THE ROLE OF TECTONISM IN THE DEVELOPMENT OF STRATIGRAPHIC SURFACES IN THE COLOMBIAN LLANOS FORELAND BASIN

by

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ABSTRACT

During the Campanian-Paleogene, a regional basin extended from the Magdalena Valley in the west to the Llanos Basin in the east. Subsequently, the Llanos Basin was separated from the Magdalena Valley and became an independent depocenter from the Oligocene to the present. This study combines the facies analysis from the late Campanian – early Oligocene rock units in the southern Llanos Basin, with a regional chronostratigraphic correlation to provide a better understanding of the stratigraphic response to the tectonic changes. Based on outcrop data from the Sagu creek and cores from three wells in the southern Llanos Basin this study identified four unconformities present at the limits between the Campanian-Maastrichtian, Cretaceous-Paleocene, Paleocene-Eocene, and Eocene-Oligocene. The oldest and youngest developed under subaqueous conditions, whereas the others developed under subaerial conditions. They control the distribution of the Maastrichtian to Eocene facies across the southern Llanos Basin. Indeed, the ±80 m of the Upper Guadalupe and Guaduas formations from the Sagu creek are absent in the sedimentary record of the studied wells. The early-middle Eocene Mirador Formation preserves the coarsest sediment along the area, which is truncated by a subaqueous unconformity and is overlain by shallow marine facies from the earliest Oligocene. Chronostratigraphic correlation with adjacent basins demonstrates the magnitude of these unconformities. The subaqueous unconformities are locally presented across the southern Llanos Basin, while the subaerial unconformities extend across the Colombian territory. Each of the latter indicates a hiatus ±16 My along the Southern Llanos Basin. The variations in magnitude, type, and correlatability of the surfaces unveil how the tectonic reorganization influenced the southern Llanos Basin from the Late Cretaceous to the Oligocene. Compared to other similar basins worldwide, the data reveals a complex depositional

setting, where the type, magnitude, diachroneity, and complexity of the unconformities is the result of the compressional tectonism.

The Magdalena Valley, Eastern Cordillera, and westernmost Llanos Basin comprised the major depocenters of the basin. However, the western flank of the Eastern Cordillera and most of the Llanos Basin were uplifting. A late Campanian first-order maximum regressive surface preserved at the base of the retrograding marine facies of the Upper Lidita, Buscavidas and Umir, Guadalupe, and Palmichal units, is the lower boundary of the retroarc foreland sequence. This surface does not extend across the whole basin. In the uplifting areas, subaerial unconformities truncate the middle Campanian rocks. These surfaces compound the lower first-order boundary and its diachroneity is controlled by the northward migration of the orogen. The Teruel, Hoyon, Bogota, Cacho, Socha, Barco, and Cuervos formations are truncated by a regional first-order subaerial unconformity formed during orogenic unloading that marks the termination of the foreland basin in the Eocene. Therefore, it is the upper boundary of the first-order sequence.

Outcrop and well cores data from the southern Llanos Basin indicate the sedimentary record preserves four second-order sequences, formed during the under- and overfilled stages of the foreland basin. Tectonism controlled their development. The diachroneity of the surfaces and sequences is related to the northward migration of the orogen that influenced the tectonic stages and architecture of the basin. The southern Llanos Basin was at the marginal part of the foreland, where the role of the tectonism resulted in the formation of multiple unconformities. Their formation processes vary regarding the proximity of the shoreline and the tectonic stage. These unconformities reworked the boundaries of the sequences, so their connection towards the depocenter also varies. In the Sagu area, the three lowermost four second-order sequences deposited during the underfilled stage are incomplete and pinch out eastward as subaerial unconformities truncate them. The uppermost sequence was formed during the overfilled stage when fluvial deposition took place across the basin, and the eastward migration of the depocenter renewed the sedimentation along the basin margins. At this time, accommodation was outpaced by sedimentation due to the high sediment supply resulted from the uplifting orogen and forebulge. Albeit, the reduced amalgamation of the channels suggests the creation of accommodation during this stage. Their partial or total absence and the facies changes are the consequence of the basin architecture and tectonism.

PREFACE

This research study is an original work by Juan Sebastian Carvajal Torres and was developed as part of the master research project. The conclusions from this work have led to three research papers that have been submitted to different scientific journals, which compose the body of the following chapters. I was in charge of the fieldwork and the analysis of the well data (well logs and cores); also, I was responsible for the regional collection of data and correlation. Octavian Catuneanu supervised the research work and was involved with the interpretation and technical support throughout the research process and the manuscript composition. The co-authors contributed with manuscript edits for the submitted papers and guide part of the well data analysis. The well data for this study was delivered by the Geological Survey of Colombia (SGC), while the ICP-ECOPETROL collaborated with the development of the fieldwork.

Chapter 1 introduces the study purpose and the generalities of the area of study, as well as the location of the reviewed outcrop and the wells.

Chapter 2 of the thesis was submitted to the Sedimentology Journal by J. S. Carvajal-Torres, O. Catuneanu, M. Reyes, and V. Caballero. This chapter exposes the sedimentary logs created from the fieldwork and the well data, which served to analyze the facies and depositional environments. Moreover, I collected data from several previous studies across the adjacent basins and established the chronostratigraphic correlation between the rock succession from the study area and the regional context. The co-authors contributed with the definition of the depositional model, the facies analysis, and the manuscript edits.

Chapter 3 of the thesis was submitted to the Basin Analysis Research Journal by J. S. Carvajal-Torres, O. Catuneanu, A. Mora, V. Caballero, and M. Reyes; expose the stratigraphic response to the first-order changes and the relationship with the regional tectonic context. Based on previous studies, I produced a series of palinspatically restored paleogeographic maps that contributed to the basin analysis. I identified and interpreted the first-order stratigraphic surfaces in the Campanian-Earliest Oligocene rock succession from the outcrop and the wells. Following the chronostratigraphic correlation, I carried out the same process in the other control points. The co-authors assisted with the identification of the stratigraphic surfaces, the analysis of the basin architecture and evolution, and the manuscript edits.

Chapter 4 of the thesis was submitted to the Journal of South American Geosciences by J.S. Carvajal-Torres, O. Catuneanu, M. Reyes, A. Mora, V. Caballero, and L. Quiroz. This paper consists of the sequence stratigraphic framework of the study area and the correlatable stratigraphic surfaces across the regional context. I interpreted the stratigraphic surfaces from the outcrop and well data and established their correlation and connection towards adjacent basins. In addition, I analyzed the relationship between the tectonic stages of the basin and the development of the interpreted stratigraphic surfaces. The definition of systems tracts and sequences and the examination of the tectonic phases of the basin were supported by the co-authors.

Chapter 5 comprises the summary of the main conclusions of Chapters 2, 3, and 4 as well as the suggestions for future work on this field of study within the Colombian territory.

To my wife, my parents, my godmother, my grandmother, and my brothers.

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Chapter 1: Introduction

The Llanos Basin is one of the most important sedimentary basins along the Colombian territory, covering an area of nearly 200,000 km^2 across the eastern states of Colombia (Arauca, Casanare, and Meta), Fig 1.1. In the west, it is bounded by the Guaicaramo Faults System that separated it from the Eastern Cordillera. The Llanos Basin contains the sedimentary record from the Paleozoic to the Present, but the sedimentary record is not continuous because the tectonic activity created multiple unconformities (Barrero et al. 2007, Reyes-Harker et al. 2015 and Sarmiento 2011). During the Mesozoic and part of the Paleogene, the Llanos Basin was part of a regional basin that extended at least from the Magdalena Valley in the west to the Llanos Basin (Cooper et al. 1995, Dengo & Covey 1993, and Horton et al. 2010). Paleogeographic restorations indicate this basin comprised the current Upper and Middle Magdalena Valley, the Eastern Cordillera and the Llanos Basins (Bayona, 2018, Bayona et al. 2013, Cediel et al. 2011, Martínez & Roncancio 2011, and Sarmiento, 2001). The faulting of pre-existing faults that accelerated the exhumation of the Eastern Cordillera during the Oligocene to Miocene separated the Magdalena Basin and the Llanos Basin into a hinterland and a foreland basin, respectively (Mora et al. 2006, 2010, and Ochoa et al. 2012).

During the Cretaceous to the Paleogene, the interaction of the Farallones, Caribbean, and South America tectonic plates produced changes in the regional setting (Pindell & Erikson 1994, and Pindell & Kennan 2009). The regional basin passed from back-arc to retroarc foreland basin during the end of the Cretaceous (Villagómez & Spikings, 2013). Subsequently, the faulting of pre-existing faults that accelerated the exhumation of the Eastern Cordillera during the Late Paleogene to Early Neogene separated the Magdalena Basin and the Llanos Basin into a hinterland and a foreland basin, respectively (Mora et al. 2006, 2010, and Ochoa et al. 2012). Techniques such as thermochronology, detrital zircon analysis, and U-Pb dating carried out along the Colombian Andes have improved the understanding of the tectonic events (e.g., Moreno et al. 2011, Nie et al. 2012, and Parra et al. 2009). In addition, several studies have aimed to establish the relationship between the sedimentary record and the evolution of the basin (e.g., Bayona et al. 2013, Sarmiento 2001, and Villamil, 1999), and some of them identified stratigraphic surfaces along the Cretaceous rock succession (e.g., Föllmi et al. 1992, Hoedemaeker 2004, Vergara & Rodriguez 1997, and Villamil 1998).

