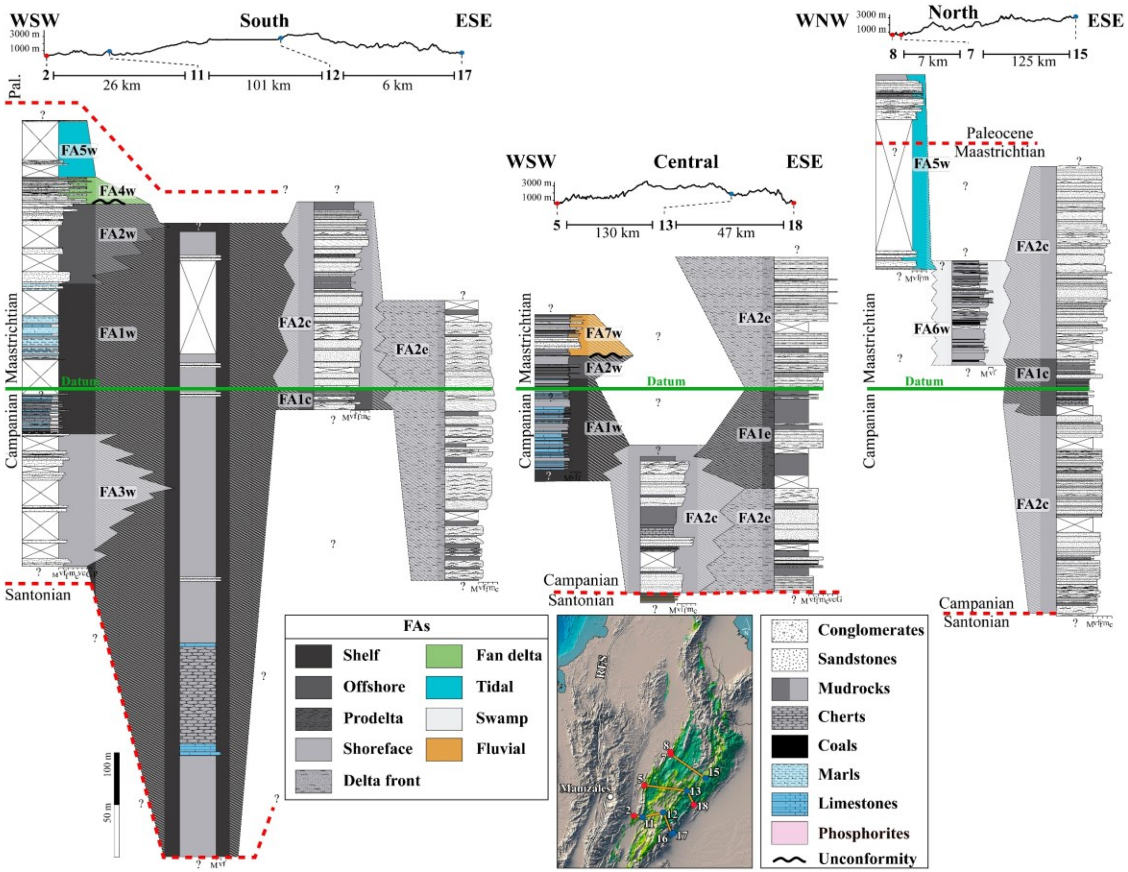

Figure 5.13. South, central and north cross-strike correlation transects. The topographic profile shows the current location of the studied sections. Datum: approximate Campanian-Maastrichtian boundary. Light areas with steep lines represent uncertainty in the stratigraphic correlation of the depositional settings.

(interflood deposits). Overall, there was a strong interaction between fluvial- and marine-dominated processes in the delta front environments. To the south, Section 16 provides evidence of shoreface environments (FA3e) during the Campanian and early Maastrichtian, suggesting limited delta influence. During the late Maastrichtian there was no deposition in the region surrounding this section as it was a zone of positive relief (< 500 m; Carvajal-Torres et al., 2022).

5.5 Discussion

5.5.1 Sedimentary system dynamics: western vs central-eastern zones

Sedimentology and stratigraphy

From its beginnings, the studied NNE-SSW oriented basin bounds different geologic domains on either side. To the west, a volcanic arc was active since Jurassic times, whereas stable areas to the east were linked to the Amazonian Craton (Cooper et al., 1995; Sarmiento-Rojas, 2001; Guerrero et al., 2020). Campanian-Maastrichtian deposits beyond the eastern side of the Eastern Cordillera Basin (within the Eastern Llanos Basin, Fig. 5.1), and beyond the western side, toward the north of the Middle Magdalena Valley Basin (i.e., east and west of the studied eastern and western section), are identified only from borehole studies. Thus, in order to establish the differences in the depositional processes and settings on both zones of the basin, the present research considers these easternmost and westernmost sections representative of the accumulation parameters for the eastern and western sides of the basin at that time.

According to our data, the geologic reliefs surrounding the epeiric basin bore a great influence on the basin filling processes and types of deposits of the La Luna Sea, at least in the final stages during the Campanian-Maastrichtian. Comparison among the western and central-eastern sections during the Latest Cretaceous reveals significant differences (Figs. 5.14 and 5.15). The stratigraphic and spatial variation of deposits and sedimentary environments is more diverse towards the western zone (shoreface, shelf, offshore, fan delta complex, fluvial, tidal, marsh), while the eastern and central areas show a more homogeneous distribution (shoreface-delta front, offshore-prodelta) (Fig. 5.13). This suggests that the western area harbored higher activity between the feeder (source) and receiver (sink) areas, perhaps in response to the dynamics of the volcanic arc, the growth of the proto-Central Cordillera and the unroofing of the sedimentary cover tied to the Caribbean Plate collision. Further influence was induced by the major fluvial inputs to the basin (see below). Another key element that may have influenced the variability of environments, deposits, and sedimentary parameters on both sides of the basin is the size and topography of the emerged areas, which are smaller in size and higher in elevation on the western side and larger and lower in elevation on the eastern side.

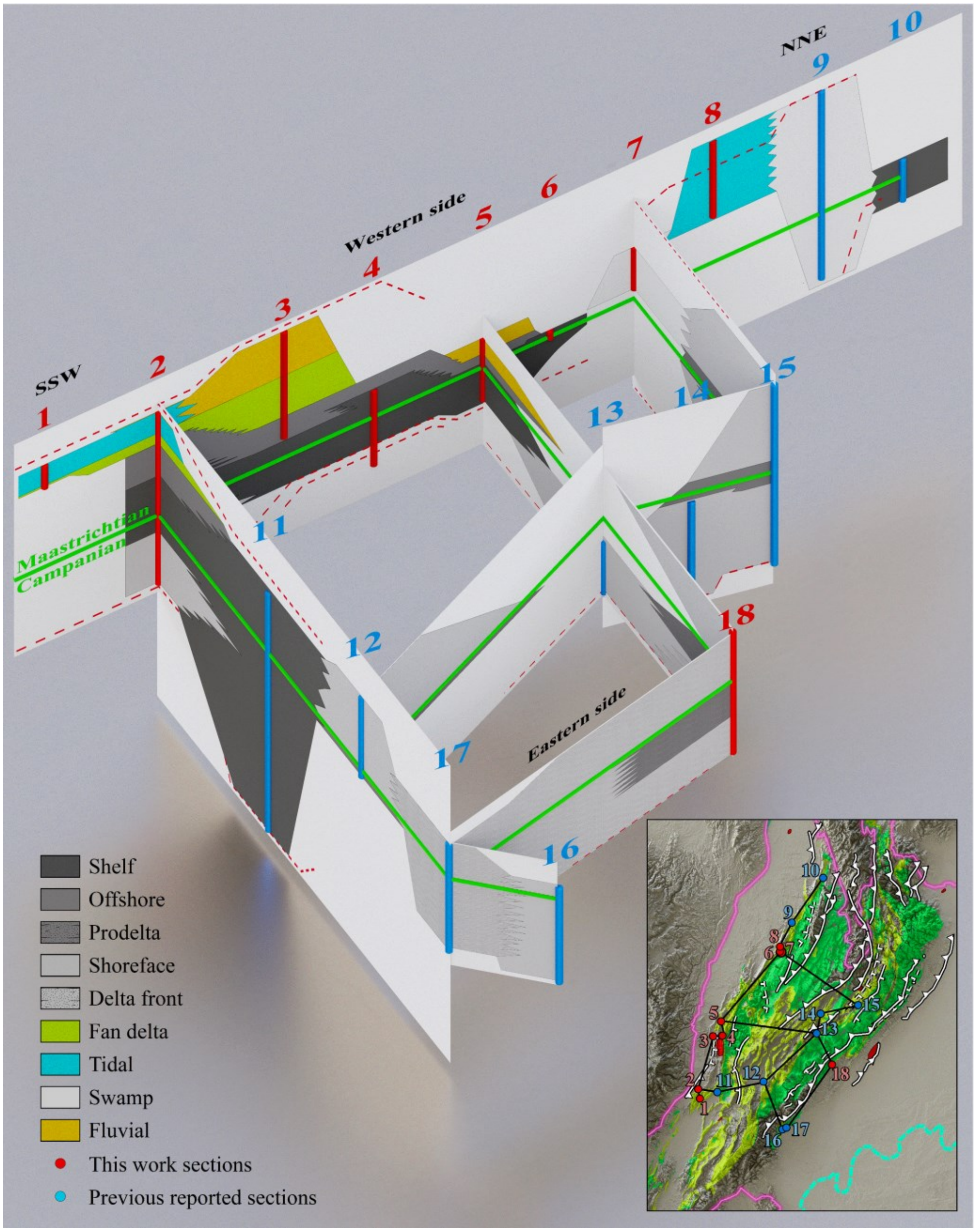

Figure 5.14. 3D diagram (not to scale) showing the correlation between SSW-NNE and WSW-ESE transects and the distribution of sedimentary environments.

Within this western side, Sections 1 to 5 show the greatest paleoenvironmental variability compared to Sections 6 to 10. It is important to consider that, according to the palinspastic reconstructions (Sarmiento-Rojas, 2001; Tesón et al., 2013; Bayona, 2018; Montes et al., 2019; González et al., 2023), these southern sections were closer to the proto-Central Cordillera (today ~20 km) than the northern sections (today ~70-100 km) during the accumulation of the deposits. Therefore, it is possible to interpret that these southern sections, being closer to the western border or coastline and thus to the proto-Central Cordillera, register a greater variability in the type of deposits compared to the northern sections, which were in more distal positions.

During the Campanian-early Maastrichtian, deeper environments dominated the western area, marking the most distal parts of the basin during this period. In contrast, the central and eastern zones correspond to shallower settings associated with shoreface and deltaic deposits (Figs. 5.14 and 5.15). Accordingly, the basin was asymmetric, possibly developed as flexural response to the uplift of the proto-Central Cordillera, or perhaps related to fault front of the Central Cordillera to the west and passive tilting of the eastern zone (e.g., Mora et al., 2020; Pastor-Chacón et al., 2023), where the shallower environments of the western area were very narrow or not preserved (Fig. 5.15). Even though the main source of terrigenous sediments was located to the east during this period, they did not affect the calcareous sedimentation at the western zone (Fig. 5.13), most likely due to the distance of these sections at the time of accumulation (> 40 km to the west of its current position; Tesón et al., 2013; Bayona, 2018) and a mainly north-south redistribution of sediments. The western zone was therefore relatively isolated, receiving sedimentation purely from marine processes.

Moreover, these uppermost Cretaceous successions highlight the role of fluvial systems along the eastern area of the epeiric La Luna Sea since the Campanian. In contrast, fluvial systems on the western zone developed sporadically during the late Campanian-early Maastrichtian, becoming dominant in the late Maastrichtian. Still, sandy deposits were regionally distributed towards the southwestern zone during the early Campanian (FA3w) (e.g., Upper Magdalena Valley Basin, Cooper et al., 1995; Guerrero et al., 2000; Veloza et al., 2008; Roncancio and Martínez, 2011; Sarmiento-Rojas, 2011, 2019; Garzón et al., 2012), and their provenance remains unclear. Although some of these deposits have been interpreted as originating from the proto-Central Cordillera (e.g., Cobre Formation, Caicedo et al., 2000), the associated land-ocean systems responsible for delivering this material to the basin are not yet documented for the western side in proximity to these sandy deposits.

Understanding the sedimentary environments in an integrated framework raises questions about the fluvial systems and associated deposits that transported these sediments to the basin during the early Campanian. Northward, Section 9 contains Campanian swamp environments most likely associated with fluvial systems carrying vast amounts of organic material to the coastal environments. It is therefore logical to infer that the early Campanian sandy deposits were transported by littoral drift from deltaic environments associated with well-established fluvial systems at more northerly or southerly areas. This premise would be supported by the north and south paleocurrents recorded in coeval deposits of the central part (e.g., Pérez and Salazar, 1978).

Similar processes occur during the early Maastrichtian —prior to the establishment of the river systems in the western side— when important changes in paleosalinity between the shelf limestones and overlying shelf and offshore mudrocks beds took place (Patarroyo et al., 2023), indicating an increase in the siliciclastic and freshwater input, but nearby sediment sources have not been reported. Coeval lower shoreface sandstones have been reported eastward in the Cocuy region (~ 130 km), towards the axial zone of the Eastern Cordillera, suggesting possible sediment sources to this area (Fabre, 1985; Bayona et al., 2021). As occurred with the Campanian deposits, these siliciclastic muddy deposits may have been transported in suspension or by longshore currents from other basin areas.

Comparable processes took place in the southern sector of the basin (Upper Magdalena Valley Basin) during the Albian. Thick sandstone deposits associated with shoreface and foreshore environments, with detrital signatures from geologic units outcropping to the west (proto-Central Cordillera; Duarte et al., 2016; Guerrero et al., 2020), show no evidence of coeval fluvial systems in proximity to these deposits sourced from westerly areas, suggesting sediment transport from other basin areas. Comparable conditions linked to deposition by littoral drift have been reported for ancient epeiric seas and present-day marine sedimentary environments (Zviely et al., 2007; Garzanti et al., 2014, 2015; Schwarz et al., 2017, 2022; Rovere et al., 2019).

Another particular case entails emerged regions that were present (proven by the detrital signal) in southerly areas during the Maastrichtian, yet apparently did not contribute sediment to the basin (e.g., Calderon-Diaz et al., 2024). This could be explained by relatively flat emerged areas, of low-elevation and not very extensive, having drainage networks close to the sea, and under particular climatic conditions unfavorable to the development of large drainage systems able to supply large sediment loads eventually preserved in the fossil record; such characteristics are more common in passive or stable tectonic settings —e.g. the eastern boundary studied here (Boggs, 2014). Another explanation could be associated with the development of small closed basins where rivers end in intracontinental lacustrine-marine systems. Nevertheless, the existence of intra-basin uplift blocks (e.g., Carvajal-Torres et al., 2022) acting as sediment traps, or the existence of very specific sedimentary pathways associated with basin floor morphology, are not excluded.

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Trace fossil assemblages also show marked differences depending on location. In the Campanian, the seafloor on the western side of the central part of the La Luna Sea shows unfavorable conditions for the macrobenthic tracemaker community (Fig. 5.15B), e.g. low-oxygen muddy bottoms generated in response to high productivity phenomena (Föllmi et al., 1992; Villamil et al., 1999; Erlich et al., 2000, 2003). In contrast, the central and eastern parts record the activity of an abundant and diverse tracemaker community, that is favorable conditions for macrofauna in shallower settings, controlled or influenced by sediment removal processes (e.g., tides, waves) providing for bottom reoxygenation and food availability from fluvial supply (Fig. 5.15B). In the Maastrichtian, although both sides of the basin harbored macrobenthic tracemaker communities, the conditions were generally less favorable than in Campanian times, probably due to increased continental input (freshwater and continental detritus) (e.g., Aumond et al., 2021). However, in the southwestern and northeastern parts of the basin, local bioturbation has been reported in the Campanian sandy deposits, even in currently producing reservoirs (e.g., Guando and Cusiana oil fields), indicating a heterogeneous distribution of environmental parameters within the basin (Warren and Pulham, 2001; Leckie et al., 2003; Rincón et al., 2003; Veloza et al., 2008; Hernández-Duran, 2021). Thus, as indicated by the depositional parameters and therefore the sedimentary environments, the behavior of the central and eastern parts is different from that of the western area (Fig 5.15B).

5.5.2 Allogenic vs autogenic depositional controls

Allogenic and autogenic depositional parameters stratigraphically control the resulting sedimentary successions. Tectonics, subsidence and climate are the main external factors, while channel avulsion, delta lobe switching, relocation of alluvial channel belts and submarine fans are the main internal depositional controls (Catuneanu, 2022). These processes interact over time and define the filling of a sedimentary basin. The distinction between tectonics and eustasy is not straightforward; they are generally related, i.e., tectonism can lead to eustatic changes. In this case, however, scale plays an important role, both in terms of area and time. The Cretaceous epeiric basin of Colombia was tectonically controlled, as evidenced by the changes in deposit thickness (Gómez et al., 2003, 2005; Sarmiento-Rojas et al., 2006; Bayona, 2018; Carvajal-Torres et al., 2022). In addition, during the Late Cretaceous-Paleocene the tectonic subsidence increased due to horizontal compressional stress from the collision of the oceanic terranes along the northwestern margin of South America (Gómez et al., 2005; Sarmiento-Rojas et al., 2006). This collision resulted in the uplift of the proto-Central Cordillera, which triggered the erosion of a sedimentary cover on its eastern flank (Cortés et al., 2005; Gómez et al., 2003, 2005; Villagómez and Spikings, 2013; Zapata et al., 2021, 2024), leading to increased sediment input into the basin. Consequently, the filling of the La Luna Sea was driven by these tectonic processes rather than by global sea-level fall (Gómez et al., 2005).

In sedimentary terms, despite significant sediment loading through fluvio-deltaic interactions on the eastern side from the early Campanian to the late Maastrichtian, related to large drainage systems developed over extensive tectonic stables settings, the collision of the Caribbean Plate with the South American margin meant even higher sediment flux on the western margin, probably resulted from unroofing of the sedimentary cover (Gómez et al., 2003; Moreno-Sánchez and Pardo-Trujillo, 2003; Zapata et al., 2021, 2024). This may have contributed to the rapid and pronounced shift between offshore and fan delta complex deposits at the western side of the basin during the Maastrichtian, as well as the earlier development of fully fluvial environments as compared to the eastern side (Fig. 5.15). Such a marked change is also registered in other western parts of the basin. To the south, in the Upper Magdalena Valley Basin, coeval deposits known as La Tabla and Moserrate formations likewise overlie fine-grained shelf deposits, and their depositional settings vary between shoreface and offshore (Guerrero et al., 2000; Veloza et al., 2008; Roncancio and Martínez, 2011). La Tabla Fm. shares characteristics with the Cimarrona Fm. —previously described fan delta facies—, yet there is a notable difference in grain-size and lithological composition between the two and the Monserrate Fm., suggesting differences in depositional processes and therefore in sedimentary environments (Veloza et al., 2008), probably related to variations in accommodation space. In Ecuador, a similar stratigraphic relationship between coarse-grained fluvial deposits of the Tena Fm. sourced from western areas in the Real Cordillera, overlying fine-grained shelf successions of the Napo Fm., has been documented (Gutiérrez et al., 2019; Vallejo et al., 2021; Jaillard, 2022). There, the deposits show a wider areal distribution than the Cimarrona Fm. in Colombia —an extension 14 km to the east this unit reaches a minimum thickness of about 5 – 15 m (Guerrero et al., 2000; Gómez et al., 2003), confirming the local character of these deposits—. This supports the interpretation of a south-north collision of the western Caribbean terrains, generating in turn the uplift of mountain ranges (Proto-Real Cordillera in Ecuador and Proto-Central Cordillera in Colombia) along the same direction. While in Ecuador important relief was already well established during the early Maastrichtian —evidenced by the wide distribution of fluvial western derived deposits—, to the north, in Colombia, the first moments of mountain growth related to collision were recorded in the late Maastrichtian with the accumulation of these coarse-grained fan delta complex deposits. In addition, it can be inferred that the Maastrichtian coarse-grained deposits of eastern detrital signatures reported by Calderon-Diaz et al. (2024), close to the studied area, are also a response of the eastern margin basin (Amazonian Craton) to the collision of the western Caribbean terranes. This means that the response of the emerging areas did not only affect the western border or proto-Central Cordillera, with growth of the volcanic arc; but also highly stable areas of the eastern margin such as the Amazonian Craton. However, reworking of the sedimentary cover accumulated in the proto-Central Cordillera is not ruled out (Moreno-Sánchez and Pardo-Trujillo, 2003; Zapata et al., 2021, 2024).

Nonetheless, the Campanian-Maastrichtian period is represented by two sand-dominated successions separated by a mud-dominated one, interpreted as a transgressive cycle followed by a regressive one (Guerrero, 2002). These two cycles exhibit good correspondence with the long-term curve for the Late Cretaceous (Haq, 2014), showing a maximum sea-level towards the late Campanian consistent with the accumulation of offshore deposits in the central part, and prodelta deposits in the eastern part, also consistent with the accumulation of shelf deposits on the western side.

While the previous discussion highlighted the significant sediment loading from fluvio-deltaic interactions on the eastern side and the high sediment flux on the western side due to tectonic activity, internal or autogenic depositional controls also played a less relevant role during the final stages of the La Luna Sea. The sedimentary structures associated with traction processes evident in the western side shelf deposits during the Campanian indicate the influence of bottom currents during their accumulation. This, along with the tidal signals recognized in the Maastrichtian western deposits are the clear record of internal controls.

The high productivity reported in the organic- and phosphate-rich Campanian-lower Maastrichtian deposits are further evidence of autogenic controls during sedimentation. The thick unbioturbated fine-grained successions observed in Sections 2, 4, 5, and 11, with dark colorations, evidence these processes, which also cause oxygen-deficient environments. Phosphorite beds associated with upwelling processes have also been described in other sectors of the basin, even for the Maastrichtian (Föllmi et al., 1992; Martínez, 2003; Martín Rincón et al., 2022). In some cases, the abundant phosphate fragments in the sandy deposits controlled the petrophysical properties of the producing reservoirs in the basin (Warren and Pulham, 2001).

Channel avulsion processes are reported by Giraldo-Villegas et al. (2024) in the fan delta complex deposits linked to interaction between fluvial- and marine-dominated successions during the late Maastrichtian. These avulsion processes are not excluded in the fluvio-deltaic systems of the eastern border.

The integration of sedimentologic, ichnologic and stratigraphic evidence directly related to the sedimentary environments leads us to recognize the simultaneous participation of allogenic and, to lesser extent, autogenic controls in the origin, transport and final accumulation of the sedimentary deposits described. Notwithstanding, the degree of influence and subsequent preservation of these depositional controls in the fossil record would depend on the characteristics of the sedimentary systems in different areas of the basin. In summary, the type of sedimentary environments developed in each region, and their temporal and spatial evolution, hold the key to a better understanding of the accumulation parameters and the stratigraphic evolution of the epeiric basins.

5.5.3 Reservoir implications

In mature sedimentary basins, the generation of new exploration ideas is essential to the search for hydrocarbons. Given that the basins in this study fall into this category, detailed analyses that provide evidence for potential exploration opportunities are particularly relevant. Sedimentary parameters associated with continent-ocean systems that supply sediments, as well as internal basin processes responsible for sediment redistribution, have a direct influence on the quality, type, and distribution of reservoirs.

Among these processes, sediment redistribution by bottom currents plays a key role in reservoir development (Viana et al., 1998; Viana and Rebesco, 2007; Rebesco et al., 2014). Unlike fluvial-marine systems (e.g., delta, submarine canyons, turbiditic fans), which typically deposit coarse-grained sediments perpendicular to the shoreline, bottom currents can redistribute these sediments parallel or oblique to the coast. In some cases, they can transport and deposit large quantities of sand far from direct the land-ocean inputs (e.g., Rovere et al., 2019), as may be the case for the Campanian sandy deposits of the El Cobre Formation in Section 1. In addition, the sustained high energy of bottom currents tends to result in well-sorted sandy deposits with minimal clay or matrix (Viana et al., 1998; Yu et al., 2020).

Bottom currents also appear to influence the Campanian shelfal facies of the La Renta Formation, a major source rock in the basin (Pastor-Chacón et al., 2023; De la Parra et al., 2024). These processes could lead to thick accumulations of coarse-grained sediments on the shelf, potentially forming source-reservoir assemblages related to unconventional hydrocarbons (Li et al., 2016). These assemblages, also know source-reservoir neighboring type, are oil and gas producers in Ordos, Junggar and Songliao basins in China (Li et al., 2016).

5.5.4 Comparison with other ancient and recent epeiric seas: sediment arrival and distribution in the basin

Epeiric seas have been recorded in the geologic past, and modern analogues are widespread throughout the world. The best-known Cretaceous fossil records are the Western Interior Seaway in USA and the Neuquén Sea in Argentina (Hampson, 2010; Schwarz et al., 2022). Outstanding modern records include the Baltic Sea, North Sea, Hudson Bay, the Persian Gulf, and the Adriatic Sea (Judd et al.; 2020; Schwarz et al., 2022). Overall, they provide insight into the processes, conditioning factors, and the resulting sedimentary deposits generated.

The input of sediments and their dispersion pathways into the sea play a key role in the context of sedimentary deposits from epeiric seas, controlling to a significant extent the distribution of the macrobenthic communities (e.g., Walsh and Nittrouer, 2009).