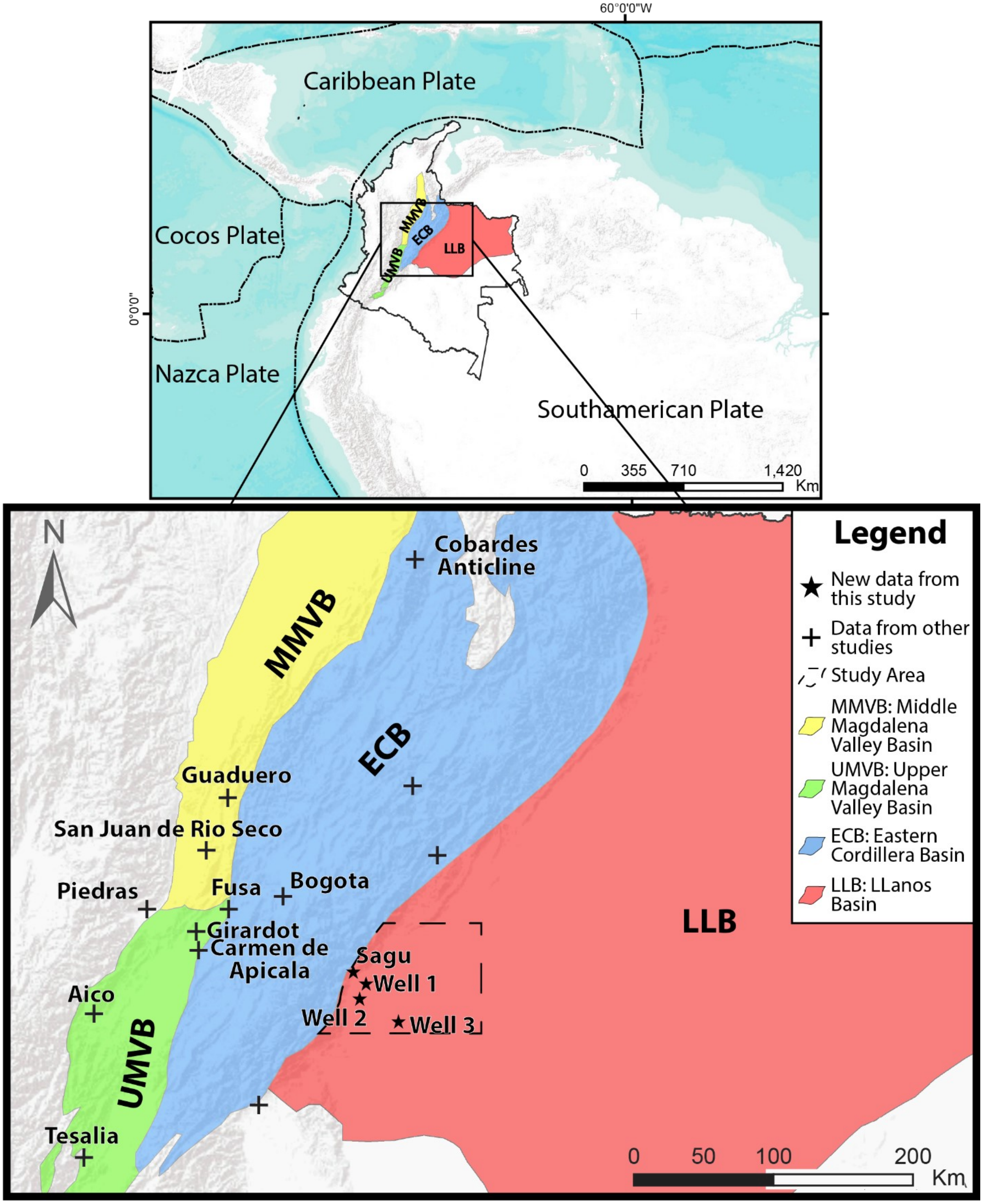

Fig. 1.1. Location of the study area and the data set. The star-points illustrate the new data from this study in the study area from the southern LLB. The cross-points expose the data reviewed from the literature, which was incorporated to define the regional correlation of the study area.

However, the stratigraphic response to the first-order changes is yet to be understood, restricting the definition of a sequence stratigraphic framework. The purpose of this study was to determine the stratigraphic response to the first-order changes within the Late Cretaceous to the Early Oligocene to construct a sequence stratigraphic framework that unveils the relationship between the sedimentary facies and the tectonism throughout the geological evolution of the basin. According to Catuneanu (2004, 2019) and Nemčok et al. (2005), the marginal parts of a foreland basin are prone to preserve unconformities formed during shoreline regressions related to the basin architecture. The latter being controlled by tectonism. Since the southern part of the Llanos Basin was the marginal part of this regional basin, and unconformities have been reported by previous studies (e.g., Guerrero & Sarmiento 1996 and Martínez 2016), we determined this as the study area (Fig 1.1).

The dataset of this study integrates outcrop and well data. The fieldwork was developed in the Sagu creek, located near Villavicencio City, where ±450 m of rock succession was reviewed at a 1:50 scale. Paleocurrent data was measured within different sedimentary structures (e.g., through cross-bedding, wave ripples, and imbricated clasts). Additionally, the ICP-ECOPETROL provided the biostratigraphic analysis and three samples to analyze the heavy minerals and detrital zircon distribution. The well data is composed of different well logs (e.g., gamma-ray and spontaneous potential), detailed well cores photoplates, drilling, and biostratigraphic reports provided by the Exploration and Production Information Service of Geological Survey of Colombia (EPIS - SGC). The interpretation of stratigraphic surfaces and the corresponding nomenclature follows the principles from Catuneanu (2017, 2019b), Catuneanu & Eriksson (2002), and MacEachern et al. (2012). Moreover, to define the relationship between the identified stratigraphic surfaces in the study area and the regional context, 13 stratigraphic sections from previous studies were compiled and analyzed using the previously mentioned methodology. They were strategically selected following the palinspastic restorations from Bayona (2018), which were key for the paleogeographic maps created to examine basin architecture through time. Based on multiple chronostratigraphic correlations built according to Qayyum et al. (2017) and Wheeler (1959), a regional sequence stratigraphic framework from the Campanian to the Earliest Oligocene was established.

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Chapter 2: Facies analysis and regional correlation of the Late Campanian to Early Oligocene strata in the Southern Llanos Basin, Colombia

ABSTRACT

During the Campanian-Paleogene, a regional basin extended from the Magdalena Valley in the west to the Llanos Basin in the east. Subsequently, the Llanos Basin was separated from the Magdalena Valley and became an independent depocenter from the Oligocene to the present. This study combines the facies analysis from the late Campanian – early Oligocene rock units in the southern Llanos Basin, with a regional chronostratigraphic correlation to provide a better understanding of the stratigraphic response to the tectonic changes. Based on outcrop data from the Sagu creek and cores from three wells in the southern Llanos Basin this study identified four unconformities present at the limits between the Campanian-Maastrichtian, Cretaceous-Paleocene, Paleocene-Eocene, and Eocene-Oligocene. The oldest and youngest developed under subaqueous conditions, whereas the others developed under subaerial conditions. They control the distribution of the Maastrichtian to Eocene facies across the southern Llanos Basin. Indeed, the ±80 m of the Upper Guadalupe and Guaduas formations from the Sagu creek are absent in the sedimentary record of the studied wells. The early-middle Eocene Mirador Formation preserves the coarsest sediment along the area, which is truncated by a subaqueous unconformity and is overlain by shallow marine facies from the earliest Oligocene. Chronostratigraphic correlation with adjacent basins demonstrates the magnitude of these unconformities. The subaqueous unconformities are locally presented across the southern Llanos Basin, while the subaerial unconformities extend across the Colombian territory. Each of the latter indicates a hiatus ±16 My along the Southern Llanos Basin. The variations in magnitude, type, and correlatability of the surfaces reveal how the tectonic reorganization influenced the southern Llanos Basin from the Late Cretaceous to the Oligocene. Compared to other similar basins worldwide, the data unveil a complex depositional setting, where the type, magnitude, diachroneity, and complexity of the unconformities is the result of the compressional tectonism.

Keywords: Campanian, Paleocene, facies, progradation, retrogradation, unconformities.

2.1. Introduction

The major sedimentary basins of Colombia were part of a regional multiphase basin that started in the Jurassic and separated during the Paleogene (Cediel et al. 2011, Colleta et al. 1990, and Cooper et al., 1995). The Llanos Basin (LLB) was the marginal part of this regional basin. Despite some sediments deposited in shelf conditions, most of the sediments preserved from the Cretaceous to the Paleogene are related to shallow-marine and continental conditions (Bayona 2018, Caballero et al. 2020 and Reyes-Harker et al. 2015). Indeed, the rocks preserved from this interval depict a shallowing upwards succession with periodic minor transgressions and are separated by an unconformity formed at the end of the Cretaceous (Guerrero & Sarmiento 1996 and Reyes-Harker et al. 2015).

According to Barrero et al. (2007), the rocks dated from that interval are the main reservoirs along the LLB. In the SLLB (SLLB), in oilfields such as Castilla or Chichimene, the operational unit T2, containing part of the Guadalupe Gp, Barco Fm, and Mirador Fm (A. Martínez, 2016), are the major producers of oil in the southern part of the LLB, Fig. 2.1. González & Gómez-Villalba (2001) reported oil shows along the Cretaceous rocks from the southern foothills, near Villavicencio, indicating the generation and migration of hydrocarbons took place before the deformation occurred that uplifted the Eastern Cordillera Basin (ECB). Based on Horton et al. (2010), Mora et al. (2006, 2010), and Parra et al. (2009), the ECB started its exhumation unevenly from the Middle to Late Maastrichtian. According to these authors, the cooling rates indicate faulting during the Oligocene-Miocene time, when the ongoing compression folded and faulted the rocks from the ECB. Therefore, these oil shows indicate that hydrocarbon was trapped before the tectonic inversion of the ECB.