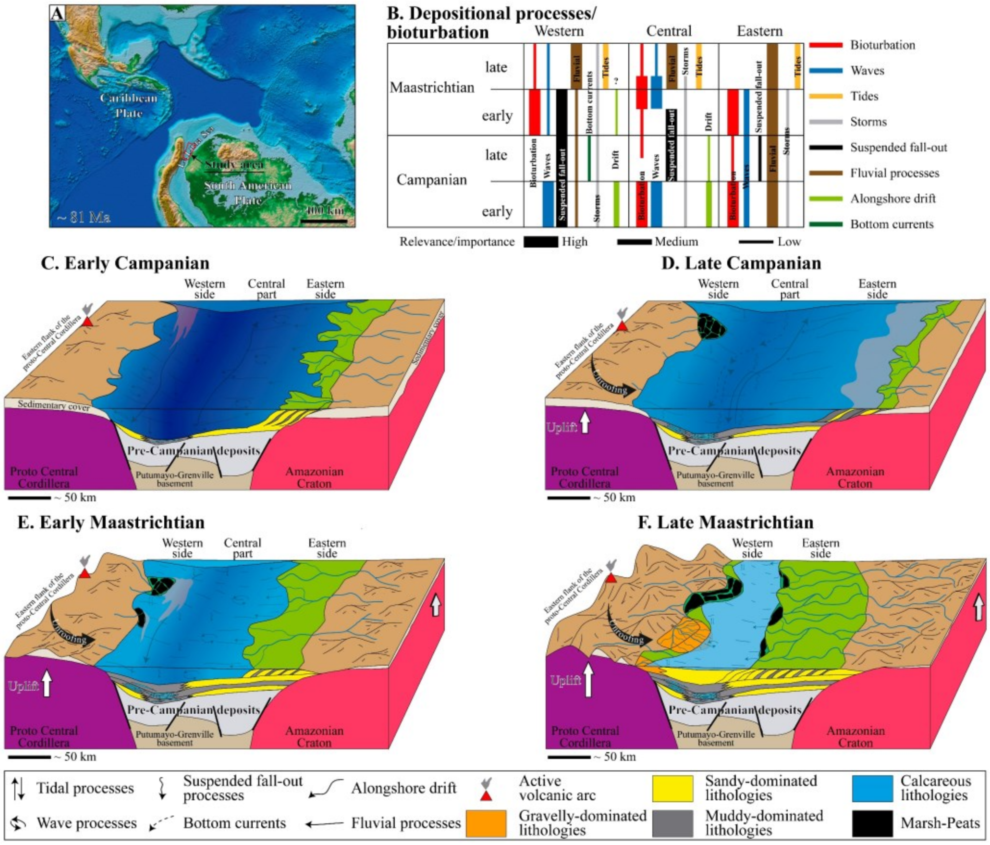

Figure 5.15. Paleogeographic reconstruction of the last stages of the central part of the La Luna Sea. **A.** Paleo-tectonic configuration of the northwestern margin of South America at 81 Ma showing the La Luna epeiric sea and the approximate location of the study area (from Salles et al., 2022). **B**. Summary of depositional processes/bioturbation and their occurrence in different parts of the basin during the Campanian-Maastrichtian. **C, F.** Schematic representation of the evolution of sedimentary systems of central part of the La Luna Sea during the early Campanian-late Maastrichtian.

Sediment distribution owes to a land-ocean dispersal system —i.e., related to topographical, geomorphological and compositional (e.g., basement, sedimentary cover) features of the emerged areas, plus the efficiency and characteristics of the transport systems involved (e.g., erosive capacity)— and may entail homogeneous distribution along the bordering coastlines, or else localized (heterogeneous) distribution towards some areas of the basin (Schwarz et al., 2022). Even though land transport systems are relatively easy to characterize, the role of internal currents on the cross-shelf vs alongshore sediment distribution within the marine basin are still poorly understood (Poyatos-Moré et al., 2016; Xu et al., 2023).

The final stages of the central part of the La Luna Sea in Colombia, show continental sediment input from the east during the Campanian-early Maastrichtian, and a relatively homogeneous distribution during the late Maastrichtian, with significant fluvial entries on both sides of the basin (Fig. 5.15). The fluvial-dominated deltas were the main basin feeders in the eastern sectors, whereas the fan delta complex and anastomosed/meandering fine-grained fluvial systems guided the continental entry by the western side. The eastern localized distribution of the fluvial entries during the Campanian-early Maastrichtian is reflected in a heterogeneous distribution in the cross-strike deposits trends, the eastern and central parts being dominated by sandy deposits, while along the western side muddy deposits prevail (Fig. 5.13). During the late Maastrichtian, as the sediment input is distributed on both sides of the basin, the deposits appear more homogeneous than in the Campanian (Fig. 5.13). Along-strike deposit trends show similar characteristics (Figs. 5.11 and 5.12); homogeneous sandy-dominated deposits in the central and eastern parts, compared to muddy-dominated deposits in the western part —in this case for both the Campanian and early Maastrichtian— indicate a generally non-uniform along-strike deposit distribution.

The larger N-S elongated Western Interior Sea had a western-located sediment input. The continental-derived sediments were transported to the basin coast and subsequently carried to distal parts of the basin by storms and bottom currents, resulting in a relatively uniform along-strike depositional trend (Elder and Kirkland, 1994; Hampson, 2010; Hampson et al., 2014). A southeast fluvial entry point was the main supply of sediments for the SE-NW extended Neuquén Sea. In this case, however, the sediments accumulated mainly in western areas and to a lesser extent than in northern regions, resulting in non-uniform along-strike depositional trends (Schwarz et al., 2022).

Comparing the three scenarios that occurred during the Cretaceous, it can be inferred that basin size plays a very important role in the internal along-strike redistribution of sediments. In the large Western Interior Sea, the western location of the fluvial inputs had no influence on the resulting homogeneous along-strike distribution of deposits, whereas in smaller basins, such as the Neuquén Sea (~ 250 km) and the central part of the La Luna Sea (~ 500 km), the location of the fluvial systems controlled the heterogeneous along-strike distribution of deposits (Figs. 5.11, 5.12 and 5.14). In the studied record, bioturbation further supports this heterogeneous sediment distribution, given the record of an abundant and diverse macrobenthic tracemaker community similarly distributed over the central and eastern parts of the basin as opposed to the western zone (Fig. 5.15). Perhaps longshore and bottom currents have a greater capacity to redistribute sediments in larger basins, where changes in salinity and temperature that favor current development are more pronounced (Rebesco et al., 2014). In the Central part of the La Luna Sea, though the distribution of fluvial inputs took place on both sides of the basin in the Maastrichtian, being completely different land-ocean sedimentary systems (fan delta complex vs fluvial systems), they resulted in a non-uniform distribution of deposits in this zone of the basin. In addition, although bottom and longshore currents were evident, they may not have been strong or prolonged enough to promote a homogeneous along-strike distribution of sediments. A non-uniform distribution of sediments has been reported in recent small epeiric seas with localized distribution of sediment inputs, such as the Adriatic Sea, and its associated Po Delta (Falcieri et al., 2014; Amorosi et al., 2022).

In contrast, the La Luna Sea shares characteristics with the Devonian North American Seaway, which had a supply of sediments from the east, accumulating deposits in this area, while on the opposite side marine sedimentation continued, resulting in non-uniform cross-strike deposit distribution (Schwarz et al., 2022 and references therein). In the central part of the La Luna Sea, during the Campanian-early Maastrichtian, the main fluvial entry was located along the eastern border (Figs. 5.13 and 5.14). Although the size of the basin may not be decisive in the cross-strike distribution of sediments, this is unlikely because processes such as gravity flows (important in cross-shelf transport, e.g., Wright and Friedrichs, 2006) are known to transport sediment seaward only about 100 km from the coast. Thus, in this case, we envisage other processes such as tidal currents, seasonal winds, and storm reworking as determinants for the cross-strike sediment distribution (Schieber, 2016). Although river-derived sediments have been found more than 1000 km from the coast (e.g., Talling et al., 2022; Baker et al., 2024), they are associated with submarine channels, which require sufficient gradients to sustain movement. Although synsedimentary deformation has been found on the eastern side that could be associated with high gradients, this evidence is too local to interpret steep slopes that could be conducive to the development of submarine channels.

It could be inferred from our study setting that maybe the N-S trending currents were more dominant than the E-W ones, leading to an isolation of the western side, impeding the arrival of continental sediments derived from the east. Finally, the influence of climate —not only on the origin and along- and cross-strike distribution of sediments, but also on the establishment and variability of ocean currents— cannot be ruled out. Similarly, another key factor that cannot be ignored and that may influence the arrival and subsequent distribution of sediment within the basin is the size and elevation of the emerged zones, which were different on both sides of the epeiric sea studied here (small with high elevations in the west and large with low elevations in the east).

5.6 Conclusions

Recent knowledge of the stratigraphic evolution of sedimentary deposits in epeiric seas contributes to better identification of the depositional controls and processes involved. The final stages of the Cretaceous epeiric sea in Colombia had two phases: one dominated by marine processes, followed by another associated with transitional and continental environments. The evolution of this basin, bounded on either side by different geologic domains, depended on the evolution of the emerged areas, the land-ocean sediment-delivery systems, and the processes of deposition and distribution of sediments within the basin. On the analyzed sections located on the western side and in the central part of the basin, a shoreface-basin profile comprising shelf, offshore, and shoreface-foreshore environments prevailed, whereas on the eastern side, prodelta and delta front environments dominated during the Campanian-Maastrichtian period. To the west, fall-out sedimentation processes were dominant during the Campanian-early Maastrichtian, reflected in the accumulation of fine-grained lithologies. In constrast, sandy and muddy deposits accumulated in the central and eastern parts of the basin: wave and fall-out sedimentation were the main parameters in the central part, while fluvial processes were mainly responsible at the eastern zone. Less important depositional processes were fluvial, bottom and longshore currents on the western side; storms, tides, and longshore currents in the central part; and suspension, wave, and storm processes on the eastern area. During the late Maastrichtian, alluvial/fluvial processes dominated the western side associated with the growth of the proto-Central Cordillera, whereas the central and eastern parts show little change. Ichnologic features suggest habitable marine bottoms during the early Campanian and the early Maastrichtian in the central and eastern parts of the basin, but paleoecological conditions on the western side (particularly oxygenation) created a challenging environment for the tracemaker community, mainly during the Campanian. During the early Maastrichtian all seafloors were colonized, suggesting favorable conditions for marine macrobenthic communities.

The sedimentologic, ichnologic and stratigraphic characteristics documented here, together with their variation in time and space, suggest that both allogenic (tectonic, subsidence, sea-level) and, to a lesser extent, autogenic processes (channel avulsion, bottom and longshore currents, tides, high productivity) simultaneously controlled the resulting sedimentary deposits. Depositional parameters provide clues as to new exploration ideas, associated with possible reservoir deposits related to longshore and bottom currents. This opens up the possibility of searching for reservoirs that are directly connected to the source rock, and in positions perpendicular to the main direction of the major fluvial systems that delivered coarse-grained sediments to the basin.

Comparison of different epeiric basins, both fossil and recent, reveals that the basin size and the emerged areas plays an important role in the internal along- and cross-strike distribution of sediments, where processes such as bottom or longshore currents, or gravity flows would play a key role.

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Supplementary material

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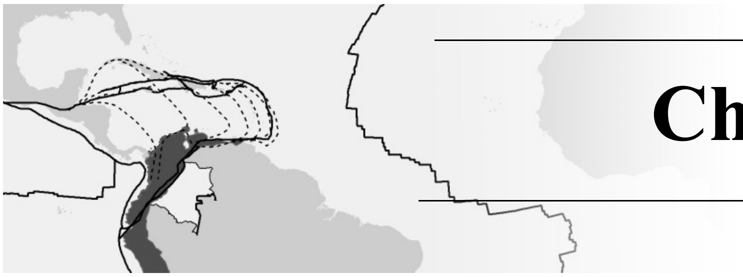

Chapter 6

EASTERN BACKARC GEOLOGICAL DOMAIN: *OPHIOMORPHA* ICHNOFABRIC IN FAN-DELTA COMPLEX DEPOSITIONAL SETTINGS

VARIABLE *OPHIOMORPHA* ICHNOFABRIC: IMPROVING THE UNDERSTANDING OF MOUTH BAR ENVIRONMENTS IN FAN-DELTA COMPLEX DEPOSITIONAL SETTINGS FROM THE UPPER CRETACEOUS OF NW SOUTH AMERICA

Carlos A. Giraldo-Villegas [a,b] , Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a,b], Andrés Pardo-Trujillo [b,c]

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain

[b] Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday, Calle 65 No 26-10, 170004, Manizales, Colombia

[c] Instituto de Investigaciones en Estratigrafía-IIES, Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia


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Variable *Ophiomorpha* ichnofabric: Improving the understanding of mouth bar environments in fan-delta complex depositional settings from the Upper Cretaceous of NW South America

Carlos A. Giraldo-Villegas [a, b, *], Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a, b], Andrés Pardo-Trujillo [b, c]

[a] *Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain*
[b] *Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday, Calle 65 No 26-10, 170004, Manizales, Colombia*
[c] *Instituto de Investigaciones en Estratigrafía-IIES, Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia*

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Abstract

Fan-delta deposits, an important sedimentary component of fan-delta complexes, are scarcely described in the ancient record because it is very difficult to distinguish them from other types of coarse-grained deposits (e.g., alluvial, fluvial, or deep marine deposits). This obstacle is overcome when a well-record of physical/biogenic sedimentary structures or fossils unambiguously marks the influence of the receiving basin. However, this is usually not the case. Here, we present the *Ophiomorpha* ichnofabric record as a key proxy of marine influence within a generally fluvial-dominated system for improving the paleoenvironmental understanding and reconstructing animal-substrate interplay during the evolution of a fan-delta complex. The ichnological record, together with detailed sedimentological analysis, allows us to define three ichnofabric types, distributed in four levels. The stratigraphic distribution of these features points to distal alluvial environments towards the base, dominated by debris and sheet flows deposits and locally shallow braided channels; they evolve upward into well-developed braided fluvial system whose facies arrangement is related to channel fills, locally influenced by debris flows. Subsequently, a basinward migration of the sedimentary system is recorded through the occurrence of the first level with *Ophiomorpha* ichnofabric A, and then ichnofabrics A and B in levels 2 and 3, respectively, suggesting marine-influenced mouth bar settings. Toward the top, another steep basinward migration is evidenced by *Ophiomorpha* ichnofabric C in level 4, indicating wave-dominated processes in distal mouth bars environments. The record of marine-influenced and dominated levels may indicate relative sea-level fluctuations related to local or autogenic processes to at the basin scale. Furthermore, the present study demonstrates the ability of *Ophiomorpha* tracemaker to colonize challenging sedimentary environments.

Keywords: Coarse-grained deposits, relative sea-level, ichnology, Late Cretaceous, Cimarrona Formation

6.1 Introduction

Fan-delta deposits, and their associated alluvial fans, may be considered indicators of tectonic and climatic activity and used to characterize the relationship between tectonics and eustasy in sedimentary basins (Nemec and Steel, 1984; Rust and Koster, 1984; Dabrio et al., 1991; Einsele, 2000; Sohn et al., 2001; Backert et al., 2010; Rees et al., 2018). Knowledge on this topic was extensively developed during the 1980s and 1990s, resulting in key publications for the study of these sedimentary settings (e.g., Koster and Steel, 1984; McPherson et al., 1987; Nemec and Steel, 1988; Colella and Prior, 1990; Dabrio et al., 1991; Chough and Orton, 1995; Steel and Marzo, 2000).

The rapid and widespread growth in the literature about these sedimentary deposits also led to some academic debates, such as how to define the fan-delta itself (Blair and MacPherson, 2008). The two most widely accepted proposals would be a delta formed by an alluvial fan (Nemec and Steel, 1988; Nemec, 1993), and an alluvial fan built into a lake or ocean (McPherson et al., 1987, 1988; Blair and MacPherson, 2008). The first option classifies the interface between the active fan and the receiving basin (standing body water), considering the landward portion of the alluvial fan as not forming an integral part of fan-delta deposits, whereas the second includes the entire alluvial fan and its subaqueous component. The characteristic feature of these deposits is their coarse-grained nature, conglomerates being the dominant lithological component. Because they can be transported to the catchment basin in different ways, Nemec and Steel (1988) proposed a classification based on the feeder system, calling “fan-delta complexes” to the settings that show an interaction of alluvial fan–fluvial–fan-delta deposits.

It is difficult to characterize these fan-delta complexes owing to the interaction between alluvial, fluvial, and marine/lacustrine processes. Therefore, it is essential to distinguish products associated with the fluvial-alluvial deposition from those reworked by the sea/lake in the receiving basin (Nemec and Steel, 1984; Siggerud and Steel, 1999). It is often problematic to identify their origin based on physical sedimentary structures, as conglomeratic deposits can accumulate in a variety of depositional environments (rivers, river mouths, submarine channels, among others). Hence, other diagnostic features such as biogenic structures and fossils —when present— should be considered.

Trace fossils studies have become a very useful tool for refining paleoenvironmental and stratigraphic interpretations in sedimentary basin research, given their close relationship with depositional and ecological factors during deposition, and the response of tracemakers to paleoenvironmental changes (Mcllroy, 2004; MacEachern et al., 2005; MacEachern and Bann, 2008; Buatois and Mángano, 2011; Knaust and Bromley, 2012). In applied ichnology, the two main paradigms are ichnofacies model and the ichnofabrics approach. The former is based on the identification of key features formed under similar environmental conditions (Seilacher, 1964; MacEachern et al., 2007, 2012; Buatois and

Mángano, 2011). The ichnofabric approach, in turn, refers to any aspect of the texture and internal structure of a substrate or rock, resulting from bioturbation or bioerosion at any scale (Ekdale and Bromley, 1983; Ekdale et al., 2012). Accordingly, features such as ichnoassemblage, bioturbation index, ichnodiversity, tiering, cross-cutting relationships, and primary sedimentary structures, afford clues as to the interaction between physical and biological processes, thus providing sedimentological, paleoenvironmental and even stratigraphic information (Ekdale et al., 2012).

Some ichnofabrics in the stratigraphic record are particularly informative, as for instance *Ophiomorpha* ichnofabric (e.g., Gibert et al., 2006; Uchman, 2009; Netto et al., 2017). This ichnofabric is composed mainly of *Ophiomorpha* traces, though it sometimes includes subordinate traces. *Ophiomorpha* is attributed to the burrowing activities of thalassinidean shrimp (particularly callianassids) and can be found in deep marine deposits or even shallow marginal marine facies, as in estuaries, tidal flats, and beaches (Frey et al., 1978; Pollard et al., 1993; Tchoumatchenco and Uchman, 2001; Gibert et al., 2006; Bromley and Pedersen, 2008; Uchman, 2009; Leaman et al., 2015; Nagy et al., 2016; Giannetti et al., 2017; Netto et al., 2017). In fact, *Ophiomorpha* is a typical component of high-energy nearshore environments, related to loose coarse-grained sediments typical of fan-delta deposits (Frey et al., 1978; Ekdale et al., 1984; Droser and Botjjer, 1989; Anderson and Droser, 1998; Buatois and Mángano, 2011; Knaust, 2017). Some reports in non-marine facies (Stewart, 1978; Bown, 1982; Merril, 1984) were apparently based on incorrect ichnotaxomonical classifications and/or associated with burrowing from overlying marine deposits (Asgaard and Bromley, 1974; Goldring and Pollard, 1995).

Ichnological records in fan-delta and, by extension, in fan-delta complex deposits are relatively scarce (e.g., Pollard et al., 1982; Lockley et al., 1987; Ekdale and Lewis, 1991; Siggerud and Steel, 1999; Siggerud et al., 2000; Soegaard and MacEachern, 2003; Gibert et al., 2007; Hovikoski et al., 2018; Sendra et al., 2020; Ichaso et al., 2022; Baucon et al., 2023). A combination of environmental stressors —high river discharge, high sedimentation rate, high erosion— can create unfavorable habitats for the production and/or preservation of trace fossils, resulting in a scarce record of ichnological features in these settings (Ekdale and Lewis, 1991; Ichaso et al., 2022). For this reason, any available ichnological information is of great significance for a paleoenvironmental understanding of these deposits, as it can provide insights into the organism-substrate relationship of such complex and challenging sedimentary environments.

In this paper, we analyze a fan-delta complex developed during the Late Cretaceous, in the last stages of an epeiric sea in NW South America, where stratigraphic features are not conclusive when reading paleoenvironmental conditions. Our focus is on the *Ophiomorpha* ichnofabric as a key for improving the paleoenvironmental understanding and reconstructing animal-substrate interplay during the evolution of a fan-delta complex, involving alluvial fan–fluvial–fan-delta deposits.

6.2 Geological setting

The Cretaceous sedimentary deposits of northwestern South America, specifically Colombia and Ecuador, are associated with two different tectonic and depositional settings as a result of the interaction between the South American, Farallon-Nazca and Caribbean plates. A western domain linked to the Caribbean Plate evolution developed in an oceanic environment (proto-Pacific Ocean), and an eastern domain, linked to the South American Plate, established in an epicontinental marine setting (Proto Atlantic Ocean) (Horton et al., 2010; Bayona, 2018; Sarmiento-Rojas, 2018; Pardo-Trujillo et al., 2020; Paez-Reyes et al., 2021). In Colombia, the western domain includes all geological units west of the Romeral Fault System (RFS) (Moreno-Sánchez and Pardo-Trujillo, 2002; Barrero et al., 2007); the eastern domain comprises the current Magdalena Valley (Upper, Middle, and Lower) and Eastern Cordillera sedimentary basins.

The Middle Magdalena Valley Basin (MMVB) harbors a complex geological history from the Mesozoic to present (Horton et al., 2010; Carvajal-Torres et al., 2022). Between Triassic to Early Cretaceous, an extensional rift basin related to the Pangea break-up accumulated red beds and volcaniclastic rocks (Etayo-Serna et al., 1983; Sarmiento-Rojas, 2001; Gómez et al., 2003; Sarmiento-Rojas et al., 2006). During most of the Cretaceous sedimentation was marine, associated with a major transgressive-regressive cycle with maximum flooding close to the Cenomanian-Turonian boundary (Villamil, 1998; Guerrero, 2002; Sarmiento-Rojas, 2018). The latest Cretaceous witnessed the final stages of marine-influenced environments in the basin, related to shelf and transitional settings. One transitional sedimentary system Is the Cimarrona Formation, defined by Wasburne and White (1922) as "a succession of 400 ft-thick (~121 m) composed of coarse-grained sandstones, millstone grits and limestone conglomerates". Despite its different stratigraphic redefinitions (e.g., Raasveldt and Carvajal, 1957; De Porta, 1966; Gómez and Pedraza, 1994) the proposal of Gómez and Pedraza (1994) is currently the most widely accepted, and the one used in this work. They define the unit as a succession ~80 m thick composed mainly of conglomerates and gravelly sandstones, and in lesser proportion sandstones, mudrocks and limestones, associated with braided-delta environments developed during the middle-Late Maastrichtian (De Porta, 1966; Tchegliakova, 1996). This unit represents the clastic record that documents the beginning of the emergence of the northern Andes related to the collision between Caribbean and South American plates (Gómez et al., 2003; Bayona, 2018; Pardo-Trujillo et al., 2020; Valencia-Gómez et al., 2020).

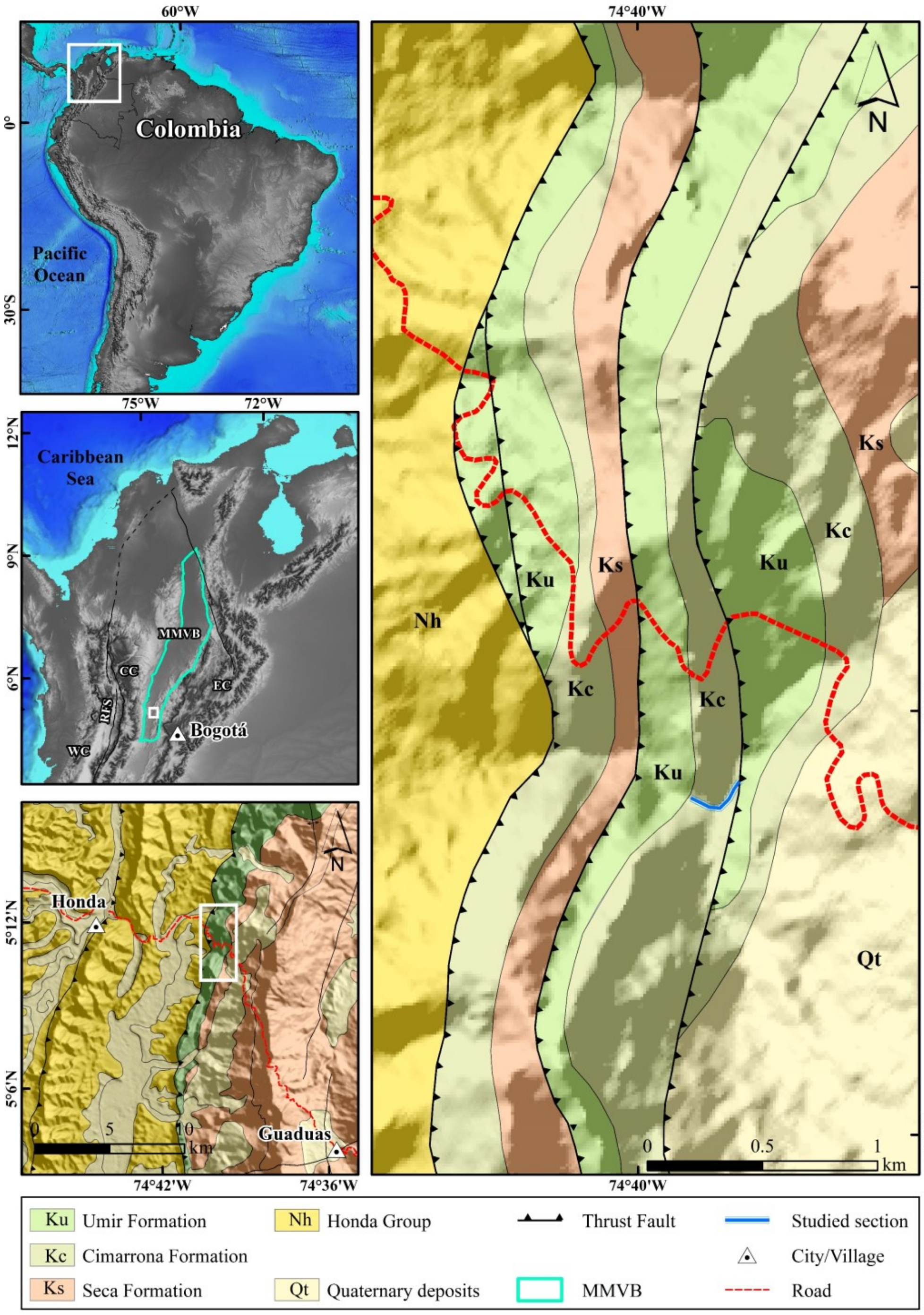

Figure 6.1. Location map of studied section. CC: Central Cordillera, EC: Eastern Cordillera, MMVB: Middle Magdalena Valley Basin, RFS: Romeral Fault System, WC: Western Cordillera. Geology adapted from Gómez and Pedraza (1994), and Gómez et al. (2015).