Paleogeographic maps from Bayona (2018), Bayona et al. (2013), Caballero et al. (2020), Reyes-Harker et al. 2015 and Sarmiento (2001) have revealed that the regional basin extended from the Upper and Middle Magdalena Valley Basins (UMVB and MMVB) to the LLB, connected throughout the ECB. Their results define the facies distribution extending along the territory from the Late Cretaceous to the Neogene. Accordingly, downstream controls dominated along the southern part of the LLB as it was under shallow-marine deposition during the Campanian and part of the Maastrichtian. Thus, the sedimentation was affected by the shoreline trajectories. However, during the Paleocene to middle Eocene, there was no influence of the shoreline as the southern part of the LLB was under fluvial conditions (upstream controls). Subsequently, marine conditions took place during the Oligocene and part of the Neogene in the LLB.

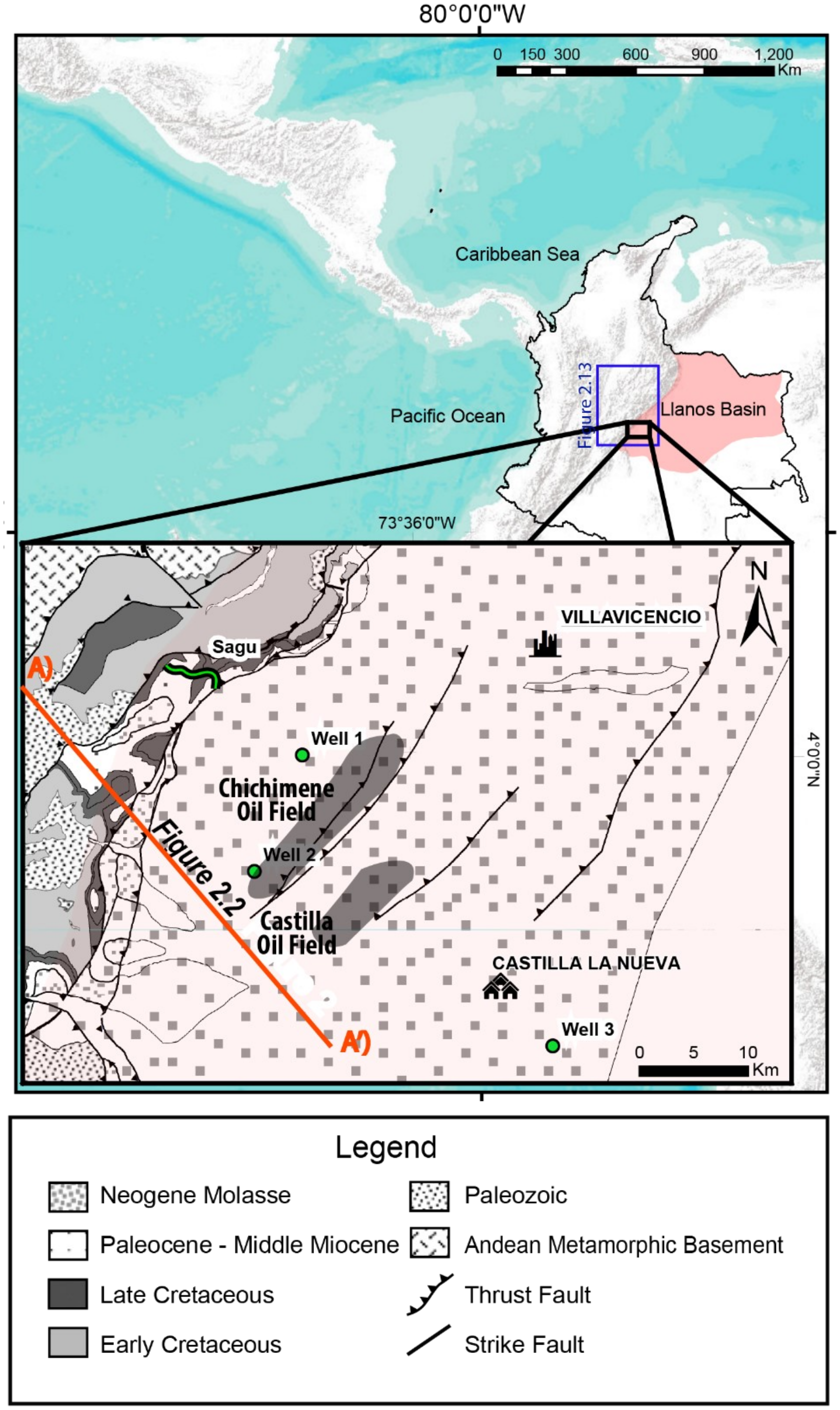


Fig. 2.1. Location map of the study area.

Local studies (e.g., Guerrero & Sarmiento 1996 and Martínez 2016) expose the facies distribution in the local SLLB, showing distinct unconformities preserved within the sedimentary record. Despite the accuracy of their results, the type and the magnitude of the unconformities are yet to be understood. The major hypothesis is that compressional tectonism influenced the formation of these unconformities across the SLLB. However, that remains unclear. Therefore, following the principles from Catuneanu (2018) and DeCelles & Giles (1997) this study pretended to determine how the unconformities and facies respond to the compressional tectonic activity that formed the Late Cretaceous to Paleogene foreland basin. Our analysis of the strata above and below of the unconformities in the Sagu creek and the area of the wells provide new insights about the generation, type, and magnitude of these stratigraphic surfaces. Hence, using regional chronostratigraphic correlation across the adjacent basins (UMVB, MMVB, and ECB) we evaluated and determined which factors controlled the sedimentation. The facies analysis from part of the Late Cretaceous to Paleogene in four localities from the SLLB (Fig. 2.1), indicates the conditions (subaerial or subaqueous) that influenced the formation of these unconformities and the effect caused by the tectonic activity. The results are compared with analog cases worldwide.

2.2. Geological framework

The Llanos Basin, located in the easternmost part of the Colombian territory, Fig. 2.1, comprises more than 200000 km² filled with sediments from the Paleozoic to the Quaternary (Gomez Tapias & Mateus-Zabala, 2019). At the present time, the basin receives the molasse derived from the unroofing of the ECB (Amorocho et al., 2011). The LLB is westward limited by the deformation front of the Eastern Cordillera. In the south, the Mirador, Villavicencio, and Tesalia-Servitá Faults, which are high angle and thick skin faults, represent the westward boundary of the basin, Fig. 2.2, (Bayona et al. 2008, Mora et al. 2006, and Mora et al., 2008). The structural style changes northward, passing from thick-skin faults systems (Servita Fault System) to detached thin-skin faults systems (Guaicaramo Fault System), (Jimenez et al. 2013 and Parra et al., 2010a). There a lower erosion rate is registered because the southern complex acted as an orographic barrier trapping all the moisture coming from the south (Mora et al. 2008). Despite the structural style variation, the shortening is around 18-25 Km from south to north (Jimenez et al., 2013).

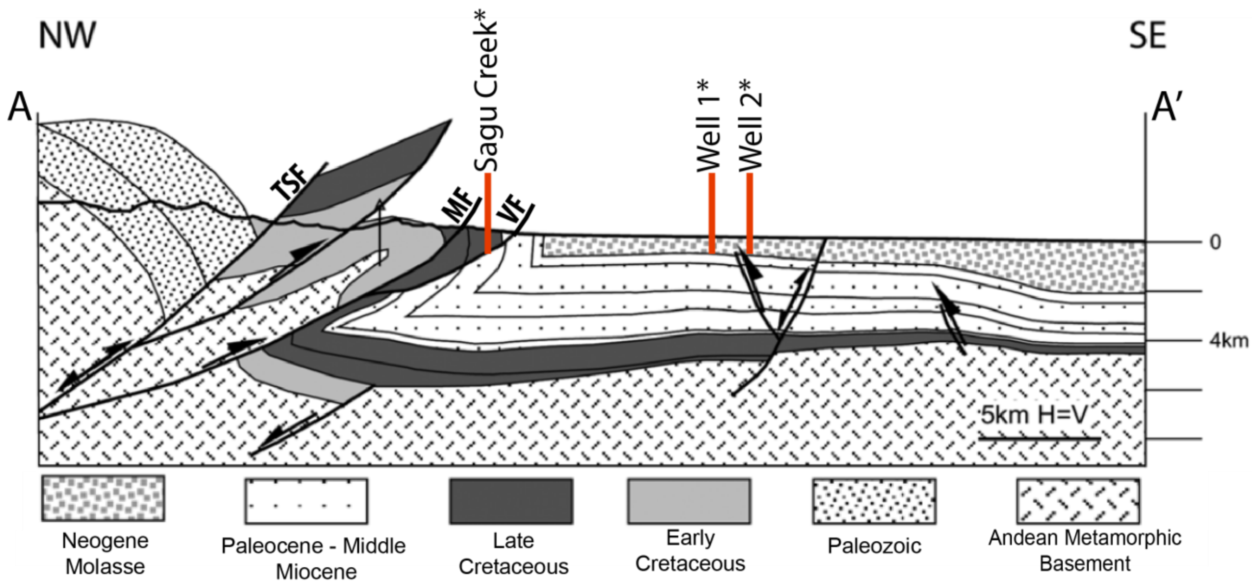


Fig. 2.2. Cross section A-A' showing the structural style of the study area. The Tesalia-Servita (TF), Mirador (MF) and Villavicencio (VF) faults are the main structures in the area, where the deformation is thick-skinned. See location in Figure 2.1. Modified from Jimenez et al. (2013). The red lines indicate the projected estimated position of the Sagu Creek, well 1, and 2. The position of the well 3 is further east.

Several rock units from Pre-Devonian (Basement) to Pleistocene (Sedimentary cover) are preserved across the Llanos Basin. Some regional studies like Bayona et al. (2013), Cooper et al. (1995), Dengo & Covey (1993), and Villamil (1999) report that the basin was part of a back-arc basin until the Late Cretaceous, whereas the Latest Cretaceous and the Paleocene-Eocene deposits were deposited in a foreland basin. According to several authors (e.g., Horton et al., 2010a&b and Moreno et al., 2011), the rock successions are not simply sedimentologically correlatable due to the complex interplay of the tectonism and eustasy. According to previous studies, unconformities with different magnitudes are preserved along the Colombian territory (Gómez et al. 2005a&b and Parra et al., 2010b). Likewise, different rocks sourced the depocenters at the different geological stages (Bayona et al. 2007, Caballero et al. 2010, Horton et al. 2010(a&b), Nie et al. 2010, and Villamil 1999).

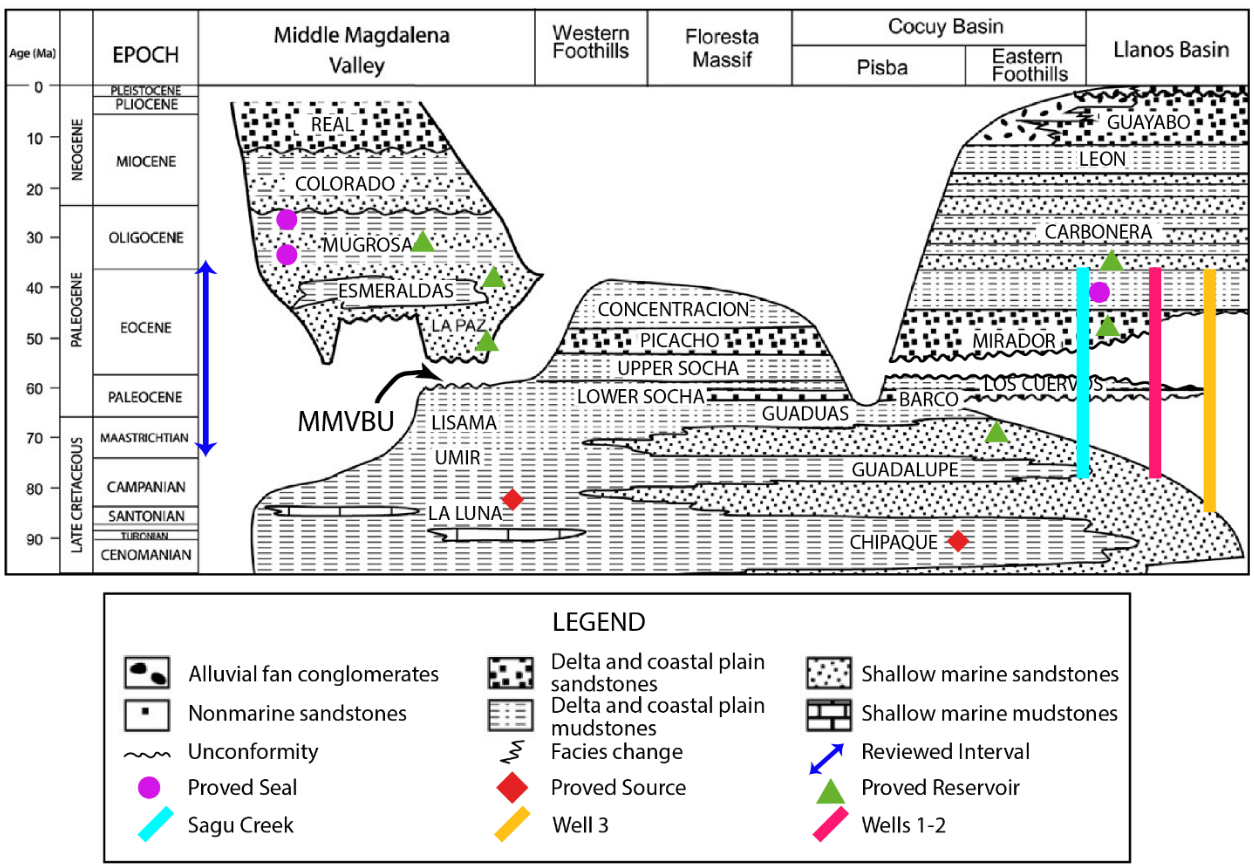


Fig. 2.3. Chronostratigraphic chart from the Middle Magdalena Valley Basin to the Llanos Basin, showing the basin-fill patterns from the Late Cretaceous to the Neogene. Modified from Cooper et al. (1995), Mora et al. (2010a), Mora et al. (2006), Parra et al. (2009ab) and Ramirez-Arias et al. (2012)

A generalized chronostratigraphic chart from the Middle Magdalena Valley to Llanos Basin is summarized in Figure 2.3. The Paleocene rocks have been targeted as the main reservoirs for the MMVB and the LLB (ANH 2012, Barrero et al. 2007, Gutiérrez 2001, Illich 1983, Morales 1958, Naranjo et al. 2017 and Ramón & Cross 1997). Meanwhile, the Cretaceous has been widely recognized as the main source rock of the oil allocated in the major oil fields of these basins (ANH 2012, Barrero et al. 2007, Ramón & Dzou 1999, Rangel et al. 2017 and Zumberge 1984). Some unconformities registered in the Magdalena Valley basin also differ in type and magnitude. The Cretaceous sequence is capped by a diachronous unconformity developed by the flexure of the lithosphere during the Late Cretaceous to Paleocene (Gómez et al, 2005a; Parra et al, 2010b).

According to Barrero et al. (2007), the exploited oil traps in the Llanos Basin are mostly structures like anticlines and faults, and the Castilla-Chichimene fields, are an example of this premise. At the eastern side of the basin, the set of antithetic normal faults are affecting the whole sequence, and some basement highs (e.g., the Melon high) controlled the local basin geometry and deposition at different times (Delgado, Mora, & Reyes-Harker, 2012; ICP - Ecopetrol, 2015). Moreover, the existence of hydrodynamic traps has also been discussed along the LLB (Mora et al., 2019). Nonetheless, the evaluation and assessment of stratigraphic traps are yet to be understood. Their existence can be related to the presence of the unconformities presented in this study.

2.3. Methodology

Outcrop data were obtained from the Sagu creek, Fig. 2.1, where exposed rock allowed detailed sedimentological logging to take place. Additionally, well cores from three wells along the Southern Llanos Basin (SLLB) were studied to build their stratigraphic sections. Biostratigraphic and paleontological analysis from previous studies (e.g., ECOPETROL, 2012; and Vergara & Rodriguez, 1997) served to determine the ages of the rock units. Indeed, the reported presence of *Paleocystodinium* and *Proteacidites dehaani* contributed to the determination of the Maastrichtian rocks in the Sagu Creek. The lithostratigraphic nomenclature was established following their equivalences in the area previously reported by other authors (e.g., González & Gómez-Villalba 2001; Martínez 2016 and Vergara et al., 1997). The analysis of the lithology, texture, bed boundaries, sedimentary structures, authigenic minerals, bedding geometry, and ichnofacies contributed to the interpretation of the hydrodynamic processes that governed their deposition. The sedimentary logs from each location are presented in Fig. 2.6 (Sagu), Fig. 2.8 (Well 1), Fig. 2.10 (Well 2), and Fig. 2.12 (Well 3).

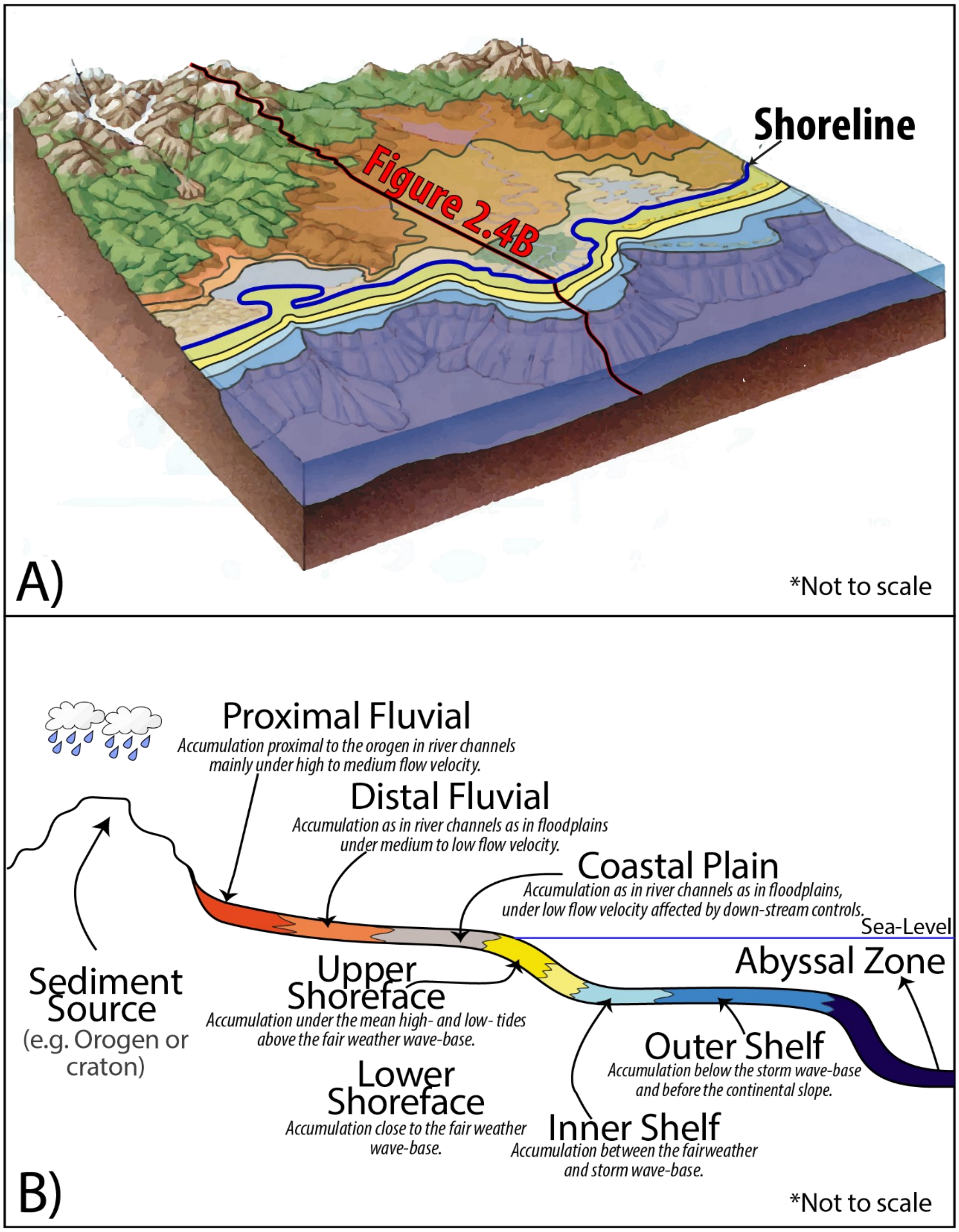


Fig. 2.4. A) depositional model built according to Boggs (2006), Jones & Jones (2012) and Nichols (2009). B) Generalized clinoform from continental to marine environments.