The stratigraphic section corresponding to the Cimarrona Formation —south of the MMVB, along the Cimarrona Creek near the Honda-Guaduas highway— is characterized by several thrust sheets. They expose the Cimarrona Formation three times within a relatively small area (Fig. 6.1). The thrusts also involve the Umir and Seca formations, which respectively underlie and overlie the Cimarrona Formation (Fig. 6.1).

6.3 Material and methods

Outcrop research is based on bed-by-bed characterization of grain size, texture, bed geometry (where possible) thickness, contact types and primary sedimentary structures. A detailed analysis of the trace fossils assemblage paid special attention to features allowing for ichnofabric characterization: trace fossil distribution, abundance, tiering, and cross-cutting relationships. Trace fossil features such as, shape, wall, lining, branching, filling and spreite were analyzed for ichnotaxonomy (ichnotaxobases of Bertling et al., 2006, 2022). To estimate trace fossil abundance, the ichnofabric index (ii) proposed by Droser and Bottjer (1986) was applied, ranging from ii = 0 (unbioturbated) to ii = 6 (completely bioturbated). In view of sedimentological and ichnological features, the different ichnofabrics were defined following Bromley and Ekdale (1986) and Ekdale et al. (2012). The ichnofabrics were classified as simple or composite according to the diversity of trace fossils. Bed thickness characteristics follow the nomenclature of Ingram (1954): laminae (<1 cm), very thin (1–3 cm), thin (3–10 cm), medium (10–30 cm), thick (30–100 cm) and very thick (>100 cm). Sedimentary facies were defined from lithological features and, according to their relationships, vertical and spatial distribution and stacking patterns were defined and grouped in facies associations. Such integration of sedimentary facies and ichnofabrics sheds light on the depositional setting, sub-environments, specific sedimentary parameters, and the overall paleoenvironmental evolution.

6.4 Results

6.4.1 Sedimentology and facies associations

An aggradational succession ~113 m thick was described, ~30 m of which being covered by vegetation, having 52% of conglomerates, 40% sandstones and conglomeratic sandstones, and 8% of mudrocks (Fig. 6.2). The integration of sedimentological and ichnological data allowed for the definition of sixteen lithofacies (F1 to F16), grouped in three facies associations (FA1 to FA3) (Fig. 6.2, Table 6.1).

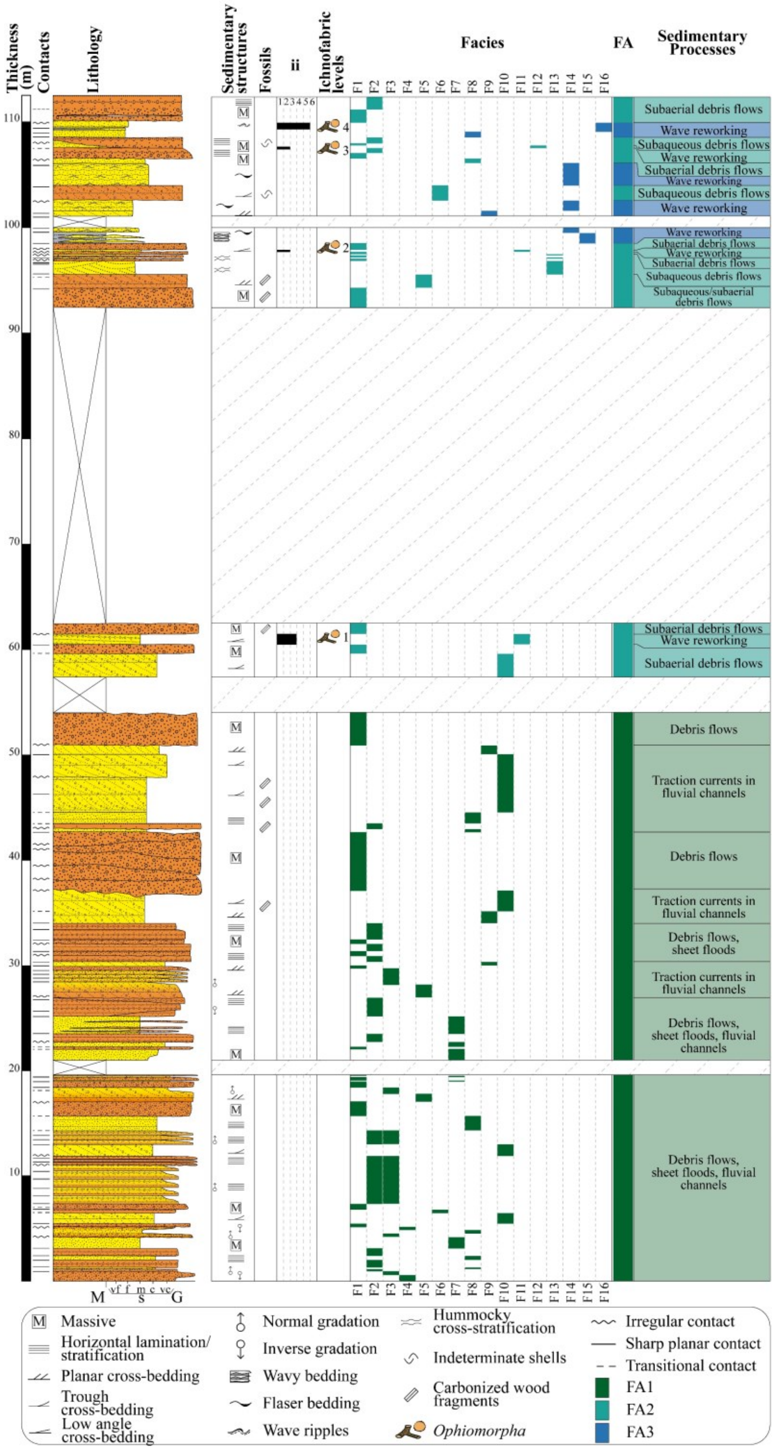

Figure 6.2. Stratigraphic log, sedimentological features, facies associations and sedimentary processes for the studied section. 1, 2, 3 and 4 represent the levels with Ophiomorpha. FA: Facies associations. ii. Ichnofabric index.

FA1

This is the thickest basal facies association (~54 m thick), found at the base of the studied succession, which can be divided in two well-differentiated parts (Figs. 6.2, 6.3A, B). The lower part of FA1 (first 27 m thick) shows a general aggradational pattern, characterized by amalgamated cuneiform- to lenticular- and tabular-shaped, medium to thick beds of clast- and matrix-supported granule- to cobble-size conglomerates, pebble-size conglomeratic sandstones, and medium- to very coarse-grained sandstones with irregular and planar sharp Bases. These lithologies show mainly massive (F1, F7; Figs. 6.3C, D), horizontal stratification (F2, F8; Figs. 6.3D, E), normal and inverse grading (F3, F4; Fig. 6.3F), and punctually planar cross- and trough cross-bedding structures (F5, F6, F10; Figs, 6.3G, H). The upper part of FA1 is 27 m thick, arranged in fining-upward packages, featuring medium to thick tabular- and cuneiform-shaped beds of clast- and matrix-supported granule- to pebble-size conglomerates; the massive (F1), horizontally stratified (F2) and normal grading (F3) structures transition upwards to medium- to coarse-grained sandstones and pebble-size conglomeratic sandstones with planar cross- and trough cross-bedding, with foresets dipping toward the east (F9, F10) and locally horizontal laminated structures (F8). The conglomerates are poorly to moderately sorted in the base (lower part), then moderate to well-sorted in the upper part, with a medium- to coarse-grained sandy matrix and showing subangular to rounded clasts mainly of quartz and chert. The sandstones and conglomeratic sandstones are poorly to moderately sorted, having subangular to subrounded grains, and clayey matrix. Carbonized wood fragments up to 25 cm are sporadically observed.

FA2

Overlying the FA1 (Figs. 6.2, 6.4), FA2 consists of medium to thick tabular- and cuneiform-shaped beds. The clast- and matrix-supported granule- to pebble-size conglomerates are up to 1.3 m-thick, showing horizontal, planar- and trough-cross stratification and massive structures, locally with indeterminate mollusk shell fragments (F1, F2, F5, F6; Fig 6.4A-D). The conglomerates are moderately sorted, having subangular to subrounded clasts of quartz and chert, and a medium- to coarse-grained sandy matrix. Locally, three fining-upward amalgamated sequences are recognized, which starts with medium to thin beds of pebble-size clast-supported, well sorted conglomerates with massive structure and subrounded clasts and a basal irregular contact (F1), followed by thin to medium beds of fine- to medium-grained sandstones with hummocky cross-stratification (F13), capped by wave-rippled fine- to medium grained sandstones (F16; Figs. 6.4E-H). Fine- to coarse-grained sandstone beds up to 0.5 m thick are also present, exhibiting horizontal, and low-angle cross-bedding structures, moderately to well sorted, and locally with *Ophiomorpha* (F11, F12; Figs. 6.4A, B).

Table 6.1. Description of facies in terms of thickness, lithology, sedimentary structures, texture, ichnology, fossils, depositional processes, and facies associations (Kleinspehn et al., 1984: Nemec and Steel, 1984, 1988; Miall, 1996; Reading, 1996; Tinterri, 2011; Collinson and Mountney, 2019). ii. Ichnofabric index. The colors represent the facies associations in Fig. 6.2.

Lithofacies and facies code	Description	Ichnology/Fossils	Hydrodynamic processes	FA1	FA2	FA3
F1: Massive conglomerates	Medium to thick beds of clast- and matrix-supported, granule to cobble-grained conglomerates or sandy conglomerates with erosional bases, poor to well sorted, with subangular to rounded clasts, and medium- to coarse sandy matrix.	Indeterminate mollusk shell fragments	Sediment gravity flows, bedload transport in high flow regime, locally with marine reworking.			
F2: Horizontal stratified (laminated) conglomerates	Medium to thick beds of clast- and matrix-supported granule to pebble-grained conglomerates or sandy conglomerates, with erosional and sharp planar bases, poor to well sorted, with subangular to rounded clasts, and medium- to coarse sandy matrix.	Indeterminate mollusk shell fragments	Tractional deposition as longitudinal bed forms “sheet bars” or sheet flows, or sediment gravity flows, locally with marine reworking.			
F3: Normally graded conglomerates	Thin to medium beds of clast-and matrix-supported granule to pebble-grained conglomerates or sandy conglomerates with erosional and sharp planar bases, poor to moderately sorted, with subangular to rounded clasts, and medium- to coarse		Deceleration of the flow with coarsest particles falling to the bed first.			

	grained sandy matrix.					
F4: Inverse graded conglomerates	Thin to medium beds of clast-and matrix-supported granule to pebble-grained conglomerates or sandy conglomerates with erosional and sharp planar bases, poor to moderately sorted, with subangular to rounded clasts, and medium- to coarse grained sandy matrix.		High-strength debris flow, or as a low strength flow with an inertial bed load transported by laminar to turbulent flow.			
F5: Planar cross-bedded conglomerates	Medium beds of clast-and matrix-supported granule to pebble-grained conglomerates or sandy conglomerates with erosional and sharp planar bases, moderately to well sorted, with subangular to rounded clasts, and medium- to coarse grained sandy matrix.		Migration of straight-crested dunes.			
F6: Trough cross-bedded conglomerates	Medium to thick beds of clast-and matrix-supported granule to pebble-grained conglomerates or sandy conglomerates with erosional and sharp planar bases, well to moderately sorted, with subangular to rounded clasts, and medium- to coarse grained sandy matrix.	Indeterminate mollusk shell fragments	Traction deposition as longitudinal bed forms, “sheet bars”; or sediment gravity flows with marine reworking. Migration of sinuous to linguoid-crested dunes. Marine reworking.			

F7: Massive sandstones	Medium to thick beds of fine- to coarse-grained sandstones, moderately to well sorted, with subangular to subrounded grains and argillaceous matrix.		Rapid deposition, most probably through the deceleration of a heavily sediment-laden current.			
F8: Horizontal stratified (laminated) sandstones	Medium to thick beds of medium- to coarse- and locally granule-grained sandstones and conglomeratic sandstones, moderately to well sorted, with subangular to subrounded grains and argillaceous matrix.		High velocity currents deposited during single dynamic events, such as flash floods.			
F9: Planar cross-bedded sandstones	Medium to thick beds of coarse-grained and locally granule-size sandstones and conglomeratic sandstones, moderately to well sorted, with subangular to subrounded grains and argillaceous matrix.		Migration of ripples or dunes with straight crest. Thalweg bars in fluvial channels.			
F10: Trough cross-bedded sandstones	Medium to thick beds of fine- to coarse- and locally granule-grained sandstones and conglomeratic sandstones, moderately to well sorted, with subangular to subrounded grains and argillaceous matrix.		Migration of sinuous to linguoid-crested ripples or dunes.			
F11: low-angle cross-bedded sandstones	Coarse- to granule-grained conglomeratic sandstone, well	ii: 2, 3, *Ophiomorpha irregulaire*, *O. nodosa*	Washed-out dunes that occur between subcritical flow regimes. Deposited by			

	sorted, with subrounded to rounded grains and argillaceous matrix. Locally, carbonized wood fragments are observed.		traction from relatively weak currents that approach upper flow regime conditions for the size of sediment being deposited. Establishment of marine tracemaker community.			
F12: Horizontal stratified (laminated) sandstones	Thin to medium beds of medium-grained sandstones, moderately to well sorted, with subangular to subrounded grains and argillaceous matrix.	ii: 2; *Ophiomorpha irregulaire*	High velocity currents deposited during single dynamic events, such as flash floods in marine environments. Establishment of marine tracemaker community.			
13: Hummocky cross stratification	Thin to thick beds of fine- to medium-grained sandstone, well sorted, with subrounded to subangular grains and argillaceous matrix.		Transformation of dense flows or different types of horizontally bipartite composite gravity flows entering seawater. Deposited by hyperpycnal flows generated by turbulent sediment-laden stream flows.			
F14: Flaser heterolytic bedded	Centimetric sandstone-mudstone couplets, with predominance of sandy material. They are associated with symmetrical ripples.		Water movement over a sand bed, as oscillatory waves. The variation in mud and sand content is the result of increasing/decreasing current speed.			
F15: Wavy heterolytic bedded	Centimetric sandstone-mudstone couplets in equal proportions, linked to symmetrical ripples.					
F16: Wave-rippled sandstones	Thick bed of medium-grained sandstone, moderately to well sorted, with subrounded to subangular grains and argillaceous matrix.	ii: 2, 5, *Ophiomorpha nodosa* and *O. irregulaire*	Oscillatory wave processes, hence deposition under wave action. Establishment of marine tracemaker community.			

FA3

Although FA3 is poorly represented in the studied succession, it is closely associated with FA2 (Figs. 6.2, 6.5). Its thick tabular beds of medium- to fine-grained wave-rippled sandstone (F16) evidence *Ophiomorpha* (Fig 6.5A). Inverse grading from bioturbated wave-rippled sandstones (F16) to massive pebble-size matrix-supported conglomerates (F1) can be recognized (Fig. 6.5A). In addition, fine-grained-sandstones are observed in association with mudrocks, developing heterolytic structures, such as flaser (F14) and wavy bedding linked to symmetrical ripples (F15; Figs. 6.5B-E), while locally fine- to medium-grained sandstones with Horizontal and planar cross-lamination are present (F8, F9). The sandstones are very well sorted, having subangular to subrounded grains.

6.4.2 Ichnology

The record of *Ophiomorpha*

Ichnological analysis reveals the exclusive presence of *Ophiomorpha*. In general, *Ophiomorpha* ranges from simple, individual burrows, to complex cylindrical tunnels. The specimens show a random distribution and a dominant horizontal to subhorizontal orientation. Two ichnogenera could be identified owing to the distinctive pelletal lining of the burrow walls: *Ophiomorpha nodosa* Lundgren, 1891 and *Ophiomorpha irregulaire* Frey, Howard and Pryor, 1978. While in most cases they appear in 2D cross-section views, locally (in bedding plane-sections) it was possible to observe the branching and geometric arrangement of some specimens.

Ophiomorpha nodosa is characterized by a knobby wall structure, regularly distributed with single subspherical sand-pellets completely covering the surface of the burrow. In cross- section, the burrows are elliptical to circular, and show active and passive fills of medium- to coarse-grained siliciclastic material (Fig. 6.6). These traces are 1 cm wide and between 5 and 10 cm long.

Ophiomorpha irregulaire, best visible in bedding-plane sections, is characterized by distorted or flame-like mud pellets, irregularly distributed; the outwardly tapering pellets are of nonuniform size, while interior surface of this lining is smooth. Active and passive fill of medium- to coarse-grained siliciclastic material is observed. In cross-section an oval to flattened circular shape is apparent. The lining, consisting of dark-colored mud, is absent in some places and well developed in others. Specimens can be 2 cm wide and up to 20 cm long (Fig. 6.6).

Figure 6.3. Sedimentological features of FA1. **A. B.** General and detail outcrop view of contact between lower and upper part of FA1. Note the lenticular- or cuneiform-shape beds of conglomerates in the lower part (right side of the photo) and the well-stratified deposits of the upper part (left side of the photo). **C.** F1 aspect showing the massive fabric/structure. **D.** Amalgamated cuneiform- and lenticular-shape beds of F1 and F2. **E.** Horizontal stratified conglomerates (F2). **F.** Normal graded conglomerates (F3) in irregular contact with massive conglomerates (F1). **G.** Trough cross-bedded sandstones (F10). **H.** Planar cross-bedded conglomerates (F5). Detailed facies descriptions and interpretations are given in Table 1.

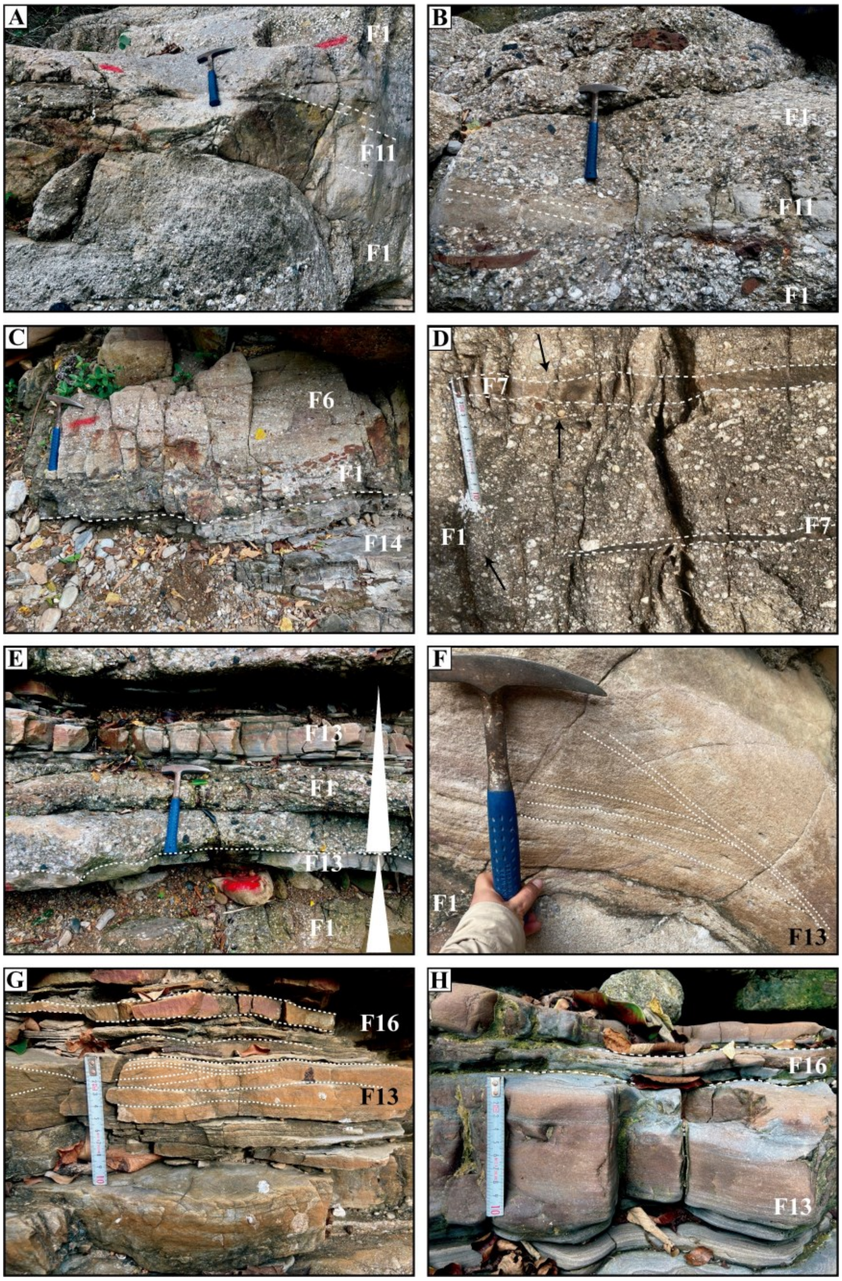

Figure 6.4. Sedimentological features of FA2. **A. B.** Massive conglomerates (F1) and low-angle cross-bedded sandstone (F11). **C.** Contact between flaser heterolytic bedding (F14) and cuneiform-shaped massive and trough cross-bedded conglomerates with indeterminate mollusk shell fragments (F1, F6). **D.** Massive conglomerates with indeterminate mollusk shell fragments (arrows) (F1) and lens-shape fine-to medium-grained massive sandstones (F7). **E.** Lithofacies related to hummocky cross-bedded sandstones (F13). **F.** Fine- to medium-grained sandstone with hummocky cross-stratification (F13). **G. H.** Medium-grained sandstone with hummocky cross-stratification (F13) capped by wave-rippled sandstones (F16). Detailed facies description and interpretation in Table 1.

***Ophiomorpha* ichnofabric**

According to sedimentological and ichnological features, three types of simple ichnofabrics were recognized, defined exclusively by *Ophiomorpha* (Oi-A, Oi-B, Oi-C), distributed in four levels along the succession from FA2 (levels 1, 2, 3) and FA3 (level 4) (Figs. 6.2, 6.6).

Oi-A is characterized by medium-grained sandstone to locally granule-size conglomeratic sandstones with low-angle cross-bedding (F11). Solitary burrows of predominantly *Ophiomorpha nodosa* and locally *O. irregulaire* are recognized, showing mainly horizontal orientation, and with ichnofabric indexes between 2 and 3 (Fig. 6.6). No cross-cutting relationships were observed. It is present in levels 1 and 2, corresponding to ~ 0.2 to ~ 1 m-thick beds, and underlain and overlain by medium to thick massive conglomeratic beds.

Oi-B is characterized by medium-grained sandstones with crude horizontal lamination (F12), and solitary burrows of *Ophiomorpha irregulaire* with ichnofabric indexes up to 2 (Fig. 6.6). No cross-cutting relationships were observed. It is present in level 3, linked to a ~ 1 m-thick bed, cut (overlain) by a channel-shaped bed (~1 m-thick) of massive- to horizontal stratified conglomerates with indeterminate mollusk shells.

Oi-C is associated with wave-rippled fine-grained sandstones (F16) showing a complex network of mostly *Ophiomorpha nodosa* and locally *O. irregulaire*, and ichnofabric indexes between 3 and 5 (Fig. 6.6). Cross-cutting relationships between *Ophiomorpha nodosa* traces were observed where the highest ichnofabric indexes were reached (toward the top of the bed) (Fig. 6.6). In this ichnofabric a marked change in the fill type is observed. It is present in level 4, related to a ~1 m-thick bed, which is underlain by horizontal laminated sandstones (F8) and overlain by massive conglomerates (F1).

6.5 Discussion

6.5.1 Fan-delta complex evolution and stratigraphic variations in sedimentary processes

The coarse-grained nature of such deposits makes it difficult in most cases to identify marine-influenced deposits on the basis of sedimentological characteristics. In this particular case, however, a marine influence is clearly reflected by the *Ophiomorpha* ichnofabric record (Nagy et al., 2016). Thus, active depositional interplay between alluvial, fluvial, and marine processes can be discussed, allowing for the discernment of a fan-delta complex setting after Nemec and Steel (1988), comprising alluvial fan, fluvial-braided and fan-delta deposits (Fig. 6.7).