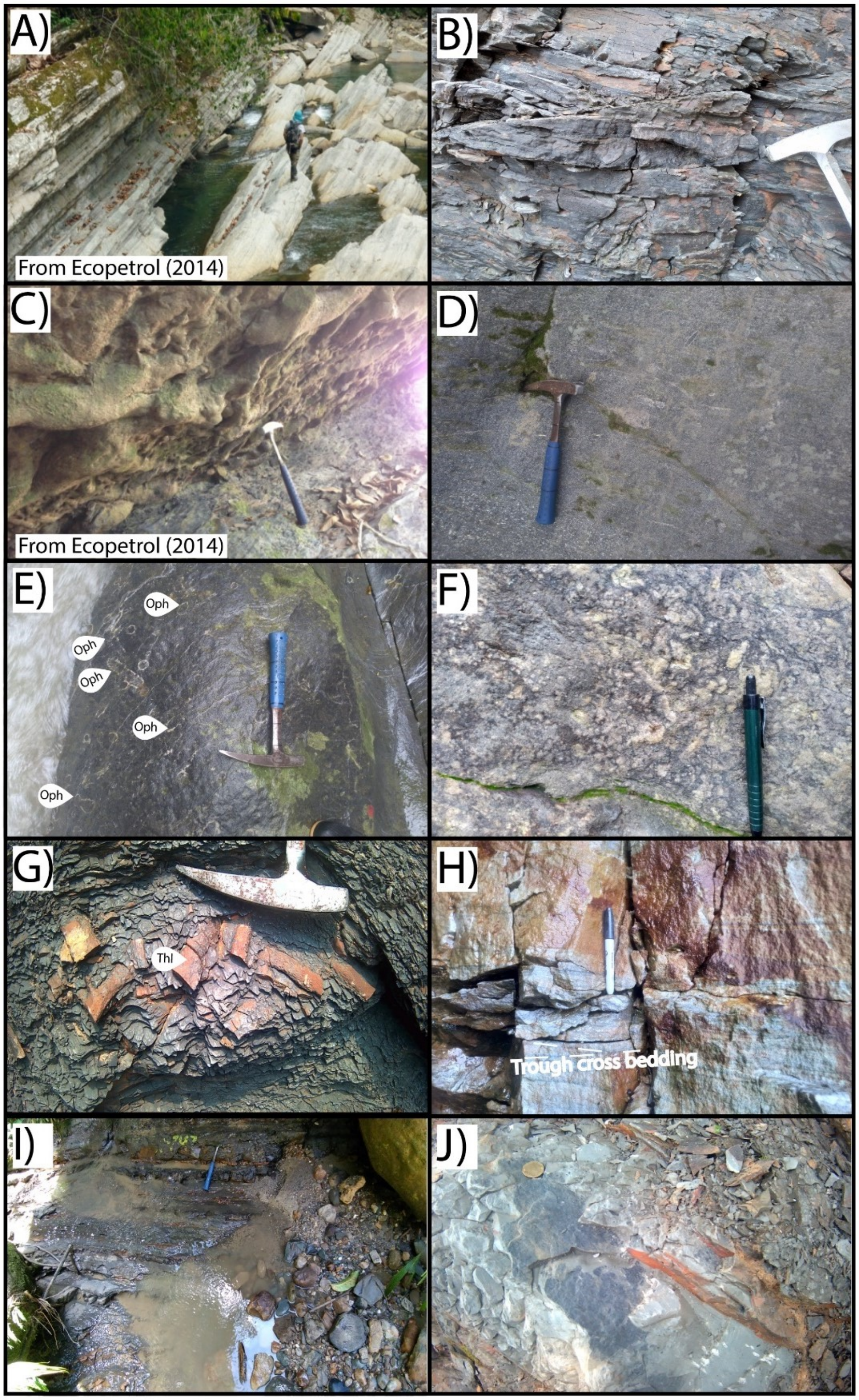
Lithofacies were defined following the standardized methodology from Farrell et al. (2012), and the subsequent interpretation of depositional environments was developed based on Boggs (2006), Buatois & Mángano (2011), Glenn & Filippelli (2007), Nichols (2009), and Odin & Matter (1981). However, to simplify the environments, a conceptual depositional model that indicates the relation of the interpreted depositional environment with the position of the shoreline and the influence of the orogen was defined, Fig. 2.4A and 2.4B. This model includes: i) Proximal fluvial: where accumulation occurs in the proximity of the orogen, and the sediment is deposited within the channels mainly because the velocity of the flow is high to medium, e.g., braided rivers; ii) Distal fluvial: accumulation away of the orogen in the marginal part of the coastal plain, where the sediment is accumulated along the channel and the floodplains due to the rise in the water level floods the river terraces and the velocity of the flow is to low flow velocities, e.g., meandering rivers; iii) Coastal plain: deposition takes place under low-velocity flow and is affected by the down-stream controls, e.g., delta plain, tidal flats or lagoons; iv) Upper shoreface: deposition controlled by the daily action of the tides and waves, accumulation occurs above the fair weather wave-base, which includes the sandy barriers; v) Lower shoreface: the accumulation takes place near the fair-weather wave-base; vi) Inner shelf: where the accumulation is controlled by the storm wave-base; vii) Outer shelf, sediment is accumulated below the storm wave-base, it includes the reefs area; and viii) Abyssal zone, where sediment is accumulated in front of the continental slope.

The depositional model illustrated in Fig 2.4 is simplistic and only shows the relationship of a single clinoform with a single source rock. The study case is more complicated as multiple highs (e.g., paleo Cordillera Central, Guiana Craton, and other paleohighs) acted as sediment source at different times from the Campanian to the Oligocene (Bayona et al., 2020; Horton, Parra, et al., 2010; Lamus, Bayona, Cardona, & Mora, 2013; C. J. Moreno et al., 2011). For that reason, this depositional model must be applied regarding the position of the sediment source. As an example, Figure 2.15 illustrates the estimated location of idealized *clinoforms* at different stages of the basin (Late Campanian, early Paleocene, and earliest Oligocene). The connection from the shoreline to the sediment source remains similar regardless of its position. We identified the estimated sediment source following previous studies (e.g., Bayona, 2018; Bayona et al., 2013; Horton et al., 2015; Horton et al., 2010). For the Sagu Creek and the wells, this study used the paleocurrents from the Sagu Creek to determine that the main sediment source from the late

Cretaceous to the late Eocene was in the east. Presumably, the Guiana Craton and local highs (e.g., Macarena or Melon highs) provided sediment to those localities.

The type of unconformities was defined using the methodology from Catuneanu (2017, 2019) and Catuneanu et al. (2011). This study recognized two types of unconformities within the sedimentary record. The first is the subaqueous regressive surface of marine erosion (RSME), defined by the diagnostic prograding lower to upper shoreface succession overlaying shelf deposits separated by an irregular contact. As an example, the middle to late Campanian facies of the Sagu Creek, interval 120 to 150 m in Fig 2.6. The second type of unconformity is the subaerial unconformity (SU), defined by their diagnostic overlaying fluvial facies. For instance, the Cretaceous-Paleocene contact in the Sagu Creek and the wells, Figs 2.6, 2.8, 2.10, and 2.12. Based on the sedimentary logs, facies analysis, and depositional environment interpretations from the study area and data from several authors from the UMVB, MMVB, and ECB, a chronostratigraphic chart was built to indicate the rock unit equivalence and the generalized depositional environment determined for the rock units. Consequently, following the correlation of the unconformities, their magnitude and extension were established.

Once the depositional environments were independently established using the facies analysis, we correlated the chronostratigraphic units from the Sagu and wells with the adjacent areas. We followed the principles from Qayyum et al. (2015) and Wheeler (1959). The isochrones were firstly correlated accordingly to the biozones and reported age from previous studies. Subsequently, the unconformities were correlated. Their time gap was constrained based on the biostratigraphic gaps and numerical methods from Bayona et al. (2013), Caballero et al. (2015), Caballero et al. (2020), Contreras et al. (2010), De La Parra (2009), Gómez et al. (2003), Jaramillo (1999), Jaramillo et al. (2011), Vergara & Rodriguez (1997), and Yepes (2001a). Although their data is highly effective and relative age changes were identified, those lacunas are yet to be further constrained. Lastly, the correlation of the chronostratigraphic units took place based on the facies association and the depositional environment defined. In cases where the facies association and depositional environment laterally changed, we interpreted the change following the depositional model from Fig. 2.4.