Figure 6.5. Sedimentological features of FA3. **A.** Bioturbated wave-rippled fine-grained sandstones (F16) and upward transition to massive conglomerates (F1). **B. C. D.** Flaser heterolytic bedding (F14). **E.** Wavy heterolytic bedding (F15). Detailed facies description and interpretation in Table 1.

Distal alluvial fan-braidplain settings

The lower part of FA1, characterized by F1, F2, F3, and F4 reveals a dominance of sedimentary processes related to cohesionless debris and sheet flows deposits (Fig. 6.2), interpreted as related to alluvial fan setting (Nemec and Steel, 1988; Reading, 1996; Einsele, 2000; García-García, 2004; Boggs, 2014). The punctual record of F5 and F10 within the general gravelly-size massive, horizontal stratified, and graded deposits (Fig. 6.2) might result from the development of downstream accretion elements and bar forms in shallow braided channels atop sheet and debris flow deposits, typical of distal parts of alluvial fans (Nemec and Steel, 1984; Miall, 1996; Einsele, 2000). The upward increase in tractional sedimentary structures is indicative of a change in the prevailing sedimentary processes; and together with their coarse-grained nature, the increase in sorting, the development of fining upward trends, and the lithofacies arrangement linked to channel filling (Fig. 6.2), would point to the well-establishment of a braided channel system, able to drain the underlying distal alluvial fan deposits (Miall, 1996; Einsele, 2000). This transition from the basal distal alluvial fan deposits dominated by sheet and locally debris flows deposits to the subsequent well-developed fluvial system could be related to decreasing (gentler) slope, where fluvial processes are more efficient in transporting sediment (Hooke, 1967; Rust and Koster, 1984; Nemec and Steel, 1988). Successions up to ~ 4 m thick of amalgamated F1, located between F9 and F10 (Fig. 6.2) most likely reflect rapid runoff during or just after sudden rainstorms over the alluvial fans (Siggerud and Steel, 1999). This further suggests that the fluvial system operated in the distal segment of the alluvial fan (Orton, 1988). The domain of parallel (horizontal to sub-horizontal) erosional surfaces indicates multiple stages of vertical aggradation, which implies fairly straight channels (Marzo and Anadón, 1988; Shan et al., 2018).

Distal distributary channels to proximal wave-influenced mouth bars

Upward, in the FA2 and FA3, the record of the four levels with *Ophiomorpha* ichnofabric unequivocally marks marine influence within the system. This interaction between fluvial and —in this case— marine processes related to the interplay between the feeder system and receiving basin evokes the development of fan-delta deposits (Nemec and Steel, 1988), representing a seaward transition of the sedimentary system (FA2). The onset is marked by the first record of *Ophiomorpha* ichnofabric (Oi-A) in level 1, then Oi-A and Oi-B in levels 2 and 3, in low-angle cross-bedding and horizontally stratified sandstones related to swash zone deposits in proximal (gravelly-sandy) wave influenced mouth bars (MacEachern et al., 2005; Vakarelov et al., 2012; Ainsworth et al., 2016). The absence of marine elements and tractive structures in the gravelly beds could indicate the rapid arrival of debris flows deposits to the basin, linked to distributary channels prograding seaward (Kleinspehn et al., 1984; Nemec and Steel, 1984; García-García et al., 2006). The punctual record of conglomeratic beds having tractive structures and indeterminate mollusk shells fragments suggests a reworking by marine processes, associated with proximal mouth bar deposits (Kleinspehn et al., 1984; Nemec and Steel, 1984; van Yperen et al., 2019).

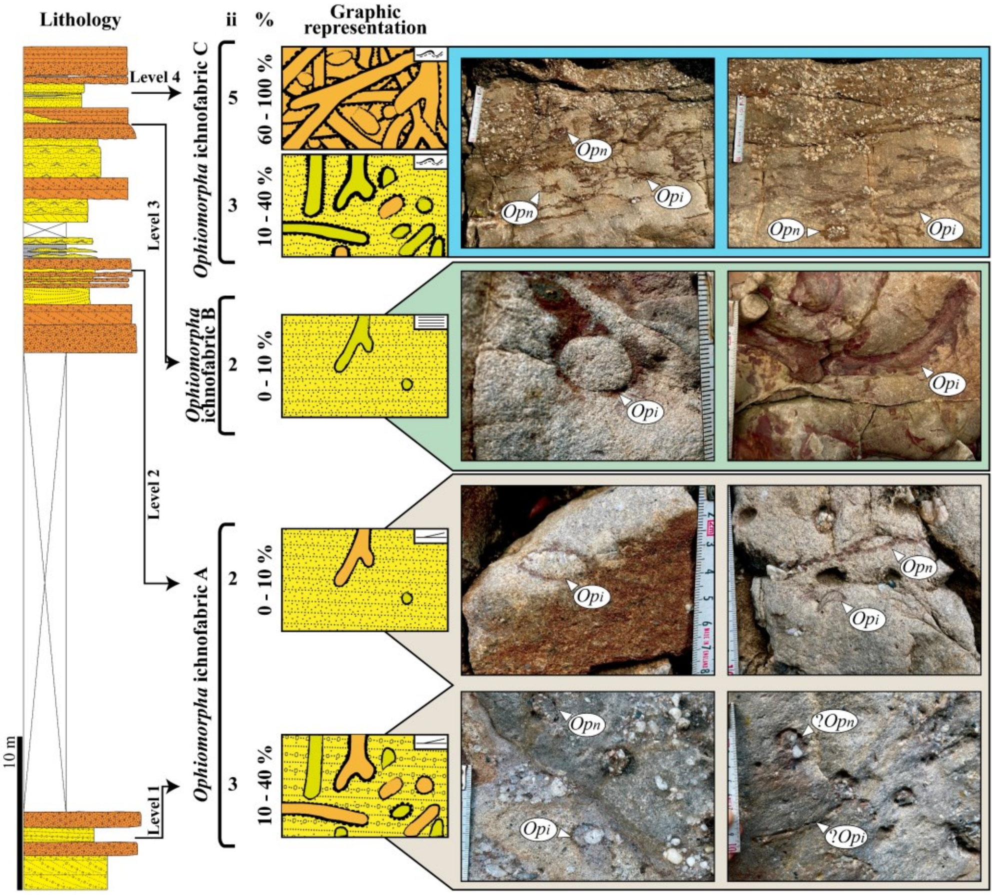

Figure 6.6. Distribution of *Ophiomorpha* ichnofabrics OiA, OiB, OiC. *Ophiomorpha irregulaire* (*Opi*), and *O. nodosa* (*Opn*). Note the upward increase in *Ophiomorpha* traces density (from ii 3 to 5) in the *Ophiomorpha* ichnofabric C and the marked change in the fill type. Graph modified from Droser and Bottjer (1989). For conventions see Fig. 6.2.

Found interlayered among these conglomeratic beds are sandstone with hummocky cross-bedding-HCS, which in fan-delta systems may be interpreted as 1) deposited by the transformation of dense flows, or 2) by different types of horizontally bipartite composite gravity flows entering seawater (Tinterri, 2011 and references therein). These deposit successions —channel/mouth bar/channel— would be linked to periodical increases/decreases in river discharge to the basin, or else to variable sediment supply related to channel avulsion, enabling the establishment of a marine-influenced environment during no-discharge periods, quickly interrupted by a progradation of fluvial deposits (Fig. 6.2). This sequence of events is evidenced, on a smaller scale, by the presence of thin sandy beds (Fig. 6.4E) between the conglomeratic beds associated with these mouth bar deposits, reflecting interflood sediments deposited during low-energy periods between river flood episodes (van Yperen et al., 2019).

The record of swash zone deposits related to these high-energy sedimentary environments is rarely recognized in ancient sequences, since they tend to be thin beds that are easily eroded by coarse-grained overlying deposits, making their preservation unlikely (Nemec and Steel, 1984). Although the sedimentological features and the monospecific record of *Ophiomorpha* described here broadly suggest a nearshore high-energy depositional environment, the predominantly horizontal to sub horizontal orientation of *Ophiomorpha* observed in the sandy bioturbated levels along with the subsequent preservation, suggest relatively low-energy episodes in uncohesive/loose substrates during their accumulation (Goldring, 1995; Bromley, 1996; Anderson and Droser, 1998; Sendra et al., 2020).

Distal wave-dominated distributary mouth bars

Within the fan-delta deposits, the record of *Ophiomorpha* ichnofabric C in level 4 evidence that the paleoenvironmental conditions were completely dominated by marine processes in FA3, related to wave reworking and fair-weather sedimentation in distal (sandy) wave-dominated distributary mouth bars, marking the more distal deposits of the fan-delta, and therefore of the fan-delta complex (Einsele, 2000; MacEachern et al., 2005; Dashtgard et al., 2009; Collinson and Mountney, 2019). This is also indicated by the heterolithic bedding with wave ripples. An increase in the ichnofabric index towards the top of the beds (from ii 3 to ii 5) is associated with the maintenance of favorable conditions, allowing for the growth of an abundant and homogeneous tracemarker community, possibly related to a decreasing sedimentation rate.

6.5.2 The variable-range record of marine incursion in dominated continental settings: the ichnofabric role

One challenge in defining fan-delta deposits, hence fan-delta complexes, resides in determining the marine influence (Nemec and Steel, 1984; Blair and MacPherson, 2008). The characteristics and processes of the catchment area play an important role in the development —and stratigraphic record— of fan-delta deposits (Nemec and Steel, 1988). In these marine sedimentary basins, sea-level variations (magnitude and duration) substantially control the accommodation space and redistribution of sediment (Koss et al., 1994). The general aggradational pattern observed in the fan-delta deposits (Fig. 6.2) reflects a good balance between sediment supply and accommodation space (Catuneanu, 2022). However, the integration of the differentiated facies associations and their distribution throughout the studied succession, as well as the record and type of

Ophiomorpha ichnofabrics, particularly in these four levels, suggest a variable prevalence of marine versus fluvial processes (Figs. 6.2, 6.6) (Pedersen and Rasmussen, 1989). The features of each *Ophiomorpha* ichnofabric are the result of different range of marine incursions in the general fluvial-dominated setting. Thus, *Ophiomorpha* ichnofabrics A and B, of comparatively low ichnofabric indexes, reveal a minor marine influence into proximal mouth bar settings, impeding a well-established marine macrobenthic tracemaker community because of stressful conditions. On the contrary, *Ophiomorpha* ichnofabric C, associated with higher ichnofabric indexes, indicates a strong marine influence in distal wave-dominated distributary mouth bars environments, and a maintenance of favorable conditions, allowing for the growth of an abundant and homogeneous tracemarker community.

The four identified marine-dominated incursions could mean local evidence of relative sea-level variations associated with basin-scale processes (autogenic) such as channel avulsion or local tectonic activity. This higher-scale characterization could help to improve the relative sea-level calibration linked to the last stages of the epeiric sea developed in NW South America during the Late Cretaceous, further detailing global/regional sea-level proposals.

6.5.3 Substrate colonization

It has been demonstrated that grain-size plays a major role in the ichnological record of marginal marine deposits (Dasthgard et al., 2008). In coastal deposits, high-energy wave reworks lead to an accumulation of coarse-grained deposits, preventing preservation of shallower biogenic structures (Dasthgard and Gingras, 2005); what remains is a scarce record of the deeper and/or more resistant deeper structures, lending paleoenvironmental information about these challenging sedimentary systems.

Ophiomorpha has been considered a substrate-controlled trace fossil (Ekdale, 1992; Gibert et al., 2006) in view of its constructional lining (Bromley, 1996). The thick well-developed pellet-walls of *Ophiomorpha nodosa* are accordingly generated in response to loose sandy substrates to prevent burrow collapse (Ekdale et al., 1984; Bromley and Pedersen, 2008). In contrast, the thin irregular-developed patchily distributed mud-wall of *O. irregulaire* is indicative of a less resistant wall, resulting in functional differences between the two lining types (Bromley and Ekdale, 1998; Bromley and Pedersen, 2008). In our record, both ichnospecies were observed in levels 1, 2 and 4, with a domain of *O. nodosa.* Cross-cutting relationships between the different ichnospecies were not observed in levels 1 and 2, which being associated with a simple ichnofabric type reflect a single colonization event (Taylor et al., 2003; Buatois and Mángano, 2011). Thus, the loose consistency of the substrate is evidenced by the dominance of *O. nodosa*.

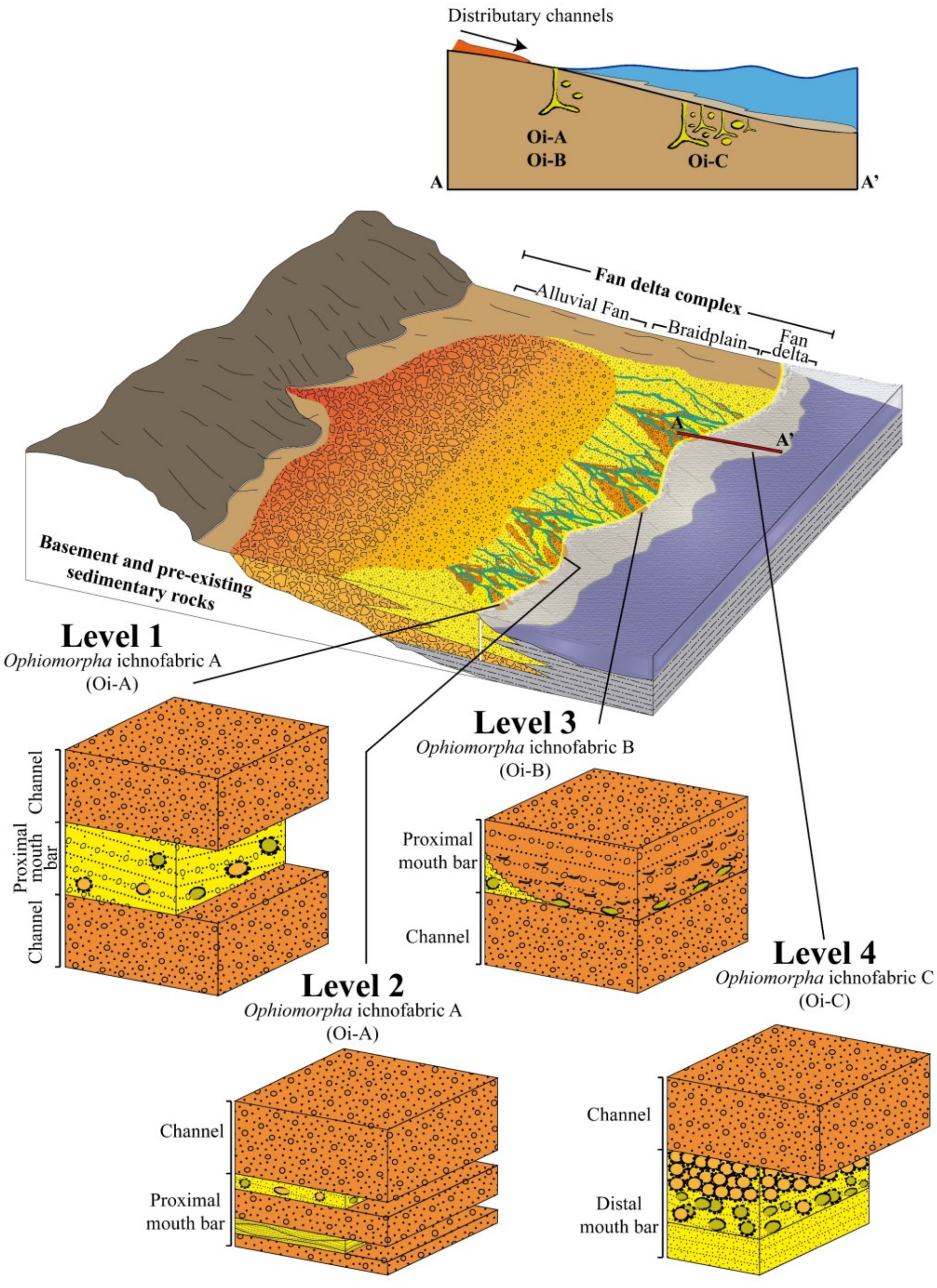

Figure 6.7. Depositional settings and *Ophiomorpha* ichnofabric distribution. A – A' show the development of *Ophiomorpha* ichnofabric in relation to marine influence.

Notwithstanding, under such conditions the traces of *O. irregulaire* could not be produced/maintained, hence their collapse. Yet if the substrate was not too loose, the organism would not need to build the resistant wall of *Ophiomorpha*, or at least that of *O. nodosa*. These considerations lead us to various possibilities, including: i) a loose consistency favoring higher comparative preservation of *O. nodosa* and only occasional preservation of *O. irregulaire* (in this case the dominance of *O. nodosa* is preservational while the record of *O. irregulaire* is only part of the originally produced); ii) an intermediate loose consistency in which both ichnospecies can be preserved (in this case the dominance of *O. nodosa* is originally established); and iii) the importance of other features, in addition to the type of substrate, determining *Ophiomorpha* ichnospecies. An alternative interpretation might be that both ichnospecies are linked to different colonization events: the initial stages of substrate allowing for the development of *O. nodosa*, followed by a subsequently firmer substrate favoring *O. irregulaire*. While this latter interpretation is not supported by the cross-cutting relationships, we do not rule out that the low ichnofabric indexes could have prevented trace overlap.

The variable infilling material could indicate changes in feeding strategies, being the passive infill mainly related to dwelling structures of suspension feeders and the active infill linked to the activity of deposit and detritus feeders (Buatois and Mángano, 2011). In the four levels, *Ophiomorpha* show both fill types, suggesting variable trophic conditions. Level 4 in particular shows a marked change in fill type, from active fill at the base to passive fill at the top (Fig. 6.6), in conjunction with an increase in the ichnofabric index towards the top of the bed, possibly related to a decreasing sedimentation rate. This finding evidences the ability of the monospecific macrobenthic community to adapt to strong changes in sedimentary conditions.

6.6 Conclusions

Ophiomorpha ichnofabric record as a key proxy for improving the paleoenvironmental understanding and reconstructing animal-substrate interplay during the evolution of fan-delta complexes. Detailed sedimentological and ichnofabric analyses enabled us to define the alluvial, fluvial, and fan-delta components of a fan-delta complex. The distal alluvial fan setting is dominated by sedimentary structures linked to debris and sheet flows, which stratigraphically evolve upwards toward a system dominated by tractional sedimentary structures linked to the channel fills characteristic of a braided fluvial environment. Subsequently, the fan-delta deposits record three *Ophiomorpha* ichnofabric types, distributed in four levels, unequivocally marking the marine influence in the system. These ichnofabrics composed exclusively of *Ophiomorpha nodosa* and *O. irregulaire*, having a variable ichnofabric index (between 2 and 5), with a predominantly horizontal orientation, are indicative of different sub-environments and sedimentary parameters.

Ichnofabrics A and B in levels 1, 2 and 3 are associated with relatively low-energy proximal wave-influenced mouth bars deposits, capped by debris flows related to channel mouth bars. In turn, ichnofabric C in level 4 is indicative of wave-dominated sedimentation associated with distal mouth bars. This distribution of ichnofabrics reflects variable marine influence in a generally fluvial-dominated system. Thus, *Ophiomorpha* ichnofabric is proving to be a fundamental tool for understanding and reconstructing paleoenvironmental of fan-delta complex deposits.

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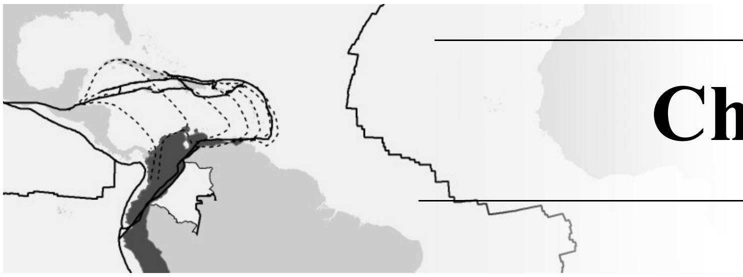
Part III INTEGRATION AND DISCUSSION



Chapter 7

TRACKING THE EVOLUTION AND DYNAMICS OF DEPOSITIONAL PARAMETERS AND SEDIMENTARY ENVIRONMENTS LINKED TO THE CARIBBEAN PLATE COLLISION

FOREARC VS. BACKARC SEDIMENTATION DURING THE LATEST CRETACEOUS IN THE NW MARGIN OF SOUTH AMERICA-COLOMBIA: TRACKING THE EVOLUTION AND DYNAMICS OF DEPOSITIONAL PARAMETERS AND SEDIMENTARY ENVIRONMENTS LINKED TO THE CARIBBEAN PLATE COLLISION

Carlos A. Giraldo-Villegas [a,b] , Francisco J. Rodríguez-Tovar [a], Sergio A. Celis [a,b], Andrés Pardo-Trujillo [b,c]

[a] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Av. Fuente Nueva s/n, 18071, Granada, Spain

[b] Instituto de Investigaciones en Estratigrafía-IIES, Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

[c] Departamento de Ciencias Geológicas, Universidad de Caldas, Calle 65 No 26-10, 170004, Manizales, Colombia

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Abstract

Two distinct geological domains formed the northwestern margin of South America during the latest Cretaceous (Campanian-Maastrichtian). A western allochthonous forearc domain associated with the Caribbean Plate and an eastern allochthonous backarc domain related to the South American Plate, separated by the active volcanic arc of the proto-Central Cordillera and the Romeral Fault System-RFS.

The western forearc basin was predominantly filled with deep-water deposits, accumulated by suspended fall-out and turbiditic processes, and colonized by a macrobenthic tracemaker community associated with the *Zoophycos* ichnofacies, with oxygenation and hydrodynamic energy as the main ecological controlling parameter. The overall sedimentary evolution of the forearc domain remained relatively stable throughout the Campanian–Maastrichtian, with no major shifts in depositional patterns or ecological conditions recognized. The backarc basin was heterogeneous in terms of depositional environments sedimentary processes, and the resulting patterns of substrate colonization. During the early Campanian, the most distal environments (shelf), associated with suspended fall-out deposition were established along the western side, while proximal shoreface and delta-front environments—associated with wave and fluvial processes, respectively—were established in the central and eastern parts of the basin. An ichnoassemblage belonging to the *Cruziana* ichnofacies was recorded in the central part, whereas the *Rosselia* ichnofacies dominated the eastern sector. In the western side, only scarce occurrences of *Thalassinoides* are documented. In the early Maastrichtian, favorable conditions in offshore and shoreface environments, promoting the development of the *Cruziana* ichnofacies in the western and central parts, respectively, while the *Rosselia* ichnofacies continued to characterize delta-front deposits in the eastern sector. Oxygen-rich bottoms resulting from the constant waves, and the permanent supply of organic matter from the continent were responsible for the development of macrobenthic tracemaker communities in this basin. By the late Maastrichtian, the development of fan deltas along the western side reflects an increase in coarse-grained sedimentation driven by enhanced erosion rates from emerged source areas, coupled with the continued stabilization of fluvio-deltaic systems along the eastern side.

Both basins, although coeval, evolved differently through time, mainly in relation to the variable influence of allogenic controls caused by the collision of the Caribbean Plate and in less extent autogenic processes, possibly related to the oceanographic dynamics of each of the basins.

Keywords: Deep and shallow marine environments, sedimentology, ichnology, allogenic and autogenic controls, Late Cretaceous.

7.1 Introduction

Forearc and backarc are the sedimentary basins formed in subduction zones according to their position with respect to the volcanic arc (Karig, 1971; Busby and Ingersoll, 1995; Balázs et al., 2022). Forearc basins are formed between the trench and the magmatic arc and are shaped by accretionary wedge dynamics, sediment influx and eustatic sea level. Backarc basins, formed by extensional processes behind the volcanic arc on the overriding plate, are influenced by the relationship between subduction and convergence velocities (Balázs et al., 2022; Artemieva et al., 2023).

Extensive research on the origin, types, and tectonostratigraphic evolution of these basins is found in the literature (e.g., Fuller et al., 2006; Sdrolias and Müller, 2006; Noda, 2016, 2018; Mannu et al., 2017; Balázs et al., 2022; Artemieva et al., 2023). However, data on the sedimentology, depositional and ecological parameters involved in the coeval filling, as well as their relation to the tectonic, paleogeographic and paleoceanographic evolution of surrounding areas, remain scarce.

The tectonic framework that developed in the NW corner of South America at the end of the Cretaceous provides an ideal context for studying depositional parameters in these type of basins during the same period. The collision of the Caribbean Plate—an allochthonous oceanic geological domain—with the NW margin of South American Plate—an autochthonous continental plate—led to the formation of forearc and backarc basins, separated by an active volcanic arc: the pro-Central Cordillera (Fig. 7.1; Villagomez et al., 2011; Spikings et al., 2015; Leal-Mejía et al., 2019; Restrepo and Toussaint, 2020; Toussaint and Restrepo 2020). Although the Proto-Central Cordillera geologically divides these two basins, the tectonic boundary or suture separating the allochthonous and autochthonous domains is the Romeral Fault System (RFS), which is now located on the western flank of the Central Cordillera (Moreno-Sánchez and Pardo-Trujillo, 2002; Vinasco, 2019).

The forearc basin has an oceanic-origin basement, with oceanic plateau and island arc rocks interbedded with sedimentary deposits, overlain by a sedimentary fill closely related to the proto-Pacific Ocean (Kerr et al., 1997a, 1997b; Moreno-Sánchez and Pardo-Trujillo, 2003; Pindell and Kennan, 2009; Pardo-Trujillo et al., 2020). In contrast, the backarc basin, which formed on the South American Plate through extensional processes associated with the breakup of Pangaea and/or backarc extension, has a continental basement, and its sedimentary fill is more closely related to the proto-Atlantic Ocean (Fig. 7.1; Cooper et al., 1995; Sarmiento-Rojas, 2001, 2019; Sarmiento-Rojas et al., 2006; Bayona, 2018; Paez-Reyes et al., 2021).

This study presents a comprehensive review, integration, and analysis of sedimentological, ichnological, micropaleontological, and stratigraphic data from the allochthonous (forearc basin) and autochthonous (backarc basin) domains of the NW margin of South America, specifically Colombia, during the Campanian-Maastrichtian period. The primary objective is to compare these two areas, highlighting their similarities and differences in terms of depositional processes, sedimentary environments, and controlling factors. At a local scale, it will help address longstanding misconceptions about the origins of these deposits and their potential similarities, ultimately refining our understanding of geological history and tectonic evolution of the NW margin of South America. On a regional and global scale, this will enhance our understanding of the stratigraphic evolution of coeval forearc-backarc marine basins providing insights into the effects of the Caribbean Plate collision on these basins.

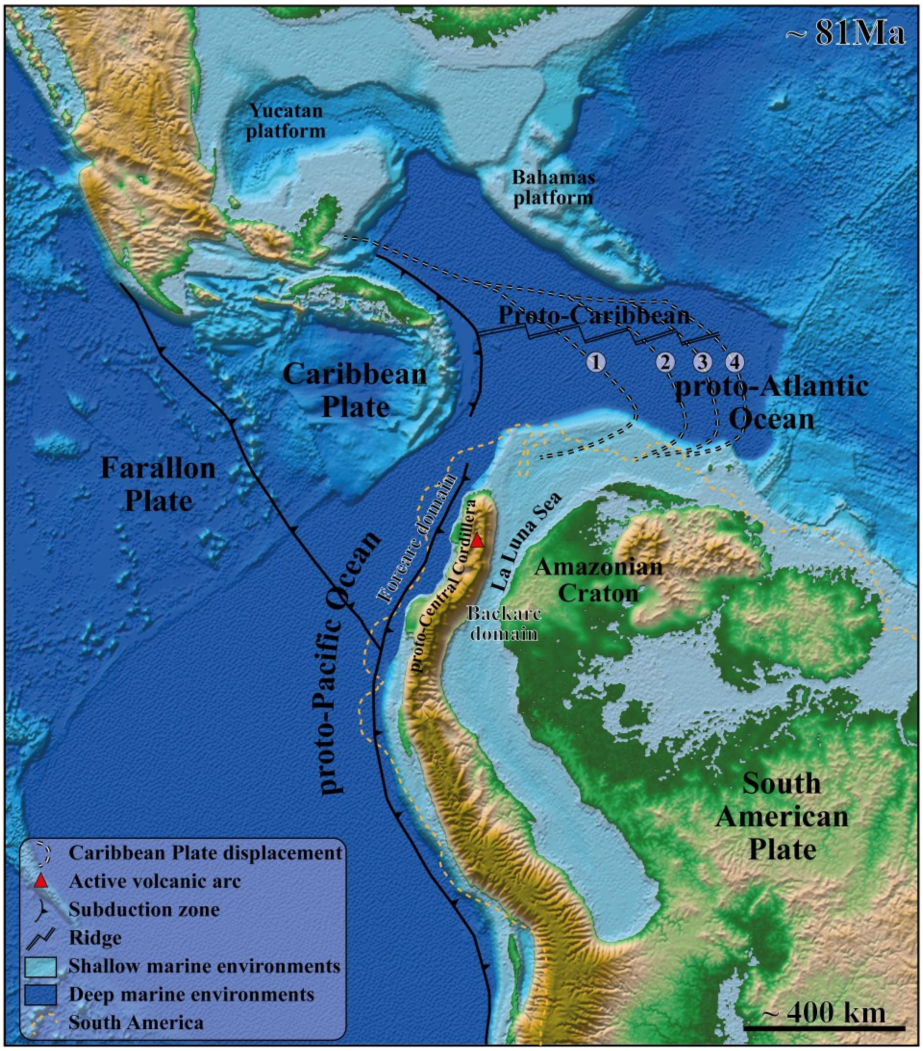


Figure 7.1. Paleotectonic and paleogeographic configuration of northwestern margin of South America during the latest Cretaceous. Base map from Salles et al. (2022) to 81 Ma. Modified from Mann (2021), and Romito and Mann (2021). Caribbean Plate displacement based on Escalona and Mann (2011): 1: Eocene; 2: Oligocene; 3: Miocene; 4: Pliocene.

7.2 Geological setting

The Andes in the northwestern corner of South America, specifically Colombia and Ecuador, show significant differences from the central and southern Andes. While most of the Andes were formed by the interaction between the Nazca-Farallones and South American plates, the Caribbean Plate also intervened in the northern Andes, giving this region a distinctive geological character (Fig. 7.1; Pindell and Kennan, 2009; Montes et al., 2019; Mora-Páez et al., 2019; González et al., 2023). During the Mesozoic, the interaction among these plates divided the region into two distinct geological domains; a western or allochthonous domain, composed of accreted oceanic terranes, and an eastern or autochthonous domain, corresponding to the continental South American Plate, separated by the RFS (Fig. 7.2; Moreno-Sánchez and Pardo-Trujillo, 2002; Vinasco, 2019; Toussaint and Restrepo, 2020). In Colombia, the Andes are divided into three mountain ranges associated with these domains. West of the RFS, within the allochthonous domain, lies the Western Cordillera, which represents a Late Cretaceous forearc basin associated with the Caribbean Plate that accreted onto the NW margin of South America at the end of the Cretaceous (León et al., 2018; Pardo-Trujillo et al., 2020; Botero-Garcia et al., 2023; Giraldo-Villegas et al., 2023). East of the RFS, within the autochthonous domain, lies the Central Cordillera, with a Paleozoic basement intruded by a volcanic arc from the Permian to the present (Bustamante et al., 2016; Leal-Mejía et al., 2019; Rodríguez-García et al., 2019; León et al., 2022; Restrepo et al., 2022; Bustamante et al., 2023), and the Eastern Cordillera, which, along with the Upper Magdalena, Middle Magdalena, Catatumbo, Cesar-Ranchería, Caguán-Putumayo, and Eastern Llanos basins, constituted a backarc basin during the Mesozoic and evolved into a retro-foreland basin during the Cenozoic, with sedimentary infill from the Late Jurassic to the present (Cooper et al., 1995; Sarmiento-Rojas, 2001, 2019; Gómez et al., 2003, 2005a; Bayona, 2018; Etayo-Serna, 2019; Bayona et al., 2021; Carvajal-Torres et al., 2022).

Both the forearc and backarc basins contain Campanian-Maastrichtian sedimentary deposits, accumulated during the collision of the Caribbean Plate with the NW margin of South America. The forearc basin deposits, from north to south, include the Cansona, Penderisco (Nutibara and Urrao Members), Nogales, Espinal and Cisneros formations. The backarc basin deposits are represented by various lithostratigraphic units, including the Cobre, La Renta, Arenisca Dura, Arenitas de San Luis de Gaceno, Lidita Superior, Pleaners, Lodolitas de Aguacaliente, Buscavida, Umir, Arenisca Labor-Tierna, Arenitas de San Luis de Gaceno, La Tabla, Cimarrona, Seca, Lisama, and Guaduas formations (Fig. 7.2).

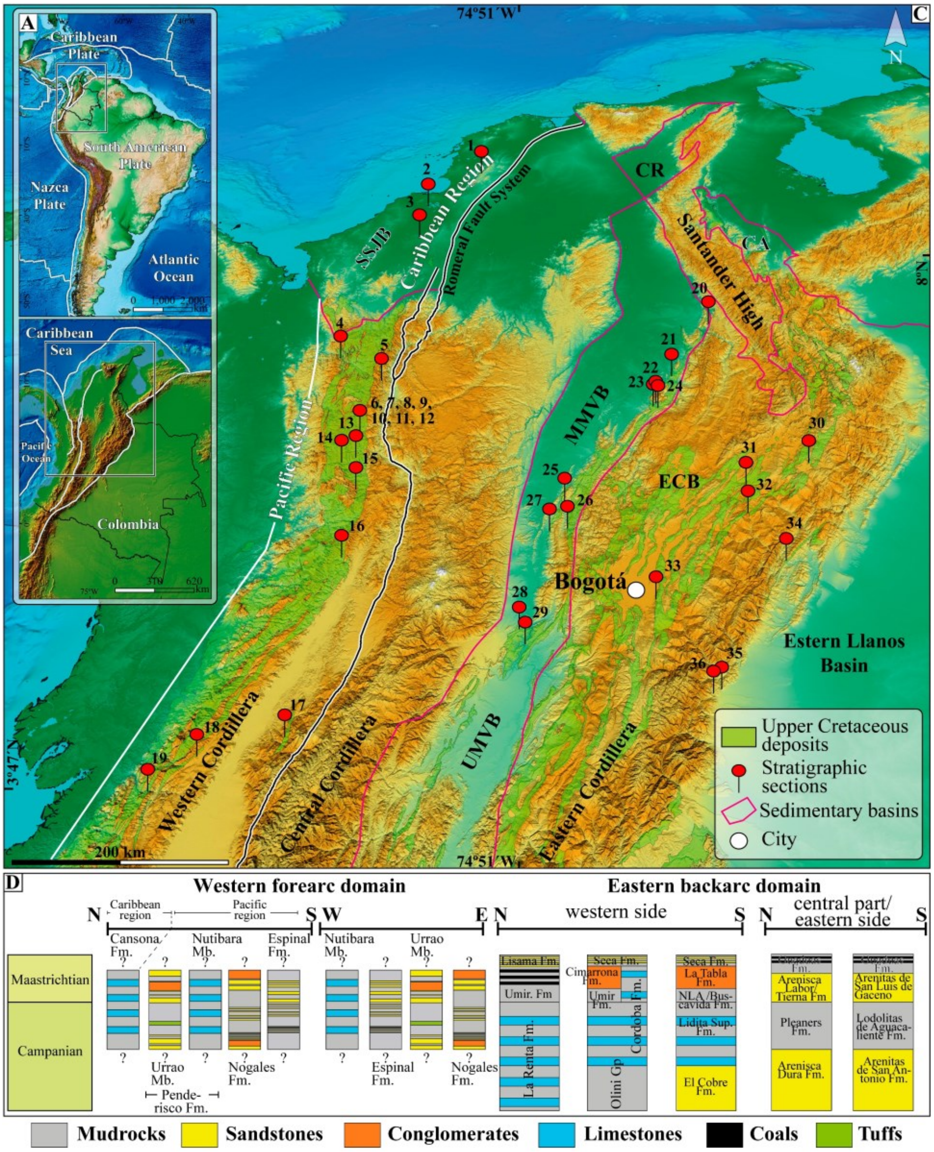


Figure 7.2. Location maps. **A.** Colombia in South America and tectonic plates boundaries (solid white lines). **B. S**tudied area in Colombia. **C.** Location of Campanian-Maastrichtian stratigraphic sections integrated in this work and sedimentary basins associated. **Western forearc domain:** 1, 5 this work; 2, 3, 4, 15, 18, 19 from Giraldo-Villegas et al. (2023); 6, 7, 8, 9, 10, 11, 12, 13, 14 from Pardo-Trujillo et al. (2020); 16 from Rueda (2018); 17 from Pardo-Trujillo et al. (2002). **Eastern backarc domain:** 20 from Terraza (2019) and Patarroyo et al. (2023); 21 from Montaño et al. (2016); 22, 23, 24, 25, 26, 27, 28, 29 from Giraldo-Villegas et al. (2025); 30, 31, 32, 34, 36 from Vergara and Rodriguez (1997); 33 from Guerrero and Sarmiento (1996) and Giraldo-Villegas et al. (2025); 35 from Carvajal-Torres et al. (2022). ECB: Eastern Cordillera Basin, MMVB: Middel Magdalena Valley Basin, SSJB: Sinú-San Jacinto Basin, UMVB: Upper Magdalena Valley Basin. **D.** Lithostratigraphic nomenclature for the Campanian-Maastrichtian deposits in the western forearc and eastern backarc domains (modified from Pardo-Trujillo et al., 2020 and Giraldo-Villegas et al., 2025).

7.3 Sedimentary environments during the latest Cretaceous

The following is a general description of the lithological and paleontological features, including trace fossils, microfossils and macrofossils, associated with each basin or domain.

7.3.1 Forearc western domain

Sedimentological/lithological features

This area is represented by the deposits outcropping to the west of the Romeral Fault System over basalts and sedimentary successions of Lower Cretaceous age, corresponding mainly to the current Sinú-San Jacinto Basin-SSJB and Western Cordillera (Fig. 7.2; Etayo-Serna et al., 1980; Moreno-Sánchez and Pardo-Trujillo, 2002, 2003; Cerón et al., 2007; Villagómez et al., 2011; Pardo-Trujillo et al., 2020; Giraldo Villegas et al., 2023). This forearc region can be divided into two zones: a) the northern or Caribbean region, corresponding to the present-day SSJB, which consists of Campanian-Maastrichtian successions of limestones, siliceous and calcareous mudrocks, mudrocks and cherts, distributed in the form of patches within the basin, and b) the southern o Pacific region showing a more continuous Campanian-Maastrichtian outcrop distribution, and consisting of relatively homogeneous thick deformed successions, mainly composed of interbedded mudrocks, siliceous mudrocks, sandstones and pebbly sandstones, and in lesser proportion conglomerates-breccias, bioclastic conglomerates, limestones and rarely cherts and phyllites (Figs. 7.2 and 7.3). Locally, these Pacific deposits show a high degree of diagenesis, in some sectors reaching the characteristics of metamorphic rocks such as phyllites, associated with the collisional deformational history of the basin. Although the deformation is intense in these Pacific deposits, the preserved lithologies generally exhibit a trend, with the coarse-grained, channelized deposits concentrated toward the central and easternmost sectors (closer to the Central Cordillera) and the tabular fine-grained deposits being more abundant toward the northern and southern, and the westernmost parts of the basin (Figs. 7.2 and 7.3).

In both regions, the structureless limestones occur as tabular beds, classified as mudstones (according to Dunham, 1962). The mudrocks have a tabular geometry, with horizonal lamination and massive structures that vary in composition, sometimes appearing as calcareous and siliceous mudrocks. The pebbly sandstones are coarse-grained, with tabular and lenticular geometries, with massive and normal grading structures, and volcanic and muddy clasts, which compositionally are classified as feldspathic litharenites and lithic arkoses (León et al., 2018; Pardo-Trujillo et al., 2020). The tabular beds of fine- to coarse-grained sandstones are characterized by massive, parallel lamination and normal grading, rich in volcanic lithics. The conglomerate beds are lenticular-shaped, clast-supported (cobble- and pebble-sized), structureless, normally graded, and occasionally crude laminated, formed by the incipient long axis orientation of the clasts. Plutonic, volcanic, and sedimentary lithic fragments constitute the gravel fraction, and fine- to medium-grained sandstone makes ups the matrix. Macrofossils are sporadically observed as bioclasts forming bioclastic conglomerates. The chert beds are tabular- and lenticular-shaped, with massive structure and typical conchoidal fractures. The phyllites show foliation and satin luster, which are typically characterized by well-preserved bioturbation.

Trace fossil assemblages

Bioturbation in these deposits is mainly associated with fine-grained lithologies (mudrocks and limestones), showing a great variability in their distribution, with areas where it is abundant and areas where there is no preserved evidence of macrobenthic community activity (Fig. 7.3). Regionally, this western forearc region shows a relatively low abundance (locally high) and diversity of trace fossils. An ichnoassemblage composed of *Chondrites*, ?*Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Spyrophyton*, *Thalassinoides* and *Zoophycos*, belonging to the *Zoophycos* ichnofacies, with bioturbation indexes varying between 1 and 4, and with a relative homogeneous distribution in the Campanian-Maastrichtian deposits, characterized this region (Giraldo-Villegas et al., 2023). Despite the low abundance and diversity of trace fossils, some ichnological variations are recorded. In the northern stratigraphic successions of the Sinú-San Jacinto Basin, the ichnoassemblage consists of *Chondrites*, *Planolites*, and *Zoophycos*, while to the south in addition to the aforementioned association, there are traces of ?*Nereites*, *Phycodes*, *Phycosiphon*, *Spyrophyton*, and *Thalassinoides*. Particularly, the highest abundance and preservation of traces is observed in the phyllites. The bioturbation of these deposits, which is closely associated with fine-grained lithologies, becomes more intense towards the southern and northern deposits (Fig. 7.3). The high deformation of these western forearc deposits does not allow us to determine if there is a possible zonation or variation in the ichnological record according to a proximal/distal gradient in sedimentary environments.

Micro/macropaleontological considerations

The microfossil record in these deposits also shows two distinct zones. A northern zone corresponding with the Caribbean region in the Sinú-San Jacinto Basin-SSJB , where abundant, diverse and well-preserved assemblages of calcareous microfossils (foraminifers and nannofossils), palynomorphs, and radiolarians have been recorded, which has also contributed to a better constraint of the age interval (e.g., Chenavert, 1963; Duque-Caro, 1967, 1972; Guzmán, 1994; Herrera et al., 2009; Dueñas and Gómez, 2013;

Juliao-Lemus et al., 2016; Angulo-Pardo et al., 2023; Rincón-Martínez et al., 2023; Vallejo et al., 2023; Plata-Torres et al., 2024). On the contrary, the deposits currently located further south in the Pacific region, specifically the Western Cordillera, show low abundance, diversity and preservation of calcareous (foraminifers, calcareous nannofossils) and siliceous (pollen, radiolarians) microfossils (e.g., Pardo-Trujillo et al., 2020; Angulo-Pardo et al., 2023), hindering the definition of a precise chronological framework from microfossils, compared to the northernmost deposits.

The macrofossil record, although patchy, is better represented in the southern deposits of the Western Cordillera, where ammonites, bivalves, corals, gastropods, leaf, and wood fragments have been reported, helping to constrain the age of the Upper Cretaceous deposits (Fig. 7.3; Etayo-Serna et al., 1982; Etayo-Serna, 1985, 1989; Moreno-Sánchez et al., 2002; Pardo-Trujillo et al., 2002a, 2002b, 2020; Díaz-Cañas and Patarroyo, 2014), while the northern deposits have very few macrofossils, including a single report of ammonites and leaf remains (Camacho, 1967; SGC, 2019).

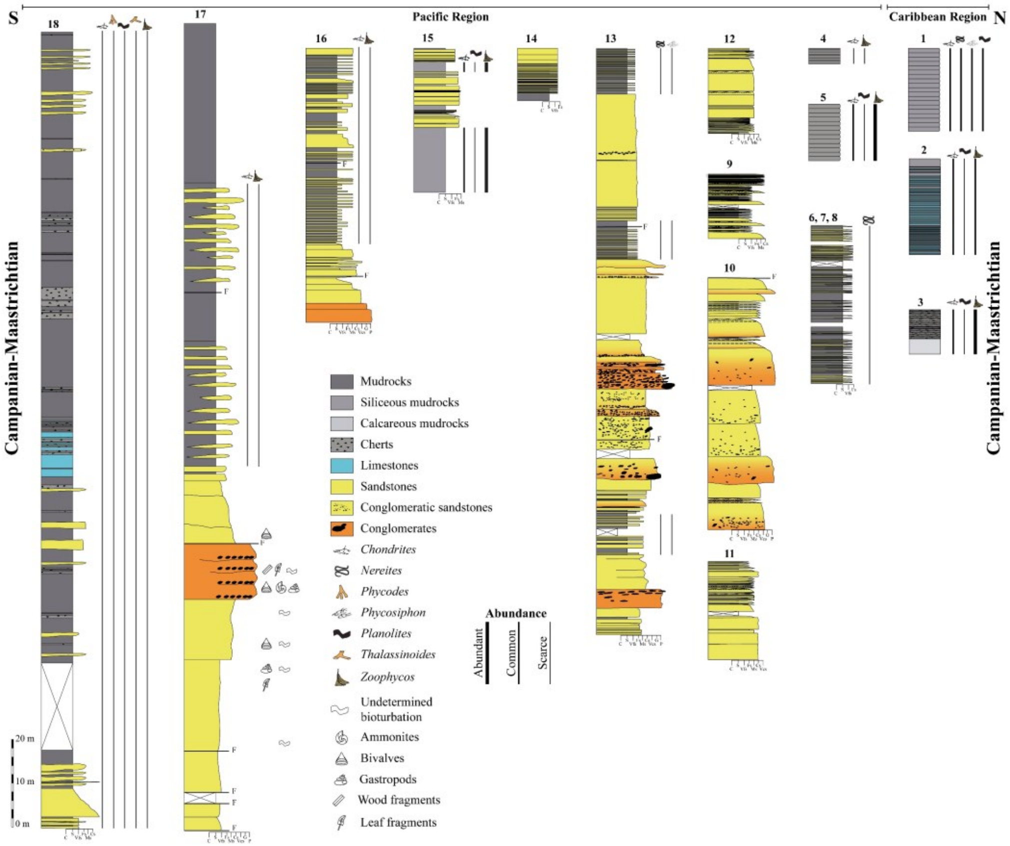


Figure 7.3. Compilation of lithological logs, ichnological and paleontological features related to western forearc deposits. The high deformation prevents the establishment of reliable stratigraphy; therefore, the order of the sections does not represent a stratigraphic arrangement. 1, 5 this work; 2, 3, 4, 15, 18 from Giraldo-Villegas et al. (2023); 6, 7, 8, 9, 10, 11, 12, 13, 14 from Pardo-Trujillo et al. (2020); 16 from Rueda (2018); 17 from Pardo-Trujillo et al. (2002). Section 19 is not shown; it corresponds to the phyllites, and it was not possible to make a stratigraphic log.

7.3.2 Backarc eastern domain

Sedimentological/lithological features

This region corresponds to the deposits now exposed in the Upper and Middle Magdalena, Caguán-Putumayo, Cesar-Rancheria, Catatumbo, Eastern Cordillera and Eastern Llanos basins (Fig. 7.2). These basins have a sedimentary record ranging from the Late Jurassic to recent times. In particular, the Campanian-Maastrichtian deposits of these basins are characterized by a wide lithological variability in space and time, in contrast to the rocks of the forearc domain. Due to the high variability in types of deposits, depositional parameters and sedimentary environments, the central part of this backarc basin has been divided into three zones: western, central and eastern (Fig. 7.2 and Table 7.1; Giraldo-Villegas et al., 2025). In the Campanian, the western side includes claystones, siltstones, shales, limestones (mudstone, wackestone, packstone according to Dunham, 1962), marls, and in lesser proportion cherts, sandstones and phosphorites. In the Maastrichtian, the presence of coarse-grained lithologies increases, including conglomerates and sandstones, and mudrocks, limestones, marls, and coals (Fig. 7.4). The central part includes sandstones, mudrocks and diagenetic cherts in the Campanian, and sandstones and mudrocks in the Maastrichtian (Fig. 7.5). Mainly sandstones and in lesser proportions mudrocks characterize the eastern side in the Campanian, while sandstones, and locally mudrocks and conglomerates featured the Maastrichtian (Fig. 7.5). The fine-grained beds (claystones and siltstones) show tabular geometry and horizontal lamination, fissility (shales), massive, and current ripple structures. Fine- to coarse-grained tabular- and lenticular-shaped sandstones beds show massive, planar cross-, trough cross-, and horizontal laminations, normal and inverse grading, symmetrical and asymmetrical ripple structures, also forming sandy-muddy couplets of flaser, lenticular and wavy bedding. Cuneiform- and lenticular-shaped beds of matrix- and clast-supported conglomerates are composed of granule- and pebble-size clasts of quartz and locally metamorphic lithics embedded in a sandy matrix. The limestones occur as tabular beds, generally associated with shales and mudrocks, showing massive and horizontal lamination structures. Chert and phosphorites beds are the less common lithologies, occurring as lenticular and tabular beds, with massive structures, commonly associated with fine-grained lithologies.

Trace fossil assemblages

In general, the Upper Cretaceous deposits of this backarc domain show a relatively moderate to high abundance and high diversity of trace fossils, associated with both fine and coarse lithologies. The bioturbation in these deposits evidence two important moments of seafloor macrobenthic colonization, during the early Campanian and during the early Maastrichtian, characterized by variable abundance and diversity depending on the area of the basin (west, central, east), separated by late Campanian deposits with absence or scattered traces (Table 7.1). In the western side, the lower Campanian deposits are characterized by absence of trace fossils in the muddy deposits and the punctual record of *Thalassinoides* in the sandy deposits (Fig. 7.4). In the early Maastrichtian of this western side, an abundant and diverse ichnoassemblage composed of *Arenicolites*, *Asterosoma*, *Chondrites*, *Gyrochorte*, ?*Gyrolithes*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Schaubcylindrichnus*, *Scolicia*, *Skolithos*, *Spongeliomorpha*, *Taenidium*, *Teichichnus*, and *Thalassinoides* characterize some muddy and sandy deposits of this zone (Fig. 7.4; Veloza et al., 2008; Lemus-Restrepo et al., 2018; Giraldo-Villegas et al., 2025). In the central part of the basin, the lower Campanian sandy deposits contain an abundant and diverse trace fossils assemblage composed of *Arenicolites*, *Arthrophycus*, *Asterosoma*, *Crossopodia*, *Cylindrichnus*, *Diplocraterion*, *Gordia*, *Helminthopsis*, *Laevicyclus*, *Ophiomorpha*, *Phycodes*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Rosselia*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos* (Fig. 5; Pérez and Salazar, 1978; Leckie et al., 2003). *Arenicolites*, *Cylindrichnus*, *Gordia*, *Planolites*, *Protovirgularia*, *Rhizocorallium*, *Scolicia*, and *Thalassinoides* characterize the lower Maastrichtian deposits of this central part (Fig. 7.5). The eastern Campanian deposits contain a low diverse ichnoassemblage characterized by abundant *Ophiomorpha*, in sometimes as monospecific association, and *Rhizocorallium* and *Thalassinoides*, mainly associated with the base of the sandstones, while the Maastrichtian deposits contain a diverse and abundant ichnoassemblage composed of *Conichnus*, *Ophiomorpha*, *Palaeophycus, Planolites*, *Rhizocorallium*, *Skolithos*, *Taenidium*, *Teichichnus*, and *Thalassinoides*. Unlike the western forearc deposits, the distribution of trace fossils in the backarc deposits shows an east-west variability, with greater abundance and diversity of trace fossils towards the central part and eastern side of the basin (Fig. 7.6; Giraldo-Villegas et al., 2025).