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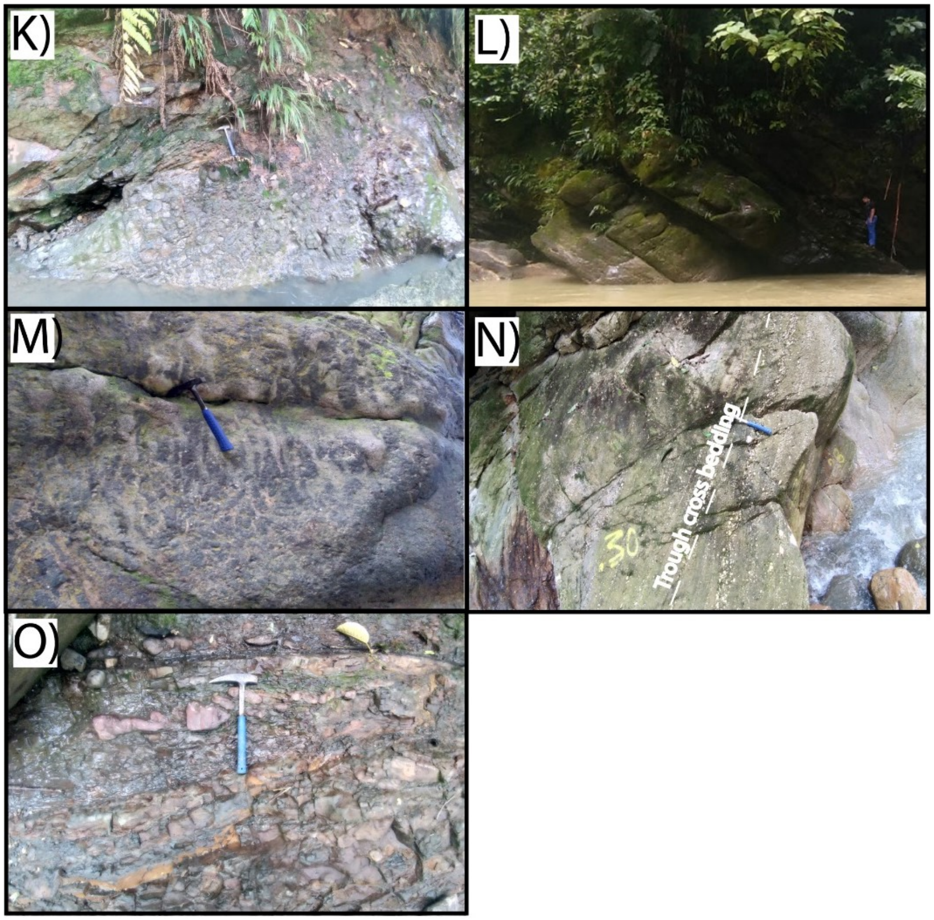
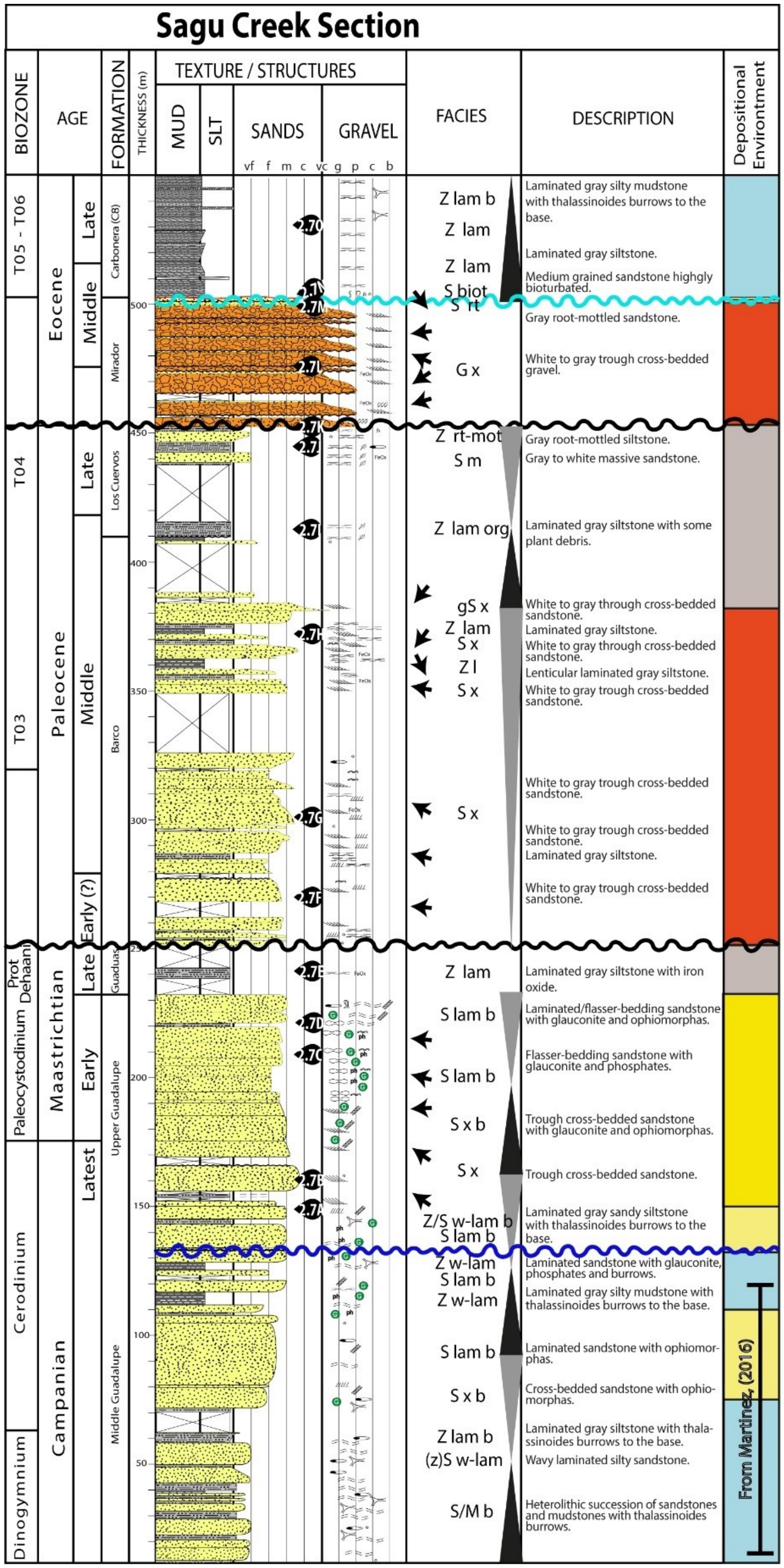


Fig. 2.5. Late Campanian to Eocene Facies of the Southern Llanos Basin Photoplate: A) S/m b heterolithic sandstones and mudstones with horizontal burrows (thalassinoides); B) S w-lam wavy laminated silty fine grained sandstones; C) Wavy laminated siltstones with horizontal burrows (thalassinoides); D) S lam b laminated fine to coarse grained sandstones with vertical burrows (ophiomorphas); E) S x b Cross-bedded medium grained sandstone with vertical burrows (ophiomorphas); F) S biot bioturbated medium grained sandstones; G) Z/S w lam b wavy laminated heterolithic siltstones and sandstone with horizontal burrows (thalassinoides); H) S x Trough cross-bedded medium to coarse grained sandstone; I) Z lam laminated gray siltstone with iron oxides; J) Z lam org Laminated gray siltstone with plant debris; K) Z rt-mot Gray siltstone with root traces and iron oxides; L) S m massive fine to medium grained sandstone; M) S rt fine to medium grained sandstone with root traces; N) G x cross-bedded gravel; and O) Z l lenticular bedded gray to reddish siltstone.

2.4. Facies of the Southern Llanos Basin

2.4.1. Outcrop and Well cores description

The exposed rock section observed is along the Sagu creek, located in the southern part of the LLB, ±25 km to the southwest of Villavicencio city, Fig. 1. This ±450 m section was reviewed from southeast to northwest (bottom to top), and the age of the rock units from the outcrops was established based on the reports from Caballero et al. (2020), ICP - Ecopetrol, (2014), Martínez (2016) and Vergara & Rodriguez (1997). Likewise, the biozones were established according to Contreras et al. (2010), De La Parra (2009), Jaramillo (1999), Jaramillo et al. (2011), Muller et al (1987), and Yepes (2001). The Late Cretaceous to late Eocene section from this creek contains siliciclastic units (sandstones, conglomerates, mudstones and siltstones beds) which based on previous studies such as González & Gómez-Villalba (2001), Martínez (2016) and Vergara & Rodriguez (1997), correspond to the Guadalupe (middle and upper member), Barco, Los Cuervos, Mirador and Carbonera (C8 operational unit) formations. Characteristics such as cross-bedding, wavy lamination, flaser, and horizontal bedding are identified throughout the sedimentary record. A general pattern of shallowing upwards is recognized, and the variations preserved in the rocks indicate minor transgressions or regressions (e.g., the presence and absence of glauconite and phosphates). Ichnofacies are recognized along the bottom and top of the section, mainly *skolithos* and *Cruziana* ichnofacies. The unconformities were recognized due to changes in the facies and also to the presence of paleosols, roots, and mots preserved in some parts of the section. The generalized section from the outcrop is illustrated in Fig. 2.6.