Thus, the ichnoassemblages of the lower Maastrichtian fully marine (offshore) deposits on the western side, and lower Campanian and lower Maastrichtian (shoreface) deposits of the central part, can be assigned to the *Cruziana* ichnofacies (MacEachern et al., 2007, 2012). The environments on the eastern side, being associated with a fluvial-dominated delta, are characterized by fluctuations in salinity, generating important changes in the macrobenthic tracemaker community. According to this context, the ichnological features of the eastern Campanian and Maastrichtian deposits may be assigned to the *Rosselia* ichnofacies (MacEachern and Bann, 2020).

Micro/macropaleontological considerations

The abundance of microfossils and macrofossils in the eastern backarc basin is very high compared to the rocks of the western forearc basin. Campanian-Maastrichtian deposits of this region are characterized by the record of both calcareous (foraminifera, calcareous nannofossils) and siliceous (palynomorphs and dinoflagellates) microfossils, allowing a better temporal calibration compared to the western area. Calcareous nannofossil assemblages with rare to common abundances and poor to good preservation have been recorded in these deposits (Navarrete et al., 2018; Patarroyo et al., 2022, 2023a, 2023b; Angulo-Pardo et al., 2023). Associations with high diversity and good preservation of mainly planktonic and, to a lesser extent, benthic foraminifera have also been reported in these Campanian-Maastrichtian deposits in different parts of the basin (Bürgl and Dumit Tobon, 1954; Gandolfi, 1955; Petters, 1955; Colom, 1962; De Porta. 1965; Martínez, 1989, 1995, 2003; Martínez and Hernández, 1992; Tchegliakova, 1993, 1995, 1996; Tchegliakova et al., 1997; Guerrero et al., 2000; Tchegliakova and Mojica, 2001; Cruz-Guevara et al., 2011; Patarroyo et al., 2017, 2022; 2023a, 2023b; Navarrete et al., 2019). The record of continental and marine palynomorphs, including pollen, spores and dinoflagellates, is also very abundant in these Campanian-Maastrichtian deposits, allowing in some cases the study of relative sea level variations and some paleoclimatic interpretations in the basin (Solé de Porta, 1971, 1972a, 1972b; Dueñas-Jiménez, 1989; Guillande et al., 1990; Sarmiento, 1992; Jaramillo and Yepes-Amézquita, 1994; Guerrero and Sarmiento, 1996; Sarmiento and Guerrero, 2000; Yepes, 2001; Garzón et al., 2012; Dueñas and Gómez, 2013; Bayona et al., 2021; De la Parra et al., 2022; Plata-Torres et al., 2023).

Macrofossils including ammonites, bivalves, gastropods, fish remains, leaf and wood fragments are common in these deposits (Figs. 7.4 and 7.5). Marine organisms are very abundant in the Campanian shelf environments and decrease in the Maastrichtian, where continental elements (leaf and wood fragments) are abundant.

Table 7.1. Summary of dominant lithology, trace fossils, and ichnofacies of the three sectors of the backarc basin.

Age	Western side			Central part			Eastern side			Traces fossils
	Lithology	Traces	Ichnofacies	Lithology	Traces	Ichnofacies	Lithology	Traces	Ichnofacies	
Maastrichtian	conglomerates and sandstones, and mudrocks, limestones, marls, and coals	X	*Cruziana* ichnofacies	sandstones and mudrocks	X	*Cruziana* ichnofacies	Sandstones, and locally mudrocks and conglomerates		*Rosselia* ichnofacies	*Arenicolites*
		X								*Arthrophycus*
		X								*Chondrites*
								X		*Conichnus*
					X					*Cylindrichnus*
		X								*Gyrochorte*
					X					*Gordia*
		X						X		*Ophiomorpha*
		X						X		*Palaeophycus*
		X			X			X		*Planolites*
		X			X					*Protovirgularia*
		X			X			X		*Rhizocorallium*
		X								*Schaubcylindrichnus*
		X			X					*Scolicia*
		X								*Spongeliomorpha*
		X						X		*Skolithos*
		X						X		*Taenidium*
		X						X		*Teichichnus*
		X			X			X		*Thalassinoides*
Campanian	claystones, siltstones, shales, limestones (mudstone, wackestone, packstone), marls, and in lesser proportion cherts, sandstones and phosphorites		Scarce occurrences of *Thalassinoides*	sandstones, mudrocks and diagenetic cherts	X	*Cruziana* ichnofacies	Mainly sandstones and in lesser proportions mudrocks		*Rosselia* ichnofacies	*Arenicolites*
					X					*Arthrophycus*
					X					*Asterosoma*
					X					*Crossopodia*
					X					*Cylindrichnus*
					X					*Diplocraterion*
					X					*Gordia*
					X					*Helminthopsis*
					X					*Laevicyclus*
					X			X		*Ophiomorpha*
					X					*Phycodes*
					X					*Planolites*
					X					*Protovirgularia*
					X			X		*Rhizocorallium*
					X					*Rosselia*
					X					*Scolicia*
					X					*Skolithos*
					X					*Teichichnus*
		X			X			X		*Thalassinoides*
					X					*Zoophycos*

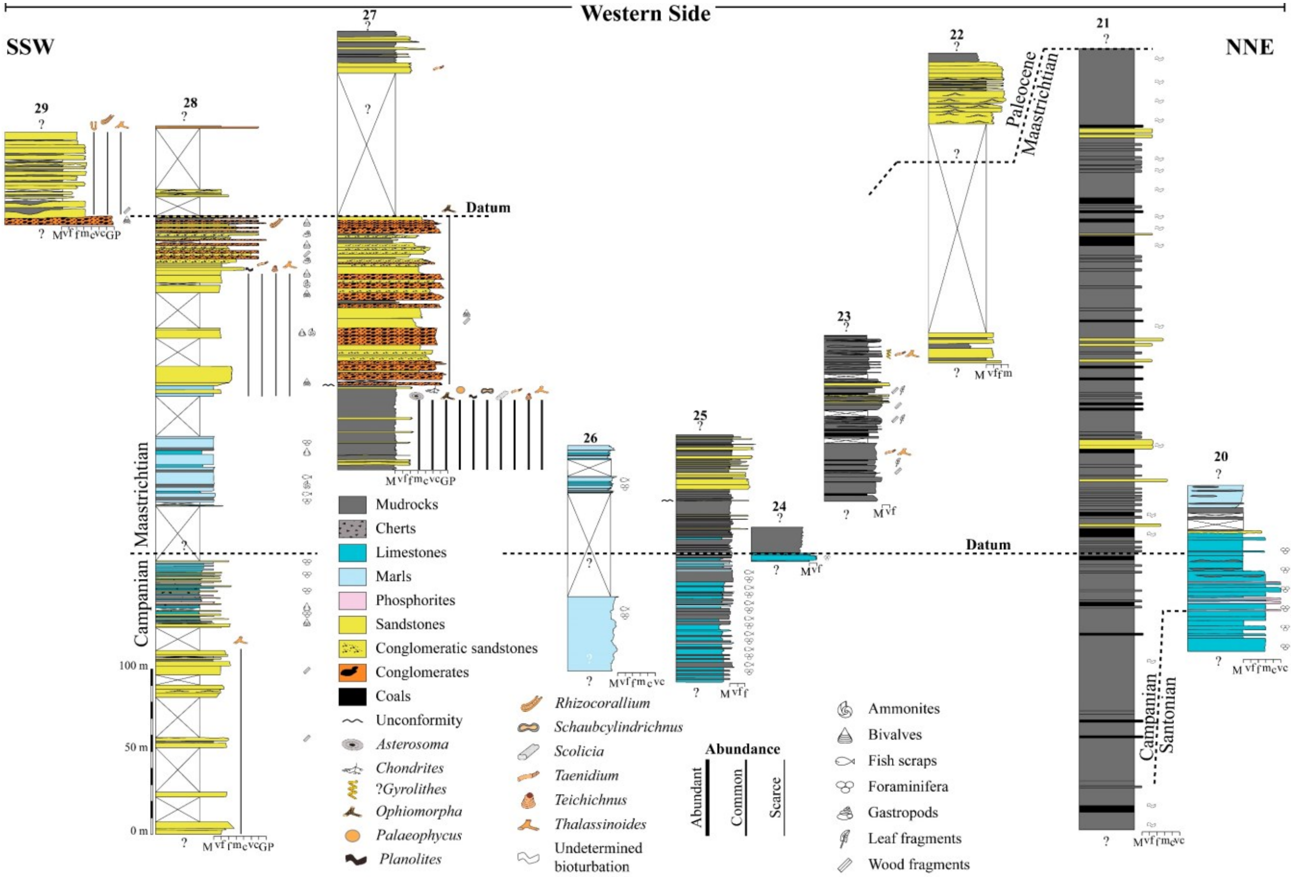


Figure 7.4. Compilation of lithological logs, ichnological and paleontological features related to the western side of the eastern backarc deposits. From north to south: 20 from Terraza (2019) and Patarroyo et al. (2023); 21 from Montaño et al. (2016); 22, 23, 24, 25, 26, 27, 28, 29 from Giraldo-Villegas et al. (2025). The traces that do not show a distribution line are due to punctual recording within the stratigraphic section.

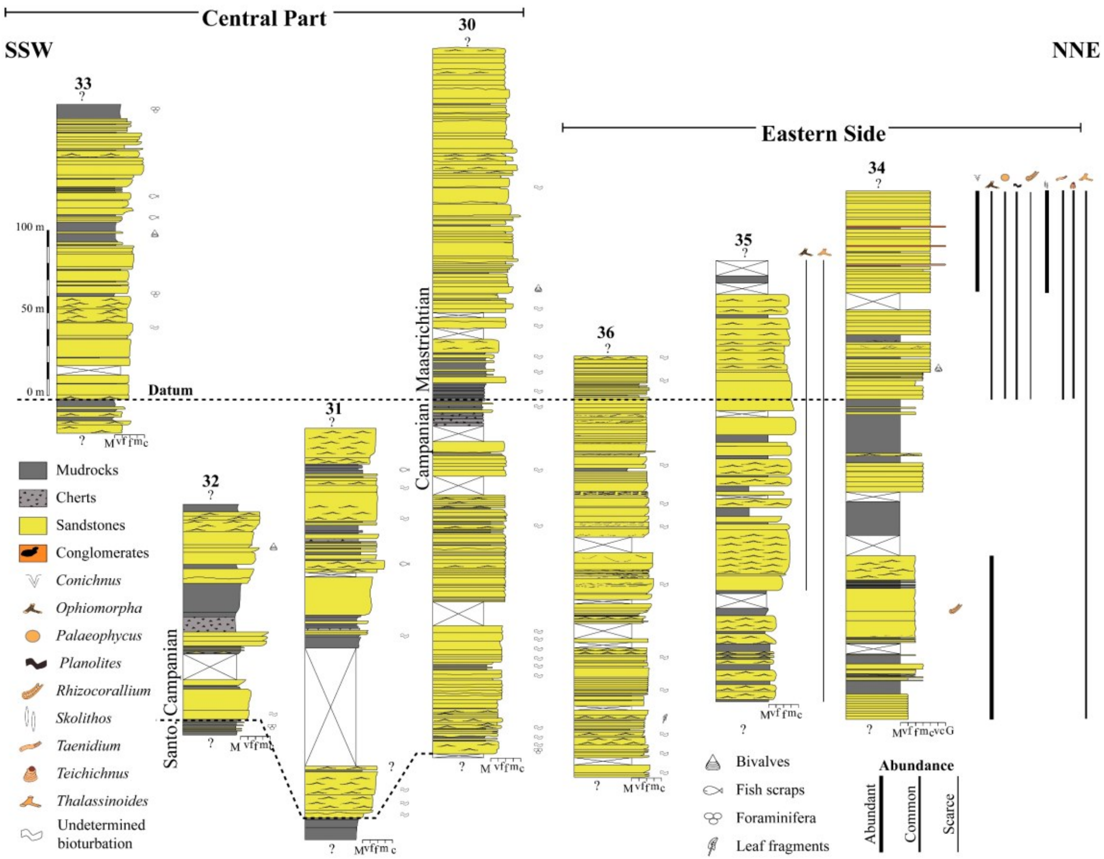


Figure 7.5. Compilation of lithological logs, ichnological, and paleontological features related to central part and eastern side of the eastern backarc deposits. From north to south: 30, 31, 32, 34, 36 from Vergara and Rodriguez (1997); 33 from Guerrero and Sarmiento (1996) and Giraldo-Villegas et al. (2025); 35 from Carvajal-Torres et al. (2022). The traces that do not show a distribution line are due to punctual recording within the stratigraphic section

7.4 Discussion: forearc western domain vs. backarc eastern domain

7.4.1 Sedimentary processes and depositional environments

The characteristics of emerged land areas that supply sediment, the land-ocean systems that transport it, and the specific conditions of the receiving basin (e.g., subsidence, bathymetry, oceanic connections, currents, waves, tides, geographic location) collectively control the spatiotemporal evolution of sedimentary environments and their resulting deposits.

The types of deposits and their associated sedimentary structures reveal marked differences in the physical depositional processes that controlled accumulation in the two domains. The western domain is characterized by deposits formed predominantly through suspended fall-out and turbiditic processes—generating pelagic/hemipelagic and turbiditic deposits respectively. These, along with trace fossil assemblages of the *Zoophycos* ichnofacies, indicate deep marine environments, including basin plains, basin-floor fan lobes, submarine channels and levees deposits (Figs. 7.6 and 7.7; Pardo-Trujillo et al., 2020; Giraldo-Villegas et al., 2023).

Within the western deep-sea environments, the distribution of turbiditic deposits indicates submarine channels located towards the central and easternmost parts (sections 9 to 13, and 17), while turbiditic fans (sections 6, 7, 8, 14, 15, 16) and pelagic/hemipelagic deposits are distributed to the southern, northern and westernmost parts (sections 1 to 5 and 18, 19), the latter being most dominant in the north (Figs. 7.3 and 7.6). This reflects an east-west proximal-distal trend, which in turn suggests the location of the major source areas and the major land-ocean systems that transported sediment into the basin. Two particular cases stand out where the macrofossil record suggests shallow marine environments; one in the northern or Caribbean region, associated with the record of leaf and carbonized wood fragments, and the other in the southern or Pacific region, associated with the record of bioclasts of coastal origin (Moreno-Sánchez et al., 2002; SGC, 2019). Although the authors suggest a shallow marine environment for the accumulation of these deposits, since they are clastic rocks, other interpretations based on depositional processes could be considered (e.g., hyperpycnal flows). Except for these two cases, these deposits and their associated depositional processes show a relatively homogeneous distribution during the Campanian-Maastrichtian, along the NW margin of Colombia (Figs. 7.6 and 7.7).

On the contrary, the eastern domain shows a wide spatiotemporal variability of sedimentary parameters, resulting in different types of deposits associated with the final stages of the La Luna Sea (Figs. 7.6 and 7.7). This heterogeneity includes coeval variations in sedimentary environments and processes in different zones of the backarc basin (Figs. 7.4, 7.5 and 7.6; Bayona, 2018; Sarmiento-Rojas, 2019; Bayona et al., 2021; Giraldo-Villegas et al., 2025). In general, during the Campanian, suspended fall-out and waves dominated the western side of the basin, with local influence of fluvial processes, storms, bottom, and alongshore currents associated with shoreface and shelf environments. In the central part and eastern side of the basin waves and suspended fall-out, and fluvial and waves were dominant processes, related to shoreface-offshore and fluvial-dominated delta front and prodelta environments respectively (Figs. 7.6 and 7.7). During the early Maastrichtian, suspended fall-out, with scattered influence of storms and longshore currents, were the major depositional processes responsible for the sediment accumulation on the western side associated with shelf and offshore settings. Fluvial processes associated with fan delta complex, anastomosed fluvial systems and marshes, and to a lesser degree tidal processes controlled the deposition of this area in the late Maastrichtian. In the central part, waves in the early Maastrichtian and fluvial processes in the late Maastrichtian associated with shoreface and swamp environments were the major depositional parameters. Fluvial and wave processes in the early Maastrichtian and fluvial processes in the late Maastrichtian associated with fluvial-dominated delta front and swamp environments, were the dominant parameters controlling sediment accumulation on the eastern side (Figs. 7.6 and 7.7 Giraldo-Villegas et al., 2025).

A general comparison of the most distal deposits of both basins (interbedded mudrocks and limestones, Figs. 7.3 and 7.4), which were accumulated by the same suspended fall-out processes, allows us to interpret that they may have been deposited in similar sedimentary environments. However, a detailed analysis reveals some peculiarities that allow us to precise interpretation of the above-mentioned environments. Despite their lithological similarities, one notable difference is the ichnological record. The western deposits are bioturbated by *Chondrites*, ?*Nereites*, *Phycodes*, *Phycosiphon*, *Planolites*, *Spyrophyton*, *Thalassinoides* and *Zoophycos*, while the eastern deposits are not bioturbated. This difference, although it gives a differential character, is not yet conclusive to differentiate the depositional environments. However, thinking about the spatiotemporal evolution of the sedimentary environments adjacent (central part), as well as stratigraphically above and below the more distal eastern deposits, are recorded deposits accumulated by waves that can determine the shallow marine character to this suite of sedimentary environments. On the contrary, adjacent to the distal western deposits there are sediments accumulated by gravity flows associated with steep environments, specifically the slope and their associated subenvironments (e.g., submarine channels), supporting the deep marine context.

In summary, the accumulated deposits in the western domain indicate a relatively constant and prolonged interaction through time (Campanian-Maastrichtian) between the emerged and receiving areas, resulting in the accumulation of relatively homogeneous sediments associated with deep marine environments. In contrast, the variability of shallow marine, marginal and continental deposits in the eastern domain reveals rapid and significant changes in the land-ocean sedimentary systems, associated with fluctuations in the allogenic and autogenic depositional controls.

7.4.2 Seafloor colonization: physical and paleoecological factors

Bioturbation evidence the activity of macrobenthic tracemaker communities on/into the seafloor, which is controlled not only by physical environmental parameters (e.g., hydrodynamic energy, sedimentation rate, turbidity, substrate type), but also by ecological factors, with food and oxygen as some of the most important.

The two trace fossil assemblages recognized in the Campanian-Maastrichtian deposits shows differences in both domains. The ichnoassemblage composed of eight ichnogenera belonging to the *Zoophycos* ichnofacies in the western deposits, and the assemblage of 27 ichnogenera, associated with the *Cruziana* and *Rosselia* ichnofacies in the eastern deposits, support not only the differences in physical parameters and depositional environments, but also in ecological conditions in the seafloors of both domains (Figs. 7.6 and 7.7).

The low diversity and abundance of traces in the western domain, which includes feeding (*Phycodes*, *Phycosiphon*, *Zoophycos*), dwelling (*Chondrites*, *Planolites*, *Thalassinoides*) and grazing (?*Nereites*) ethological categories (Vallon et al., 2016), reflect unfavorable conditions for macrobenthic communities. In deep marine environments the main factors controlling the establishment and development of tracemaker communities are the food availability (mainly organic matter) and oxygenation (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012; Rodríguez-Tovar and Dorador, 2014; Rodríguez-Tovar, 2022). Classically, the *Zoophycos* ichnofacies have been associated with poor-oxygenated and organic-rich environments (e.g., Frey and Seilacher, 1980; Frey and Pemberton, 1984, 1985; Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), and the turbiditic deposits are characterized by a high input of organic matter from the continent, which is evidenced in the Campanian-Maastrichtian western forearc deposits by the dark colors, the local record of carbonized wood fragments and the relatively high TOC values (between 3.5% and 4.5% in Cansona Formation; Osorno and Rangel, 2015). According to this, the evidence suggests that the main ecological factor controlling the colonization and development of macrobenthic communities along the NW margin of South America during the Campanian-Maastrichtian was oxygenation. This would also explain the scarce or almost non-existent macrofossil record. Moreover, since bioturbation is mainly associated with fine-grained rocks, it is also possible to interpret the hydrodynamic energy of the bottoms as a depositional parameter that controlled the establishment of macrobenthic communities in this western area, and therefore the deposits in the central part contain the lowest records compared to the northern and southern sectors of this region.

The trace fossil assemblage of the eastern backarc domain includes the activity of a developed tracemaker community involving a wide variety of ethological categories (Vallon et al., 2016), including feeding (*Arthrophycus*, *Asterosoma*, *Chondrites*, *Phycodes*, *Rhizocorallium*, *Spongeliomorpha Taenidium*, *Teichichnus*, *Zoophycos*), dwelling (*Arenicolites*, *Conichnus*, *Cylindrichnus*, *Diplocraterion*, ?*Gyrolithes*, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Rosselia*, *Schaubcylindrichnus*, *Skolithos*, *Thalassinoides*), grazing (*Helminthopsis*, *Gordia*, *Scolicia*), and locomotion (*Gyrochorte*, *Crossopodia*, *Protovirgularia*) associated with *Cruziana* ichnofacies (MacEachern et al., 2007, 2012) in the western and central parts The eastern side, which was under the permanent influence of fluvial processes, has different physical and ecological characteristics from those dominated by marine processes in the central and western parts of the basin. The influx of sediment-bearing freshwater into the marine basin causes significant changes in salinity and turbidity, which control the development of macrobenthic tracemaker communities in these marginal environments (e.g., La Croix et al., 2015; Solórzano et al., 2017). This is reflected in the decrease in diversity and abundance of traces in the eastern side, being the ichnoassemblage associated with the *Rosselia* ichnofacies (MacEachern and Bann, 2020). Internally, the variation in the abundance and diversity of traces between these eastern side deposits of the backarc domain suggests stressful physico-ecological conditions during the early Campanian and stable marine conditions during the early Maastrichtian, demonstrating variable influence of fluvial vs. wave processes during their accumulation.

The overall high trace fossils diversity and abundance, along with the diverse ethological categories recorded in the backarc basin, support favorable physical and ecological conditions for the establishment and development of the tracemaker macrobenthic community (Figs. 7.6 and 7.7). These good living conditions may respond to processes of bottom agitation and reoxygenation, as well as to the continuous availability of organic matter of continental origin, as indicated by the activity of waves, currents, coastal and bottom currents, and the constant fluvial input, reflected in the sedimentological characteristics of these deposits (Figs. 7.6 and 7.7).

In general, the scarce and low diverse bioturbation, closely associated with fine-grained lithologies, is homogeneously distributed in the Campanian-Maastrichtian western forearc deposits. On the contrary, the abundant and diverse bioturbation, with no lithological preference in the eastern backarc deposits shows two major episodes, one in the early Campanian and the other in the early Maastrichtian (Giraldo-Villegas et al., 2025). This suggests that the physical and ecological conditions were not very favorable for the proliferation of an abundant and diverse macrobenthic community in the western deposits, but were constant, while in the east these parameters, although favorable, were also variable through time, demonstrating the high ecosedimentary dynamics of the backarc basin compared to the forearc basin.

The late Campanian eastern backarc deposits with scarce bioturbation and dark colors have been associated with a period of eutrophication due to oceanic upwelling processes (Villamil et al., 1999; Patarroyo et al., 2023), leading to reductions in oxygenation and thus challenging bottoms for the establishment of tracemaker communities. It is possible to interpret that these eutrophication processes were either local, associated only with the oceanographic dynamics and sedimentary evolution of the backarc basin, or more connected with the shallow water masses of the proto-Atlantic Ocean. In any case, the western deposits do not allow us to interpret these upwelling phenomena.

With respect to the benthic micro- and macrofossil record, there is also a marked difference between the eastern and western deposits. Fossils from the deposits of the backarc basin show a greater diversity, abundance and degree of preservation than those from the forearc basin, supporting the interpreted differences in physical and ecological parameters of sedimentation and/or oceanographic dynamics between the two areas, demonstrating the ecosedimentary differences between the two basins. However, one factor that has not yet been evaluated and that could affect the preservation mainly of microfossils is the degree of diagenesis associated with the deformational history of the forearc deposits. Particularly, the diagenetic processes have improved the preservation of trace fossils (Giraldo-Villegas et al., 2023).

7.4.3 Allogenic vs. autogenic depositional controls

Allogenic and autogenic depositional controls are responsible for the stratigraphic evolution of sedimentary basins (Catuneanu, 2022). Thus, the final sedimentary deposits will record the degree of influence of these parameters. In a tectonically active margin, such as the NW margin of South America during the latest Cretaceous, tectonics itself was undoubtedly a pervasive allogenic depositional control.

Regarding allogenic controls, the spatiotemporal variability of sedimentary environments and processes has allowed recognition of tectonic uplift —linked to the Caribbean Plate collision— along with high erosion rates, subsidence, and eustasy in a variable degree, as the primary allogenic depositional controls on sediment accumulation during the final stages of the La Luna epeiric sea in the eastern backarc domain (Gómez et al., 2003; 2005a, 2005b; Sarmiento-Rojas et al., 2006; Sarmiento-Rojas, 2019; Giraldo-Villegas et al., 2025). In contrast, the relative homogeneity of the deep-sea deposits and sedimentary processes in the western domain makes it difficult to clearly distinguish the different allogenic depositional controls that influenced its stratigraphic evolution, but the absence of major changes in depositional processes, deposits and environments makes it possible to rule out significant changes in the degree of influence of these controls.

However, despite these differences, according to the provenance of the sediments both domains share a common sediment source: the Proto-Central Cordillera. This raises the question of why the stratigraphic and spatial evolution of deposits during the Campanian-Maastrichtian differs between the two domains, rather than simply reflecting two bathymetrically distinct basins. The eastern domain, being an epeiric basin bounded on either side by emerged landmasses, responds rapidly to changes in the source areas and in the land-ocean transport systems/processes. In contrast, the western domain, bordered only by the continent to the east and open to the ocean to the west, had greater accommodation space for sediment redistribution, leading to a slower response in the evolution of sedimentary environment. Additionally, the larger dimensions of the western basin could attenuate the record of sedimentary variability, whereas in the smaller eastern basin, amalgamated sediments could represent frequent and rapid environmental shifts.

Another key factor that must have controlled the distinct stratigraphic evolution of the two domains was the variable erosion of the sedimentary cover in both flanks of central volcanic arc. During the Late Cretaceous, a 4-5 km thick sedimentary cover overlying the basement of both flanks of the proto-Central Cordillera has been reported (Zapata et al., 2020, 2021, 2024). At present, however, remnants of these deposits —up to 2 km thick— are only preserved on the western flank (González, 1980; Gomez-Cruz et al., 1995; León et al., 2019; Zapata et al., 2019), indicating differential erosional/uplift processes between the flanks. Differential exhumation and uplift during the Paleocene on the western flank associated with block movements in the Romeral Fault System, and rapid cooling of the Ibagué Batholith on the eastern flank of the Central Cordillera during the Late Cretaceous have already been reported by Zapata et al. (2020) and Villagómez and Spikings (2013), respectively. During the Cenozoic, high rates of erosion occurred on the eastern flank, associated with the Paleocene-Eocene unconformity recorded in the Middle Magdalena Valley basin (Gómez et al., 2003). Also, there is a significant difference in the volume of sediment currently being eroded in the flanks of the Central Cordillera. The eastern flank shows erosion rates of 2.7 km^3/Ka, whereas the western flank records rates between 0.6 and 2.0 km^3/Ka (Ott et al., 2023). This variation may be attributed to asymmetric uplift or differential exhumation, being greater on the eastern flank, reflecting the higher erosional rate, as is the case of the Eastern Cordillera today (Mora et al., 2008; Ramirez-Arias et al., 2012; Ott et al., 2023). Such uplift-driven sedimentation aligns with previous interpretations suggesting that high sedimentation rates—rather than eustasy—were the main factor driving the infilling of the La Luna epeiric sea during the late Maastrichtian (Gómez et al., 2005a; Giraldo-Villegas et al., 2025). This evidence suggests that the increased sediment availability likely played a crucial role in shaping the stratigraphic evolution of both basins.

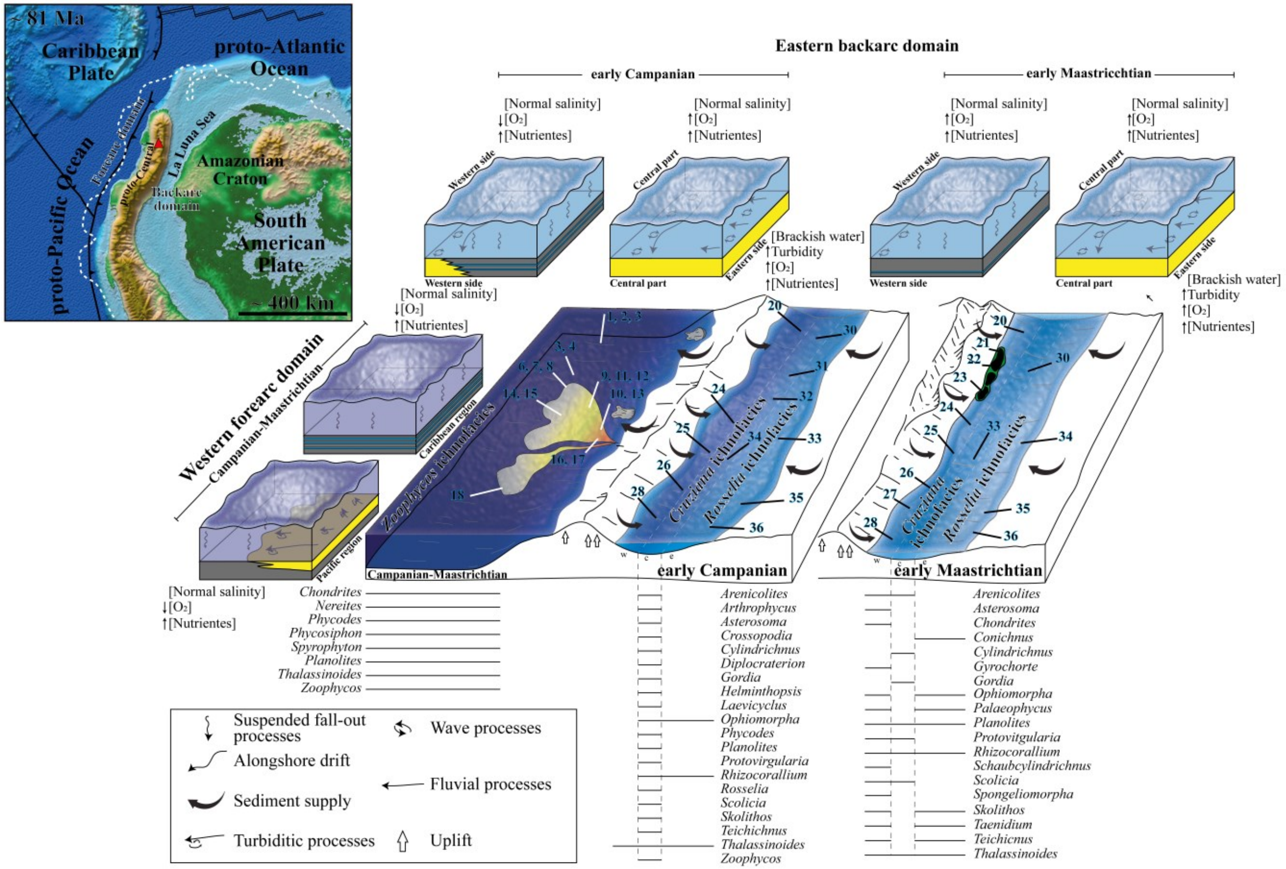


Figure 7.6. Schematic depositional model, sedimentary (physical and ecological) processes of forearc and backarc basins in the northwestern margin of South America during the Campanian-Maastrichtian. w: western side; c: central part; e: eastern side. The numbers represent the lithological logs of figures 7.3, 7.4 and 7.5.

Estimations of sedimentation rates to test these hypotheses are scarce for the Campanian-Maastrichtian period, and those that do exist are associated only with the eastern backarc basin. Values of 113 m/Ma in the Campanian-Maastrichtian (Martínez, 2003), between 10 m/Ma and 120 m/Ma in the early and middle Campanian (De la Parra et al., 2024), 17.4 m/Ma in the late Campanian and 25 m/Ma and 52.3 m/Ma in the early and late Maastrichtian, respectively (Vergara, 1997b), and of 100 m/Ma in the late Maastrichtian (Patarroyo et al., 2022) are some of the accumulation rate values reported for this period, allowing the interpretation of an increase in accumulation rates towards the end of the Maastrichtian in the backarc basin.

When considering the sedimentary environments in an integrated way, it is essential to recognize that most basin sediments originate from the continent, following a land-ocean transport system, where sediment accumulates, transitions through shallow marine environments, and ultimately reaches deep marine environments, or to the bottom of the basin. Therefore, it is expected that in the eastern domain, which was an epeiric sea, would not have developed deep marine environments during this period. However, what is unusual is the absence of recorded shallow marine environments across the ~700 km extent of the western domain with only two punctual mentions. This could be interpreted as related to erosional processes during the collision or afterwards, or because these environments did not develop given their tectonically active geologic history. In the latter case, marine environments with narrow platforms, such as those currently recorded in the Colombian Pacific, where sediments coming from the continent reached the coast and quickly moved to slope environments, where they were channeled, later arriving at the abyssal plain as turbiditic fans, could be interpreted.

Regarding autogenic controls, depositional processes such as bottom and alongshore currents interpreted in the Campanian and early Maastrichtian, upwelling phenomena leading to the development of oxygen-depleted environments during the late Campanian, tides, and channel avulsion in the late Maastrichtian, were also important in the deposit accumulation in the eastern backarc basin, which are not recorded in the western forearc basin (Villamil et al., 1999; Erlich et al., 2003: Giraldo-Villegas et al., 2025). These may be related to the oceanographic dynamics of the eastern epeiric sea associated with the proto-Atlantic Ocean.

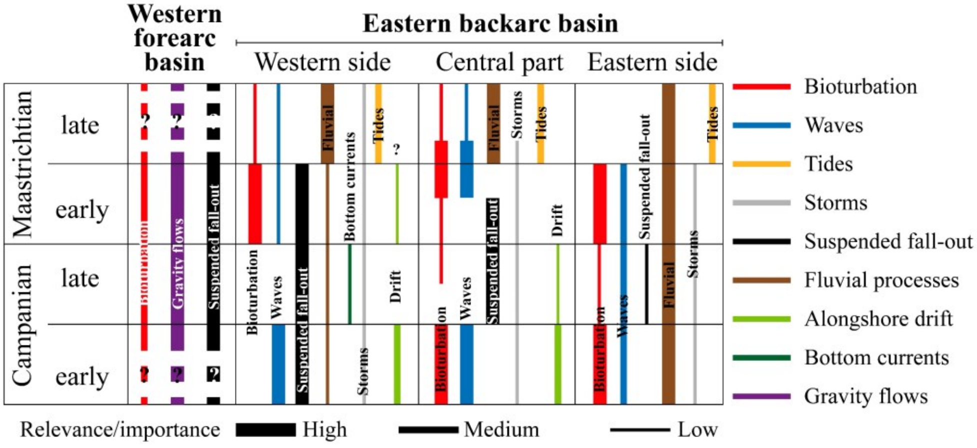


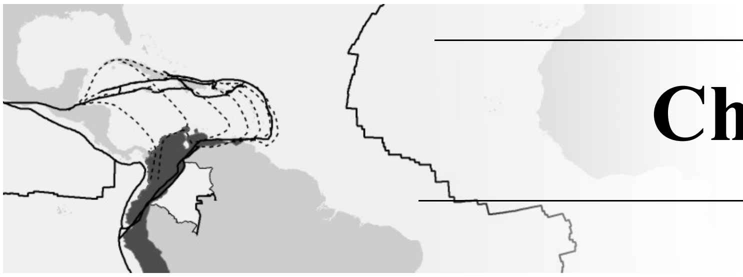
Figure 7.7. Summary of depositional processes, and bioturbation, and their relevance in forearc and backarc basins during the Campanian-Maastrichtian on the NW margin of South America.

7.5 Conclusions

The integrated and detailed study of the sedimentary rocks of the forearc and backarc basins developed in NW South America during the Late Cretaceous (Campanian-Maastrichtian), reveals marked differences in the spatiotemporal evolution of sedimentary environments and paleoenvironmental conditions between the two basins, associated with the collision of the Caribbean Plate. In the western forearc basin, sedimentation was relatively homogeneous, dominated by suspended fall-out and turbiditic processes, accumulating fine- and coarse-grained deposits in deep marine systems, where the main paleoecological and depositional factors controlling the establishment of macrobenthic tracemaker communities, represent by an ichnoassemblage assigned to the *Zoophycos* ichnofacies, were oxygenation and hydrodynamic energy. In the eastern backarc basin, sedimentation was variable and changed through time, even showing variations in different areas into the basin. During the Campanian, the western side hosted the most distal sedimentary environments of the basin (shelf), where sediment fall-out was the dominant depositional process in the accumulation of fine-grained deposits. In contrast, in the central and eastern parts of the basin, sedimentation was dominated by wave and fluvial processes, respectively, which accumulated mainly sandy deposits in shoreface and delta front settings. At the late Campanian – early Maastrichtian, fine-grained sediments were accumulated in the three sectors of the basin, but with differences in their depositional settings, shelf-offshore environments on the western side, offshore in the central part and prodelta in the eastern part, respectively dominated by suspended fall-out, suspended fall-out and storms, and fluvial processes. During the late Maastrichtian, fluvial processes accumulated fine- and coarse-grained deposits on the western side, accompanied by some tidal deposits. The central and western parts accumulated sandy deposits mainly associated with wave and fluvial and wave processes, respectively. Subsequently, fluvial processes dominated the entire basin, ultimately leading to clogging. In this backarc basin, macrobenthic tracemaker communities responded according to the spatiotemporal variation of sedimentary environments and paleoenvironmental conditions. Thus, there were two major colonization periods, one in the early Campanian and the other in the early Maastrichtian. In the early Campanian, the western side was characterized by unfavorable conditions for the proliferation of macrobenthic tracemakers, where only scarce traces of *Thalassinoides* have been recorded, while in the central part an abundant and diverse tracemaker community associated with the *Cruziana* ichnofacies was established. In the eastern part, being directly connected to fluvial systems that caused significant changes in salinity, a scarce and low-diversity macrobenthic tracemaker community associated with *Rosselia* ichnofacies was developed. During the early Maastrichtian, ecological conditions improved on the western side bottoms, as evidenced by an abundant and diverse ichnoassemblage belonging to the *Cruziana* ichnofacies. On the central and eastern sides, favorable conditions also prevailed, supported by an abundant and diverse trace fossil assemblage related to the *Cruziana* and *Rosselia* ichnofacies, respectively. The evidence suggests that the main factors that controlled the development of macrobenthic tracemaker communities in this eastern basin were the good oxygenation of the bottoms in the western and central parts, generated by the continuous wave processes that agitated the sediment, and the constant supply of organic matter by the fluvial systems and the resultant salinity and turbidity changes in the eastern side.

The contrasting stratigraphic evolution of the two basins is mainly related to the differential influence of allogenic and, to a lesser extent, autogenic processes that simultaneously controlled sedimentation in both basins. First, variable uplift of the volcanic arc associated with the Caribbean Plate collision, with higher rates on the eastern flank increasing sediment erosion that subsequently reached the basin. Second, sediment input from both borders in the backarc basin, as opposed from only one side in the forearc basin. Third, the size and bathymetry of the basins, which was smaller in the backarc basin, generated greater amalgamation of deposits in response to the arrival of large amounts of sediment. To a lesser extent, autogenic controls such as upwelling, alongshore and bottom currents, channel avulsion and tides were also responsible for the resulting deposits in the backarc basin as opposed to the forearc basin.

Part IV FINAL REMARKS, CONCLUSIONS AND FORTHCOMING RESEARCH



Chapter 8

CONCLUSIONS

CONCLUSIONES

8.1 Conclusions

The integrated analysis of sedimentological, ichnological (with special attention to the analysis of ichnofacies and ichnofabrics), micro- and macro-paleontological and stratigraphic aspects, together with the integration of previous information, has allowed to understand the spatiotemporal evolution of depositional processes (physical and ecological), deposit types and sedimentary environments, in two coeval but geodynamically distinct forearc and backarc sedimentary basins, developed during the Campanian-Maastrichtian in the NW margin of South America. The paleoenvironmental evolution and variability of both basins respond to the influence of allogenic and autogenic factors that controlled the origin, transport and accumulation of sediments. Thus, the main conclusions obtained in response to the initially proposed objectives are the following:

In the western domain or forearc basin, sedimentation was relatively homogeneous through time, dominated by turbiditic and suspended fall-out processes in deep marine environments, specifically submarine canyons, basin-floor fans and abyssal plains. The macrobenthic tracemaker communities are represented by a sparse and poorly diverse trace fossil assemblage, assigned to the *Zoophycos* ichnofacies. The main paleoenvironmental parameters that controlled the establishment and development of these communities were oxygenation and hydrodynamic energy of the bottom.

In the eastern domain or backarc basin, associated with the final stages of the La Luna Sea, sedimentation was variable over time, showing significant coeval changes in the western, central and eastern sectors of the basin. During the early Campanian, the western sector of the basin hosted the most distal (shelf) sedimentary environments, dominated by suspended fall-out processes and with unfavorable conditions for the establishment of tracemaker communities. In contrast, the central and eastern sectors represented proximal environments, dominated by wave and fluvial processes in shoreface and fluvial-dominated delta front environments. In both sectors, conditions were favorable for the establishment of macrobenthic tracemaker communities, although to a different extent, allowing the recording of a diverse and abundant trace fossil assemblage in the central sector assigned to the *Cruziana* ichnofacies, and a poorly diverse and scarce one associated with the *Rosselia* ichnofacies in the eastern part. During the late Campanian, suspended fall-out processes dominated in the western and central sectors of the basin, and fluvial processes in the eastern sector, accumulating deposits in shelf, offshore, and fluvio-dominated prodelta environments, respectively. The ecological conditions (mainly oxygenation) of these bottoms were unfavorable for this period, making their colonization difficult. During the early Maastrichtian, the western sector continued to be dominated by suspended fall-out and local wave processes associated with shelf and offshore environments. In the central and eastern sectors, wave and fluvial processes in shoreface and fluvio-dominated delta front environments, respectively, are again dominant.

Favorable conditions for the colonization of benthic habitats are reestablished in the three sectors of the basin, giving rise to abundant and diverse ichnoassemblages associated with the *Cruziana* ichnofacies in the western and central sectors and the *Rosselia* ichnofacies in the eastern sector. The main controlling parameters for the development of macrobenthic tracemaker communities in the early Campanian and early Maastrichtian were oxygenation in the western and central sectors, and salinity, turbidity and constant organic matter input in the eastern sector. During the late Maastrichtian there is a general shallowing of the backarc basin, with fluvial processes controlling the sediment accumulation in the three sectors; fan delta complexes and anastomosed rivers in the western sector, and marshes and deltas in the central and eastern sectors. Dominant fluvial processes created unfavorable bottoms for the establishment of macrobenthic tracemaker communities during this period. However, the presence of *Ophiomorpha* ichnofabrics in the fan delta complexes indicates the establishment of marine conditions within this fluvial-dominated system, suggesting relative sea-level changes associated with local depositional controls.

The spatiotemporal evolution of sedimentary environments reveals fundamental differences between the forearc and backarc domains. The forearc basin is characterized by gravity-flow deposits linked to steep-slope environments, such as submarine channels, coupled with turbiditic fans and hemipelagic deposits, confirming the predominance of deep-marine environments. In contrast, in the backarc basin, sedimentary successions adjacent to and stratigraphically associated with the more distal deposits are characterized by wave-influenced facies, supporting a general interpretation of shallow-marine environments in an epeiric sea context.

The two basins, associated with different but coeval geodynamic contexts, evolved stratigraphically differently over time in response to the variable influence of allogenic and autogenic depositional factors. In the forearc basin, the larger size and bathymetry of the basin resulted in a more extensive redistribution of sediments. In addition, the lower erosion rate of the western flank of the volcanic arc, directly connected to this basin, determined that the amount of sediments deposited in the forearc basin was lower compared to the eastern domain. The backarc basin, bounded on both sides by emerged input areas, received more sediment and had less space for its redistribution, resulting in the amalgamation of deposits and generating the wide variability of environments and sedimentary processes. This, together with a higher erosion rate on the eastern flank of the volcanic arc, directly connected to this basin, associated with differential uplift, were important depositional factors in the filling of the basins. To a lesser degree, but still present, autogenic processes such as oceanic upwelling, which caused eutrophication of the waters, bottom and alongshore currents, tides, and channel avulsion also influenced the accumulation of sediments in the backarc basin.

8.2 Conclusiones

El análisis integrado de aspectos sedimentológicos, icnológicos (con especial atención al análisis de icnofacies e icnofábricas), micro y macro-paleontológicos y estratigráficos, junto con la integración de información previa, ha permitido conocer la evolución espaciotemporal de los procesos deposicionales (físicas y ecológicos), tipos de depósito y ambientes sedimentarios, en dos cuencas sedimentarias de antearco (*forearc*) y retroarco (*backarc*) coetáneas, pero diferentes a nivel geodinámico, desarrolladas durante el Campaniense-Maastrichtiense en la margen NW de Suramérica. La evolución y variabilidad paleoambiental de ambas cuencas responden a la influencia de factores alogénicos y autogénicos que controlaron el origen, transporte y acumulación de los sedimentos. Así, las principales conclusiones obtenidas como respuesta a los objetivos inicialmente propuestos son las siguientes:

En el dominio occidental o cuenca de antearco, la sedimentación fue relativamente homogénea a través del tiempo, dominada por procesos turbidíticos y de suspensión en ambientes marinos profundos, específicamente cañones y abanicos submarinos y llanuras abisales. Las comunidades macrobentónicas bioturbadoras están representadas por una asociación de trazas escasa y poco diversa, asignada a la icnofacies de *Zoophycos*. Los principales parámetros paleoambientales que controlaron el establecimiento y desarrollo de estas comunidades fueron la oxigenación y la energía hidrodinámica del fondo.

En el dominio oriental o cuenca de retroarco, asociado a las etapas finales del mar de La Luna, la sedimentación fue variable a través el tiempo, mostrando cambios significativos coetáneos en los sectores occidental, central y oriental de la cuenca. Durante el Campaniense temprano, el sector occidental de la cuenca albergó los ambientes sedimentarios más distales (plataforma), dominados por procesos de suspensión y con condiciones poco favorables para el establecimiento de comunidades generadoras de trazas. En contraste, los sectores central y oriental representaron ambientes proximales, dominados por procesos de oleaje y fluviales en ambientes de *shoreface* y frente de delta fluvio-dominado. En ambos sectores las condiciones fueron favorables, aunque en grado variable, para el establecimiento las comunidades macrobentónicas, permitiendo el registro de una asociación de trazas diversa y abundante en el sector central asignada a la icnofacies de *Cruziana*, y una poco diversa y escasa asociada a la icnofacies de *Rosselia* en la parte oriental. Durante el Campaniense tardío los procesos de suspensión dominaron en los sectores occidental y central de la cuenca, y los procesos fluviales en el sector oriental, acumulando depósitos en ambientes de plataforma, *offshore* y prodelta fluvio-dominado, respectivamente. Las condiciones ecológicas (principalmente la oxigenación) de estos fondos fueron desfavorables para este periodo, dificultando su colonización. Durante el Maastrichtiense temprano el sector occidental continuó dominado por procesos de suspensión y localmente oleaje, asociados a ambientes de plataforma y *offshore*. En los sectores central y oriental destacan de nuevo, los procesos de oleaje y fluviales en ambientes de *shoreface* y frente deltaico fluvio-dominado, respectivamente. Las condiciones favorables para la colonización de los hábitats bentónicos se reestablecen en los tres sectores de la cuenca, dando lugar a asociaciones de trazas abundantes y diversas asociadas a las icnofacies de *Cruziana* en los sectores occidental y central y a las icnofacies de *Rosselia* en el oriental. Los principales parámetros de control en el desarrollo de las comunidades macrobentónicas bioturbadoras en el Campaniense temprano y Maastrichtiense temprano fueron la oxigenación en los sectores occidental y central, y la salinidad, turbidez y constante aporte de materia orgánica en el oriental. Durante el Maastrichtiense tardío se registra una somerización general de la cuenca de retroarco, con procesos fluviales controlando la acumulación de sedimentos en los tres sectores; complejos de abanico deltaico y ríos anastomosados en el sector occidental, y pantanos y deltas en los sectores central y oriental. El dominio de procesos fluviales generó fondos adversos para el establecimiento de comunidades macrobentónicas durante este periodo. Sin embargo, la presencia de icnofábricas de *Ophiomorpha* en los complejos de abanico deltaico indica el establecimiento de condiciones marinas dentro de este sistema fluvio-dominado, sugiriendo cambios relativos del nivel del mar, asociados a controles deposicionales locales.

La evolución espaciotemporal de los ambientes sedimentarios revela diferencias fundamentales entre los dominios de antearco y retroarco. La cuenca de antearco se caracteriza por depósitos de flujo gravitatorio asociados a entornos de pendiente pronunciada, como canales submarinos, asociados con depósitos hemipelágicos y de abanicos turbiditíicos, lo que confirma el dominio ambientes marinos profundos. En contraste, en la cuenca de retroarco, las sucesiones sedimentarias adyacentes y estratigráficamente asociadas a los depósitos más distales son caracterizadas por facies influenciadas por el oleaje, lo que apoya una interpretación general de ambientes marinos someros en un contexto de mar epírico.