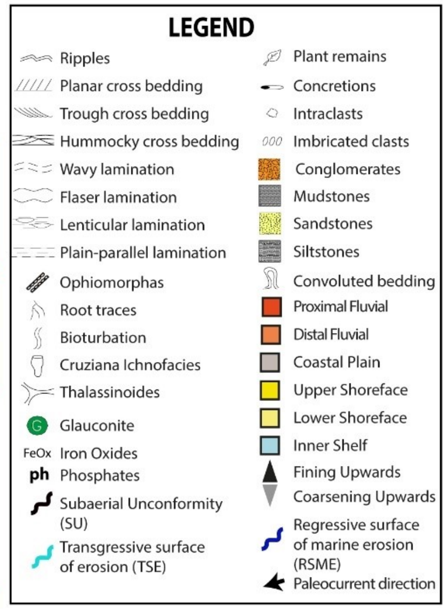
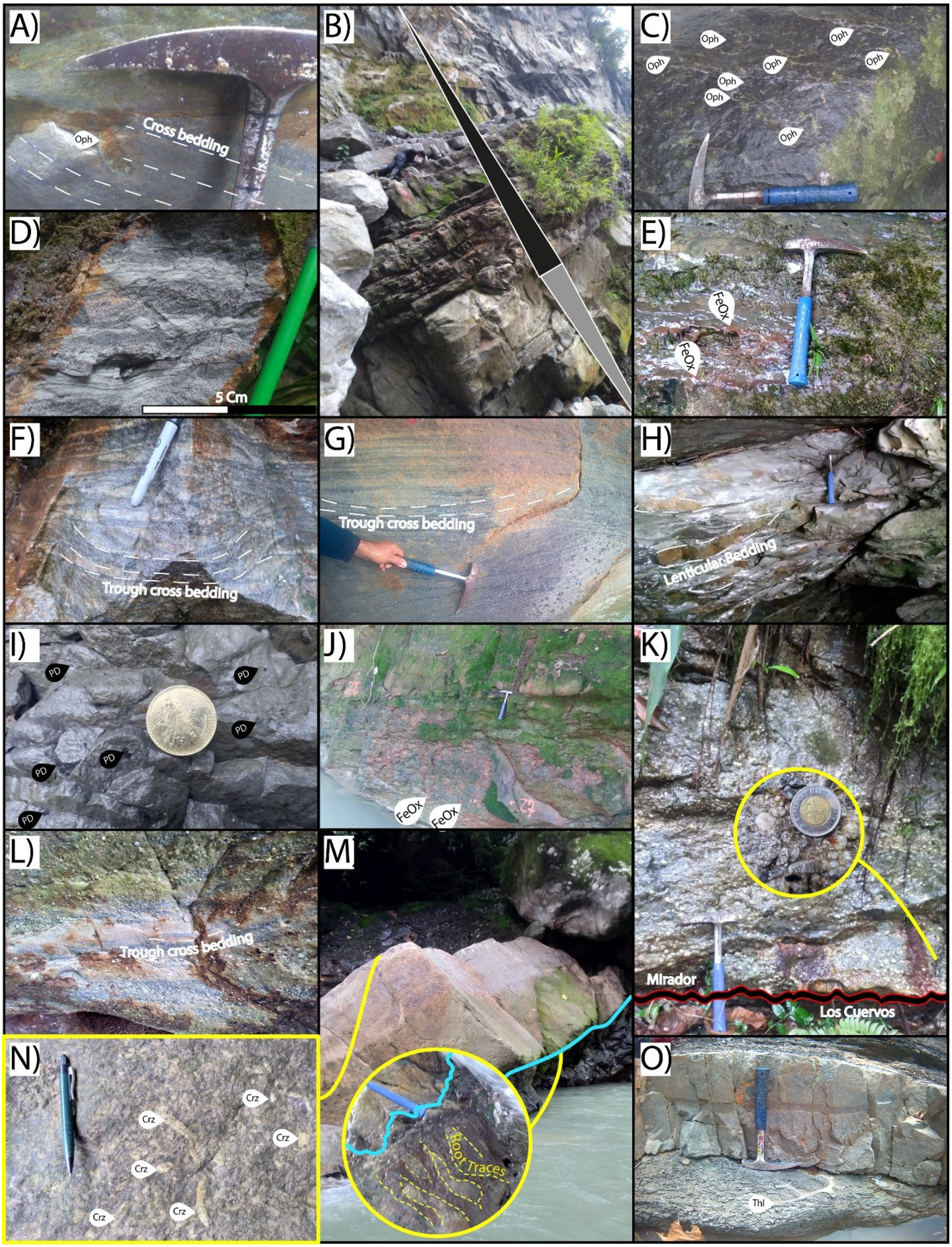


Fig.2.6. Stratigraphic section from the Sagu creek. The biozones were constrained based on Jaramillo (2011) and Vergara & Rodriguez (1997).



A)
Oph
Cross bedding
B)
C)
Oph
D)
5 Cm
E)
FeOx
F)
Trough cross bedding
G)
Trough cross bedding
H)
Lenticular Bedding
I)
PD
J)
FeOx
K)
Mirador
Los Cuervos
L)
Trough cross bedding
M)
Root Traces
N)
Crz
O)
Thl

Fig. 2.7. Photoplate of the Sagu outcrop. A) Cross-bedded medium-grained sandstones with Ophiomorphas, B) Contact between the prograding and retrograding beds succession from the Upper Guadalupe, C) Cross-bedded medium to coarse-grained sandstones with Ophiomorphas, D) Medium to fine-grained sandstones with wavy and flaser lamination, E) Laminated gray siltstones with iron oxides, F) Trough cross-bedded medium to coarse-grained sandstones, G) Trough cross-bedded coarse-grained sandstones, H) Lenticular laminated gray siltstones, I) Laminated gray siltstones with some plant debris, J) Gray reddish mottled siltstones, K) Unconformity contact between the gray root-mottled siltstones from Los Cuervos and the conglomerates from the Mirador formations, L) Trough cross-bedded gravel, M) Contact between the Gray root-mottled sandstones and the bioturbated medium grained sandstones overlaying the Mirador formation, N) Medium-grained sandstones with Cruziana burrows, and O) Laminated gray silty mudstones with Thalassinoides.

Along the SLLB, information and data from three different wells, provided by the Geological Survey of Colombia, were used to construct the sedimentary log from each one of them. The wells 1 and 2 are located near the Chichimene oil field, Fig. 2.1. The well 3 is ±10 km southeast of the town of Castilla La Nueva. Similarly, to the outcrop in the Sagu creek, the sedimentary record from the wells comprises siliciclastic sediments. Likewise, *skolithos* ichnofacies are recognized in the lower- and uppermost part of the reviewed sections, and the general trend of the sediments is shallowing upwards. According to the information and reports (e.g., ECOPETROL, 2012) provided by the Geological Survey of Colombia (SGC), the ages from these deposits range from the Campanian to the early Oligocene. The dominant sedimentary structures are the cross-bedding and some paleosols are also preserved. Figures. 2.8, 2.10, and 2.12 show the sedimentary log from well 1, well 2, and well 3, respectively.

The reviewed section from the well 1 comprises rocks from the Campanian to the Eocene, Fig 2.8. Following the biozones from Caballero et al. (2020), the interval from 9400’ to 9370’ corresponds to the *Dinogymnium* biozone, while the interval from 9220’ to 9160’ represents the biozone *T03b F. Perforatus*. Therefore, these rocks are from the Campanian and middle-late Paleocene, respectively. Lithologically, the Campanian rocks are cross-bedded medium-grained sandstones with some ichnofacies, Fig 2.8, and 2.9A. This unit may be equivalent to the middle member from the Guadalupe group. While the preserved Paleocene rock succession is mainly composed of cross-bedded very coarse-grained often conglomeratic sandstones with root traces and pyrite, and cross-bedded well-sorted conglomerates, Fig 2.9B, 2.9C, and 2.9D. This unit can be correlated to the Barco formation in Sagu Creek. The contact with the overlaying matrix sandy supported pebbly conglomerates at ±9160’ was defined as the Paleocene-Eocene contact, and this unit matches with the Mirador formation from the Sagu Creek, Fig 2.9E. At ±9090 approximately, cross-bedded medium-grained sandstones with ophiomorphas are recognized, Fig 2.9F, depicting an abrupt change in the depositional environment.

In well 2, the rock succession is lithologically similar. At the bottom, the Campanian (*Dinogymnium* biozone) is composed of cross-bedded medium-grained sandstones with iron oxides, Fig 2.10, and it is correlatable with the Middle Guadalupe. The Campanian-Paleocene contact is placed at ±8100’. The biozone *T03bF. Perforatus,* from 7990’ to ±7940, indicate the presence of the middle to late Paleocene Barco Fm, which is composed of cross-bedded medium