Las dos cuencas, asociadas a contextos geodinámicos diferentes, pero coetáneos, evolucionaron estratigráficamente de distinta manera, como respuesta a la influencia variable de factores deposicionales alogénicos y autogénicos. En la cuenca antearco, el mayor tamaño y batimetría de la cuenca propició una redistribución más extensa de los depósitos. Además, la menor tasa de erosión del flanco occidental del arco volcánico, conectado directamente con esta cuenca, determinó que la cantidad de sedimentos que se depositó en la cuenca antearco fuera menor, comparada con el dominio oriental. La cuenca retroarco, limitada a ambos bordes por áreas emergidas, recibía mayor cantidad de sedimento y tenía menor espacio para su redistribución, dando lugar a la amalgamación de depósitos y generando la amplia variabilidad de ambientes y procesos sedimentarios. Esto, acompañado de una mayor tasa de erosión en el flanco oriental del arco volcánico, directamente conectado con esta cuenca, asociado a levantamientos diferenciales, fueron factores deposicionales importantes en el relleno de las cuencas. Con menor grado de intervención, pero presentes, procesos autogénicos tales como fenómenos de surgencia oceánica que generaron eutroficación de las aguas, corrientes de fondo y corrientes a lo largo de la costa, mareas y avulsión de canales también influyeron en la acumulación de depósitos en la cuenca de retroarco.

8.3 Forthcoming research

This section lists some of the possible lines of future research related to the findings of this thesis. These include the integration of new analyses and methodologies to address or complement the research questions raised by the research conducted.

1. Detailed and accurate paleoenvironmental analyses from process-based sedimentology, integrated with ichnological analysis and micro- and macro-paleontological proxies, in other Campanian-Maastrichtian age sections of both basins that feed the proposed model.
2. Provenance studies of Campanian-Maastrichtian coarse- and fine-grained sediments in the backarc basin, with the aim of reconstructing sediment transport pathways within the basin, and the extent of bottom and alongshore currents.
3. Integration and detailed analysis of thermochronological data associated with the central volcanic arc to test differential uplift of both flanks. These will be integrated with mass balance studies to measure the amount of sediment eroded versus accumulated.
4. Increase biostratigraphic resolution and/or obtain absolute dating to measure sedimentation rates.
5. Integrate geochemical analyses of sedimentary rocks to build comprehensive paleoenvironmental models.

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APPENDIX I

Supplementary material for Chapter 4

Supplementary file 1. Correlated sections and reinterpreted paleontological ages of some studied sections and lithostratigraphic units.

Correlated units

Region	Locality	Fig 1, 10, 12 representation	Lithostratigraphic Unit	Lithology	Autor	Age	Fossils	Trace fossils	Depositional setting
CARIBBEAN	Cerro Cansona	a	Cansona Formation	Mudstones, sandstones	Juliao-Lemus et al. (2016)				Proximal settings
	Chalán Creek	b	Cansona Formation	Mudrocks, sandstones	Juliao-Lemus et al. (2016)				Proximal setting
	San Carlos quarry	1-c	Cansona Formation	Mudrocks, limestones	Jaramillo et al. (2011), Juliao-Lemus et al. (2016), this work	Santonian-Maastrichtian	Calcareous nannofossils	*Chondrites*, *Planolites*, *Zoophycos*	Intermediate setting/basin plain

	El Purgatorio-Chicoral quarrys	**2-d**	Cansona Formation	Chert, mudrocks	Jaramillo et al. (2011), Juliao-Lemus et al. (2016), this work	Campanian-Maastrichtian	Calcareous nannofossils	*Chondrites*, *Planolites*, *Zoophycos*	Deeper conditions/ basin plain
PACIFIC	La Perra section	**e**	Cansona Formation	Mudrocks, sandstones	SGC (2019a)				Shallow marine
	Río Sinú sur section	**f**	Cansona Formation	Mudrocks, sandstones, conglomerates	SGC (2019a)				Shallow marine
	El Limón Creek	**g**	Penderisco Formation	Mudrocks, sandstones, limestones	SGC (2019a)	Santonian-Maastrichtian	Calcareous nannofossils		Deep marine
	Chimurrito Creek	**h**	Cansona Formation	Mudrocks, sandstones, limestones, conglomerates	SGC (2019b)				Shallow marine
	La Esmeralda Creek	**i**	Cansona Formation	Mudrocks, sandstones	SGC (2019b)				Shallow marine
	Peque area (Antioquia)	**j**	Not indicated	Turbidity Sandstones	Etayo-Serna (1989)	Campanian-Maastrichtian	*Nostoceras*, *Trochoceramus*		Deep marine

Río Sucio bridge	**k**	Not indicated	Mudrocks	Etayo-Serna et al. (1982)	Santonian-Maastrichtian	*Rugoglobigerina* sp.		Not indicated
Dabeiba section	**3**	Nutibara Member	Mudrocks, siliceous mudstones	Pardo-Trujillo et al. (2020), this work	Santonian-Maastrichtian	*Watznaueria barnesiae*, *Micula staurophora*, *Quadrum (Uniplanarius) gothicum*	*Chondrites, Zoophycos*	Basin plain
Giraldo area (Antioquia)	**l**	Penderisco Formation	Calcareous concretions	Díaz-Cañas and Patarroyo (2014)	Campanian-Maastrichtian	*Pachydiscus* cf. *flexuosus*		Deep marine
Betulia section	**m**	Penderisco Formation	Mudrocks, sandstones, conglomerates	Pardo-Trujillo et al. (2020)			*Nereites*	Deep marine
Concordia section	**4-n**	Volcanoclastic unit/Penderisco Formation	Siliceous and calcareous mudrocks, cherts, volcanoclastic sandstones, conglomerates	Pardo-Trujillo et al. (2020), this work	Coniacian-Maastrichtian	*Madagasceramus*, *Watznaueria barnesiae*, *Micula staurophora*	*Chondrites*, ?*Nereites*, *Phycosiphon*, *Planolites*, *Thalassinoides*, *Zoophycos*	Basin plain/turbiditic deposits
Salgar section	**o**	Penderisco Formation	Mudrocks, sandstones, conglomerates	Pardo-Trujillo et al. (2020)				Deep marine
	p	Not indicated	Not indicated	Rodríguez and	Campanian-Maastrichtian	Ammonite (genus not indicated)		Not indicated

Carmen de Atrato area (Chocó)				Arango (2013)				
Ciudad Bolivar section	**5**	Penderisco Formation	Mudrocks	This work			*Chondrites*, *Planolites*, *Zoophycos*	Basin plain
Ciudad Bolivar area (Antioquia)	**q**	Not indicated	Not indicated	Rodríguez and Arango (2013)	Turonian	Ammonite (genus not indicated)		Not indicated
Ciudad Bolivar section	**r**	Penderisco Formation	Mudrocks, sandstones	Pardo-Trujillo et al. (2020)				Deep marine
Andes section	**6**	Penderisco Formation	Mudrocks, sandstones	This work			*Chondrites*, *Planolites*, *Zoophycos*	Basin plain/turbiditic deposits
Puente Umbría area (Risaralda)	**s**	Sedimentitas de Puente Umbria	Sandstones, bioclastic conglomerates	Moreno-Sánchez et al. (2002)	Campanian-Maastrichtian	*Pachydiscus*		Shallow marine
Apia area (Risaralda)	**t**	Intervalo sedimentario	Mudrcoks, sanstones, conglomerates	Pardo-Trujillo et al. (2002a)	Campanian-Maastrichtian	*Trochoceramus* sp, *Pachydiscus* sp, *Frondicularia mucronata*		Deep marine
Lázaro creek	**u**	Not indicated	Limestones		Albian-Maastrichtian	*Durania* sp.		Not indicated

				Etayo-Serna et al. (1982)	Campanian-Maastrichtian	*Archeolithothamnium*		
Consólida Creek	v	Consólida Formation	Mudrocks	Parra (1984)			*Chondrites, Zoophycos*	Deep marine
Nogales-Monteloro area (Valle del Cuaca)	w	Nogales Formation	Conglomerates, sandstones, calcareous sandstones	Pardo-Trujillo et al. (2002b)	Campanian-Maastrichtian	*Trochoceramus* sp, *Nostoceras* sp	*Chondrites, Zoophycos*	Shallow marine
Calima section	7	Espinal Formation	Sandstones, mudrocks, limestones	CPC (2013); this work	Campanian-Maastrichtian	*Archeoglobigerina sp., Globotruncanella petaloidea, Globuligerina sp., Guembelitria cretacea, Heteroheliz striata, Pseudoguembelina sp., Pseudotextularia elegans, Rugotruncana sp., Rugoglobigerina sp., Rugoglobigerina macrocephala, Ammodiscus minimus, Ataxophragmium rimosum*	*Chondrites, Phycodes, Planolites, Thalassinoides, Zoophycos*	Basin plain/turbiditc deposits
Km 49 Buga-Buenaventura road	x	Espinal Formation	Siltstones and mudrcoks	Etayo-Serna (1985)	Campanian-Maastrichtian	*Trochoceramus*		Not indicated
El Naranjo section	8- y	Cisneros Formation	Phyllite, metasandstones,	Barrero (1979),	not older than Aptian		*Chondrites, Planolites,*	Basin plain

				metalimestones, chert, slates	Etayo-Serna (1986); this work		Foraminifera *Globigerinaid* family, cf *Globutruncanella*	*Thalassinoides, Zoophycos*	

Others correlated units

Region	**Locality**	**Lithostratigraphic Unit**	**Lithology**	**Autor**	**Age**	**Fossils**	**Trace fossils**	**Depositional setting**
CARIBBEAN	Carmen-Zambrano section, Cansona Hills	San Cayetano Inferior Formation	Not indicated	Chenevart (1963)	Campanian-Maastrichtian	*Globotruncana arca*, *Globotruncana* aff. *austinensis*, *Globotruncana plummeri*, *Bulimina* sp., *Güembelina* sp., *Globigerina* sp		Deep marine
	Cacao creek, Bolivar	Cansona Formation	Chert, limestones	Camacho (1967)	Coniacian	*Reesedites subtuberculatus*, *Baculites* sp		Deep marine

	Columbita creek	Chalan Complex, San Cayetano Inferior Formation	Calcareous claystones	Duque-Caro (1967)	Late Cretaceous	*Globotruncana* spp., *Gümbelina* spp., *Globigerina* spp., *Rugoglobigerina* spp.		Deep marine
	Columbita creek	Cansona Formation	Not indicated	Duque-Caro (1972)	Campanian-Maastrichtian	*Marginotruncana concavata*		Deep marine
	Columbita and Chalán creeks	Casona Formation	Siliceous mudrocks, chert, carbonates, sandstones	Guzmán (1994)	Campanian-Maastrichtian	*Heteroelix globulosa*, *Globotruncana* sp., *Bulimina* sp., *Globigerinoides* sp., *Siphogenerinoides cretacea*		Deep marine
	Peñitas and El Salto creeks	Cansona Formation	Siliceous mudrocks, mudstones, shales chert, sandstones	Herrera et al. (2009)	Campanian-Maastrichtian	*Archaeoglobigerina cretacea*, *Globotruncana arca*, *Contusotruncana fornicata*, *Heterohelix reussi*, *Heterohelix globulosa*, *Globotruncanella havanensis*, *Globotruncanella petaloidea*, *Archaeoglobigerina blowi*, *Hastigerinoides subdigitata*, *Heterohelix globulosa*, *Rugoglobigerina*		Shallow marine

						macrocephala, *Globigerinelloides prairiehillensis*		
	Peñitas creek	Cansona Formation	Mudrocks, sandstones, limestones	Dueñas and Gomez (2013)	Campanian-Maastrichtian	*Buttinia andreevi*		Shallow marine
	Columbita and Chalán creeks	Casona Formation	Siliceous mudrocks, chert, carbonates, sandstones	Guzmán (1994)	Campanian-Maastrichtian	*Heteroelix globulosa*, *Globotruncana* sp., *Bulimina* sp., *Globigerinoides* sp., *Siphogenerinoides cretacea*		Not indicated
	Nuevo Paraiso region	San Cayetano Inferior Formation	Sandstones, chert	Dueñas and Duque-Caro (1981)	Campanian-Maastrichtian	*Globotruncana*, *Heterohelix*		Not indicated
PACIFIC	Dabeiba, Antioquia	No indicated	Not indicated	Théry (1980)	Senonian	*Globotruncana* sp.		Not indicated
	Rio verde bridge, W Dabebiba, Antioquia	Rio Verde Formation	Chert, radiolarites, sandstones, basaltic flows, carbonates	Bourgois et al. (1983)	Upper Paleocene-lower Eocene	*Globanomalina* aff. *chapmani*, *Morozovella* gr. *velascoensis*, *Acarinina* sp., *Subbotina* sp., *Morozovella* sp.		Not indicated

Reinterpreted ages

Region	Lithostratigraphic Unit	Autor	Locality	Accepted/Unaccepted name	Reported association	Reported age	Actual accepted name (WORMS database)	Age by species	Autor age (genus-species)	New sample age
Caribbean	Chalán Complex, San Cayetano Inferior Formation	Duque-Caro (1967)	Columbita Creek	Accepted	*Globotruncana* spp.	Late Cretaceous	*Globotruncana* spp.	Turonian-Maastrichtian (89,77-66,04 Ma)	Young et al. (2017)	Campanian-Maastrichtian
				Unaccepted	*Güembelina* spp.		*Planoheterohelix* spp.	Cenomanian-Maastrichtian (100,50-66,04)		
				Accepted	*Globigerina* spp.		*Globigerina* spp.	Not applicable (Eoceno-Presente)		
				Accepted	*Rugoglobigerina* spp.		*Rugoglobigerina* spp.	Campanian-Maastrichtian (83,64-66,04 Ma)		
Pacific	Cisneros Formation	Barrero (1979)	Km 66.6 Buga-road	Accepted	cf. *Globotruncanella*	Not older than Aptian	*Globotruncanella* spp.	Campanian-Masstrichtian (83,64-66,04)	Young et al. (2017)	Campanian-Maastrichtian
				Accepted	*Globigerinidae* family		*Globigerinidae* family	Cenozoic		
	Not indicated	Etayo-Serna et al. (1982)	Río Sucio bridge, Dabeiba, Antioquia	Accepted	*Rugoglobigerina* sp.	Santonian-Maastrichtian	*Rugoglobigerina* sp.	Campanian-Maastrichtian	Young et al. (2017)	Campanian-Maastrichtian

Supplementary file 2. Deformational evidence of the Western Cordillera. A. Tight folds in the Dabeiba area (the red dotted lines show the fold axis and the white dotted lines the fold flanks). B–G. Different types of folds in the Concordia area.

APPENDIX II

Supplementary material for Chapter 5

Supplementary file 1. Location, diagnostic microfossils and age of each stratigraphic section.

Section	Name	Longitude	Latitude	Diagnostic microfossils	Age	Author
1	Guataquí-Nariño	74º49´50.82´´ W	4º25´11.74´´ N	*Micula* spp., *Uniplanarius* spp., *U. sissinghii.*	Middle Campanian-late Maastrichtian	UCaldas-ANH (2021)
2	Talora Creek	74º51´7.22´´ W	4º32´7394´´ N	*E. eximius*, *R. anthophorus*, *R. levis*, *U. sissinghii*, *U. trifidus*, *T. orionatus*, *G. nacatochensis*, *A. acutulum*, *A. gabonensis*, *P. dehaani*, *S. maastrichta*.	Campanian-Maastrichtian	Ucaldas-ANH (2021)
3	Honda-Guaduas	74º40´8.43´´ W	5º11´7.22´´ N	*U. trifidus*, *E. eximius*, *S. plummeri, G. prairiehillensis*, *A. mayaroensis*, *A. blowi*, *P. dehaani*, *B. andreevi*, *S. granularis*, *Z. blanensis*.	Maastrichtian	UCaldas-ANH (2021)
4	Río Negro	74º33´23.44´´ W	5º11´32.77´´ N	*R. anthophorus*, *R. levis*, *Pyramidina prolixa*, *Alisogymnium euclaense*, *Dinogymnium* sp.	Santonian-Maastrichtian	UCaldas-ANH (2021)
5	Tunel Las Lajas	74º34´13.40´´ W	5º21´54.42´´ N	*U. trifidus*, *Bolivina spp.*, *Praebulimina prolixa*, *Neobulimina* sp., *Senegalinium* sp., *B. andreevi*, *E. protofranciscoi.*	Late Campanian-Maastrichtian	Ucaldas-ANH (2021)
6	Providencia Creek	73º49´58.77´´ W	6º12´59.16´´ N	*U. gothicus*, *U. sissinghii*, *P. prolixa*, *G. nacatochensis*, *N. latissima*, *T. proteus*, *P. kickapooensis*, *E. protofranciscoi*, *B. andreevi*	Campanian-Maastrichtian	UCaldas-ANH (2021)
7	Landazuri-Cimitarra	73º49´16.15´´ W	6º13´7.62´´ N	*E. protofranciscoi*, *S. baculatus*, *E. suescae*	Maastrichtian	UCaldas-ANH (2021)
8	La Armera Creek	73º50´43.29´´ W	6º17´2.45´´ N	*E. protofranciscoi*, *S. granularis*, *Spinizocolpites baculatus*, *Zlivisporis blanensis*	Maastrichtian-Paleocene	UCaldas-ANH (2021)
9	PG wells	73º42´0.85´´ W	6º34´36.61´´ N	*Echimonocolpites protofranciscoi*, *Proteacidites dehaani*, *Proxapertites sulcatus.*	Late Campanian-Maastrichtian	Montaño et al. (2016)
10	Agua Blanca Creek	73º18´54.52´´ W	7º7´29.33´´ N	*Ammobaculites colombiana*, *Globotruncana aegyptiaca*, *Pseudoguembelina excolata*, *Spiroplecta americana*, *Rugoglobigerina macrocephala*.	Campanian-late Maastrichtian	Patarroyo et al. (2023)

11	La Buitrera Creek	74º37´0.00´´ W	4º30´0.00´´ N	*Buttinia andreevi*, *Echimonocolpites protofranciscoi*.	Campanian-early Maastrichtian	Garzón et al. (2012)
12	Páramo del Rajadero	Not indicated	Not indicated	*Achomosphaera spp., A. sagena*, *Andalusiella* spp., *Andalusiella gabonense*, *A. mauthei*, *Cyclonephelium* spp., *Dinogymnium euclaensis*, *D. acuminatum*, *D. aff. acuminatum*, *Dinogymnium* spp., *Hystrichodinium pulchrum*, *Hystrichodinium* spp., *Longapertites* sp., *Odontochitina operculata*, *Palaeocystodinium* spp., *Proxapertites humbertoides*, *Psilamonocolpites ciscudae*, *Psilatriletes guaduensis*, *Psilamonocolpites medius*, *Senegalinium bicavatum*, *Senegalinium* spp., *Spiniferites ramosus*, *Spiniferites* spp.	Late Campanian-Maastrichtian	Vergara and Rodríguez (1997)
13	Chinavita-Tibana	Not indicated	Not indicated	*Achomosphaera* spp., *Andalusiella* spp., *A. mauthei*, *A. gabonense*, *Cerodinium granulostriatum*, *Coronifera oceanica*, *Dinogymnium* spp., *D. euclaensis*, *Dinogymmum aff. hererocostatum*, *Hystrichodinium pulchrum*, *Senegalinium* spp., *S. bicavatum*, *Spiniferites ramosus*, *Trithyrodinium* (?) spp.	Campanian	Vergara and Rodríguez (1997)
14	El Crucero	Not indicated	Not indicated	*Ammobaculites* sp., *A. colombianus*, *A. arenatus*, *Haplophragmoides* sp., *H. calcula*, *H. eggeri*, *H. rugosos*, *Saccamina globosa*, *Trochammina* (?) sp.	Campanian	Vergara and Rodríguez (1997)

15	Playonera Creek	Not indicated	Not indicated	*Alisogymnium euclaense*, *Alterbidinium* sp., *Andalusiella mauthei*, *A. polymorpha*, *Araucariacites australis*, *Camarozonosporites "tenuis"*, *Cerodinium granulostriatum*, *Circulodinium distinctum*, *Cyathidites minor*, *C. majaor*, *Dinogymnium* sp., *D. heterocostatum*, *D. acuminatum*, *D. nelsonense*, *D. longicornis*, *D. undulosum*, *D. digitus*, *D. vozzhennikovae*, *Hystrichodinium pulchrum*, *Impaagidinium grandis*, *Mauritiidites franciscoi*, *Odontochitina operculata*, *O. costata*, *Oligosphaeridium complex*, *Operculodinium iluciitioidesi*, *Polykrikos* (?) sp., *Palaeohystrichophora infusoriodes*, *Proxapertites operculatus*, *Retipollenites "afropollensis"*, *Retidiporites magdalenensis*, *Sinidinium sverdrupianum*, *Subtilisphaera* sp., *Senegalinium* sp., *S. bicavatum*, *S. laevigatum*, *Spinizonocolpites baculatus*, *Synncolporites lisamae*, *Tetradites "carolinensis"*, *Trichodinium castanea*, *Trithyrodinium fragile*, *Xenasscus ceratioides.*	Campanian-Maastrichtian	Vergara and Rodríguez (1997)
16	Caño Blanco	Not indicated	Not indicated	*Alisogymnium euclaense*, *Alterbidinium* sp., *Andalusiella mauthei*, *A. polymorpha*, *Araucariacites australis*, *Cerodinium granulostriatum*, *Circulodinium distinctum*, *Cordosphaeridium* sp., *Cyathidites minor*, *Dinogymnium heterocostatum*, *D. undulosum*, *D. nelsonense*, *D. vozzhennikovae*, *D. longicornis*, *D. acuminatum*, *D. aff. nelsonense*, *Impagidinium grandis*, *Leiosphaeridia* sp., *Odontochitina operculata*, *Operculodinium 'luciitioides"*, *Palaeohystrichophora infusorioides*, *Polykrikos* (?) sp., *Subtilisphaera* sp.,	Late Campanian-early Maastrichtian	Vergara and Rodríguez (1997)

				Senegalinium bicavatum, *Trithyrodiniuim fragile.*		
17	Sagú Creek	Not indicated	Not indicated	*Dinogymnium-Cerodinium*, *Paleocystodinium* and *Proteacidites dehaani* biozones	Late Campanian-early Maastrichtian	Carvajal-Torres et al. (2022)
18	San Antonio Creek	73º12´23.77´´ W	4º50´12.84´´ N	*Andalusiella polymorpha polymorpha*, *A. polymorpha aegyptiaea*, *A. gabonensis*, *Cerodinium granulostriatum*, *C. diebellii*, *Dinogymnium digitus*, *D. undulosum*, *D. aeuminatum*, *Eehitriporites trianguliformis*, *Odontoehitina opereulata*, *Palaeohystrichophora infusorioides*, *Paleoeystodinium australinum*, *Proteaeidites dehaani*, *Spinizonocolpites baeulatusy.*	Early Campanian-early Maastrichtian	Guerrero and Sarmiento (1996)

APPENDIX III

Other peer-reviewed publications – JCR (SCI) – indexed journal papers during the doctoral thesis

Vallejo-Hincapié, F., Pardo-Trujillo, A., Barbosa-Espitia, A., Aguirre, D., Celis, S.A., **Giraldo-Villegas, C.A.,** Plata, A., Trejos-Tamayo, R., Salazar-Ríos, A., Flores, J.A., Aubry, M-P., Gallego, F., Delgado, E., Foster, D., 2024. Miocene vanishing of the Central American Seaway between the Panamá Arc and the South American Plate. GSA Bulletin 136 (11 - 12), 4798–4814.

Celis, S.A., García-García, F., Rodríguez-Tovar, F.J., **Giraldo-Villegas, C.A.,** Pardo-Trujillo, A., 2024. Coarse-grained submarine channels: From confined to unconfined flows in the Colombian Caribbean (late Eocene). Sedimentary Geology 459, 106550.

Celis, S.A., Rodríguez-Tovar, F.J., Pardo-Trujillo, A., García-García, F., **Giraldo-Villegas, C.A**., Gallego, F., Plata, A., Trejos-Tamayo, R., Vallejo-Hincapié, F., Cardo, F.J., 2023. Deciphering influencing processes in a tropical delta system (middle-late Eocene? to Early Miocene, Colombian Caribbean): Signals from a well-core integrative sedimentological, ichnological, and micropaleontological analysis. Journal of South American Earth Sciences 127, 104368.

Angulo-Pardo, E., Vallejo-Hincapié, F., Do Monte Guerra, R., Pardo-Trujillo, A., **Giraldo-Villegas, C.A**., García González, J., Hernández Durán, S., Herrera Quijano, S., Plata Torres, A., Trejos-Tamayo, R., 2023. Late Cretaceous calcareous nannofossil assemblages from Colombia: biostratigraphic contributions to northwestern South American Basins. Journal of South American Earth Sciences 127, 104315.

Celis, S.A., Rodríguez-Tovar, F.J., **Giraldo-Villegas, C.A**., Pardo-Trujillo, A., 2021. Evolution of a fluvial-dominated delta during the Oligocene of the Colombian Caribbean: sedimentological and ichnological signatures in well-core. Journal of South American Earth Sciences 111, 103440.

Thesis results were published in the following national and international conferences

Giraldo-Villegas, C.A., Rodríguez-Tovar, F.J., Celis, S.A., Pardo-Trujillo, A., 2024. Variable *Ophiomorpha* ichnofabric: Improving the understanding of mouth bar environments in fan-delta complex depositional settings from the Upper Cretaceous of NW South America. *5th International Congress on Ichnology. Florianopolis, Brazil (Talk)*.

Giraldo-Villegas, C.A., Rodríguez-Tovar, F.J., Pardo-Trujillo, A., Celis, S.A., 2023. Sedimentary evolution of the final stages of an epeiric sea in the NW of South

America: a sedimentological and ichnological approach. *36th International Meeting of Sedimentology. Dubrovnik, Croatia (Poster).*

Giraldo-Villegas, C.A., Rodríguez-Tovar, F.J., Celis, S.A., Pardo-Trujillo, A., 2022. *Ophiomorpha* ichnofabric as indicative of marine input in fan delta deposits: a study case from the Maastrichtian of Colombia. X*XXVII Jornadas de la Sociedad Española de Paleontología. Cuenca, España (Poster).*