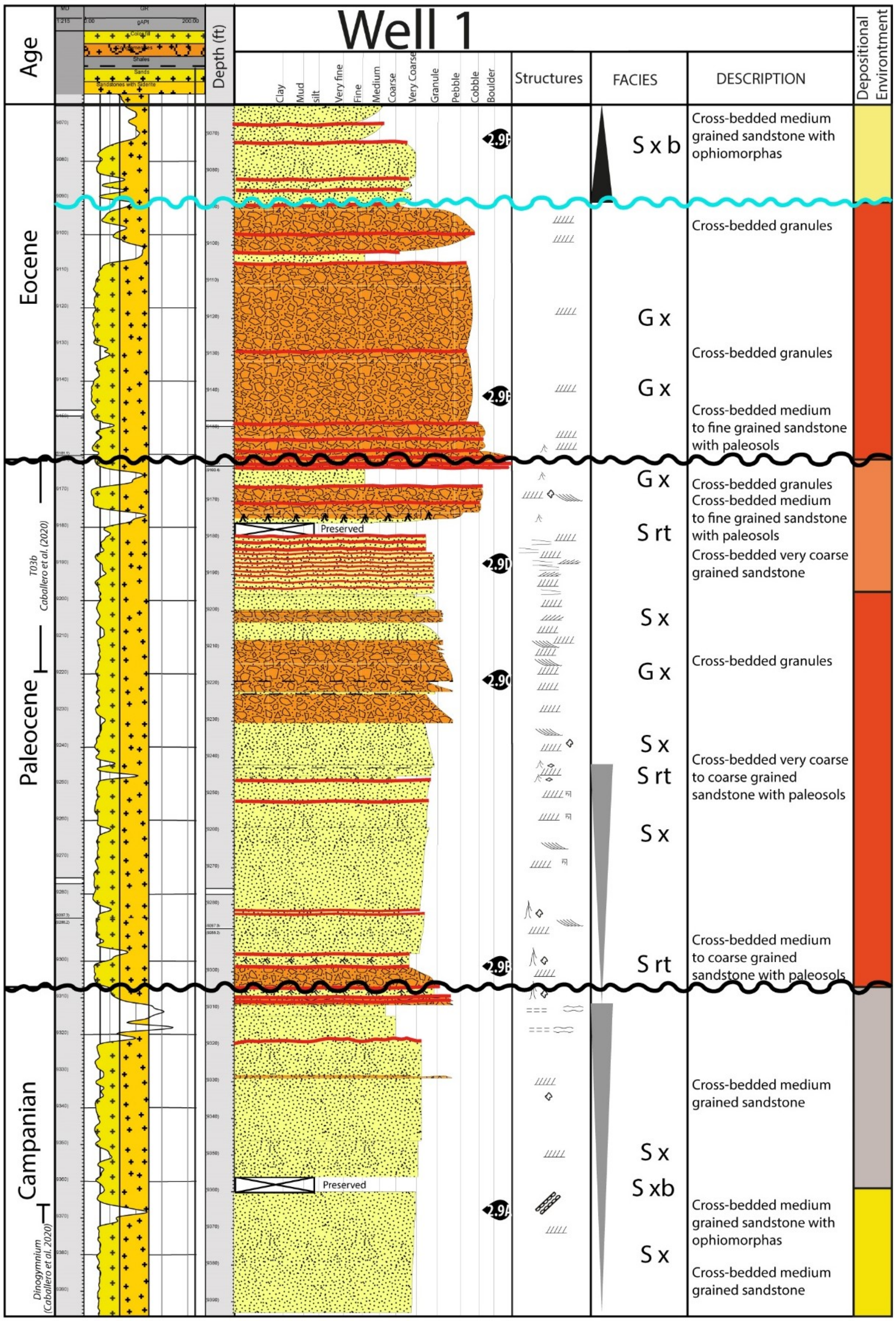


Fig. 2.8. Stratigraphic section from the Well 1. The ages and biozones are based on Caballero et al. (2020).

to coarse-grained sandstones, Fig 2.11A, 2.11C, and 2.11D. In some cases, these rocks preserve root traces and iron oxides, Fig 2.11B and 2.11E. These rocks are truncated at ±7937’ by an unconformity underlain the Eocene matrix-supported pebbly cross-bedded conglomerates of the Mirador Fm, Fig 2.11F. Similarly, cross-bedded medium to fine-grained sandstones with ophiomorphas appear at ±7890’, Fig 2.11H.

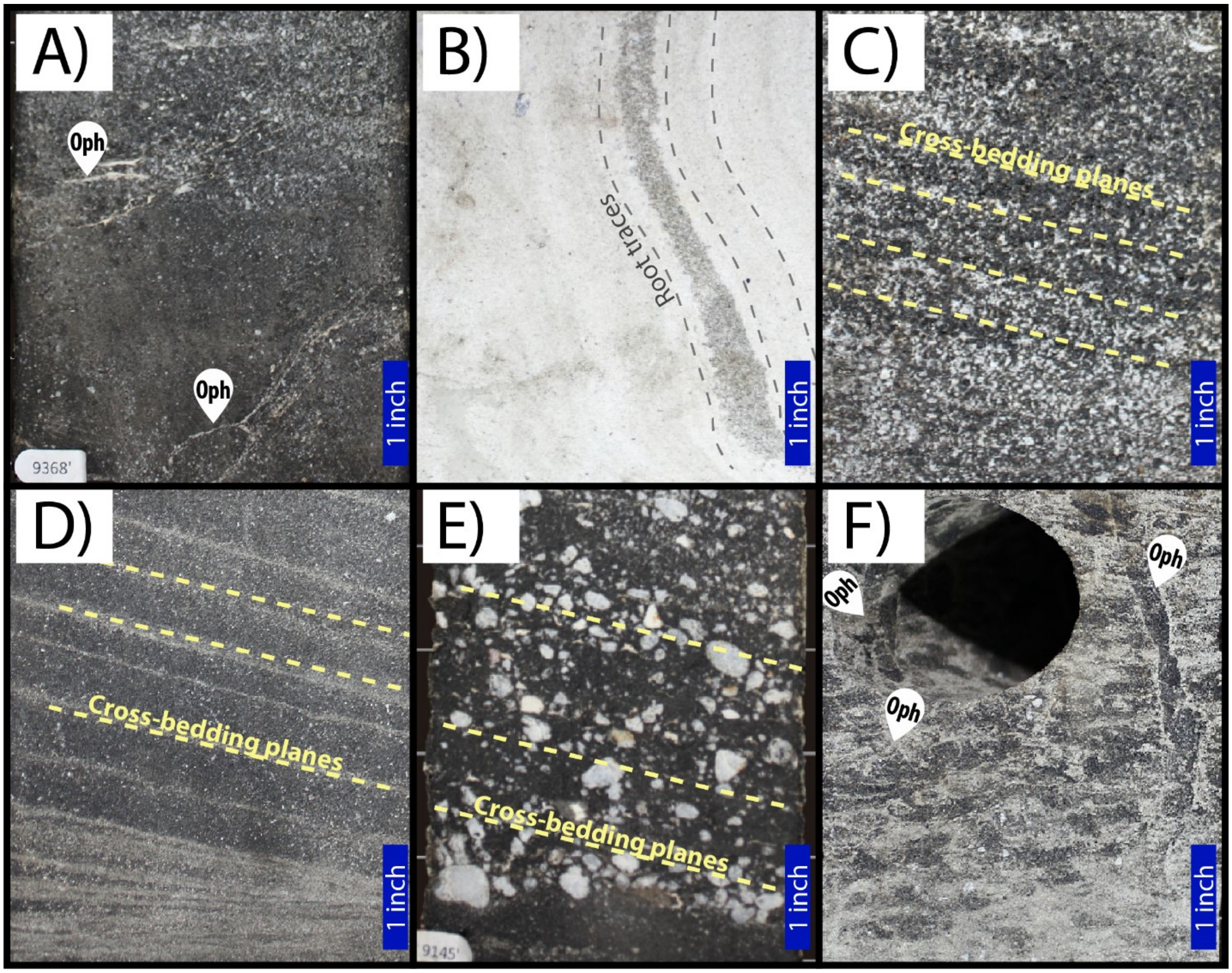


Fig. 2.9. Photoplate of the Well 1. A) Cross-bedded medium-grained sandstones with ophiomorphas, B) Cross-bedded medium to coarse-grained sandstones with root traces, C) Cross-bedded granules, D) Cross-bedded very coarse-grained sandstones, E) Cross-bedded granules, and F) Cross-bedded medium-grained sandstones with ophiomorphas.

The distribution of the facies is very similar eastwards in the well 3. Although there are no biozones reported, the lithofacies and the nearby wells from Caballero et al. (2020) provided insightful information to correlate the stratigraphic intervals. The lowermost interval corresponds to the cross-bedded medium to coarse-grained sandstones with ophiomorphas of the Middle Guadalupe, Fig 2.13A. The contact with the Paleocene Barco Fm is placed at ±8165’, which is composed of cross-bedded medium to coarse-grained sandstones with iron oxides, Fig 2.13C. The Paleocene-Eocene contact is estimated at 8113’, Fig 2.12. Figure 2.13D illustrates the overlaying cross-bedded medium to coarse-grained sandstones that would be the equivalent to the Mirador Fm, which is underlain by cross-bedded medium to fine-grained sandstones with ophiomorphas, Fig 2.13F.

2.4.2. Lithofacies Analysis

Based on Farrell et al. (2012), 15 lithofacies were identified along the sections, most of them are present in the Sagu as the section is 500 m thick while the sections from the wells are ±100 m (Well 1), ±80m (Well 2), and ± 70 m (Well 3). The description of the depositional context and mechanism is shown in Table 2.1 and the detailed Photoplate is presented in Fig 2.5. The lithofacies are:

2.4.2.1. Heterolithic sandstones and mudstones with horizontal burrows (S/M b): they vary concerning the proportion of mudstones and sandstones, and they can sometimes be wavy laminated, Fig 2.5A. The preserved burrows are *Thalassinoides*, which are usually present at the bottom of the beds. The thickness of these facies is ±40 m and is present in the lower part of the Sagu section, Middle Guadalupe, Fig. 2.6. In addition, they are associated with a retrograding pattern.

2.4.2.2. Wavy laminated silty fine-grained sandstones ((z)S w-lam): present in thick to very thick beds of silty sandstones with wavy lamination, Fig 2.5B. Some thin to very thick beds of siltstones and mudstones are found within it. The thickness of these lithofacies is ± 20 m and are present in the Middle Guadalupe of the Sagu, Fig. 2.6.

2.4.2.3. Wavy laminated siltstones with horizontal burrows (Z lam b): in some beds, the lithofacies can be muddy but it is silty in general, Fig. 2.5C. Additionally, the lamination varies from horizontal to wavy, but it is horizontal in most cases. The thickness range is around 10-15 m, and it is part of a prograding succession of the Middle Guadalupe, and the Carbonera C8 from the Sagu, Fig. 2.6 and Fig. 2.7D. The ichnofacies identified are *Thalassinoides* and are present in the lower part of the Middle Guadalupe.

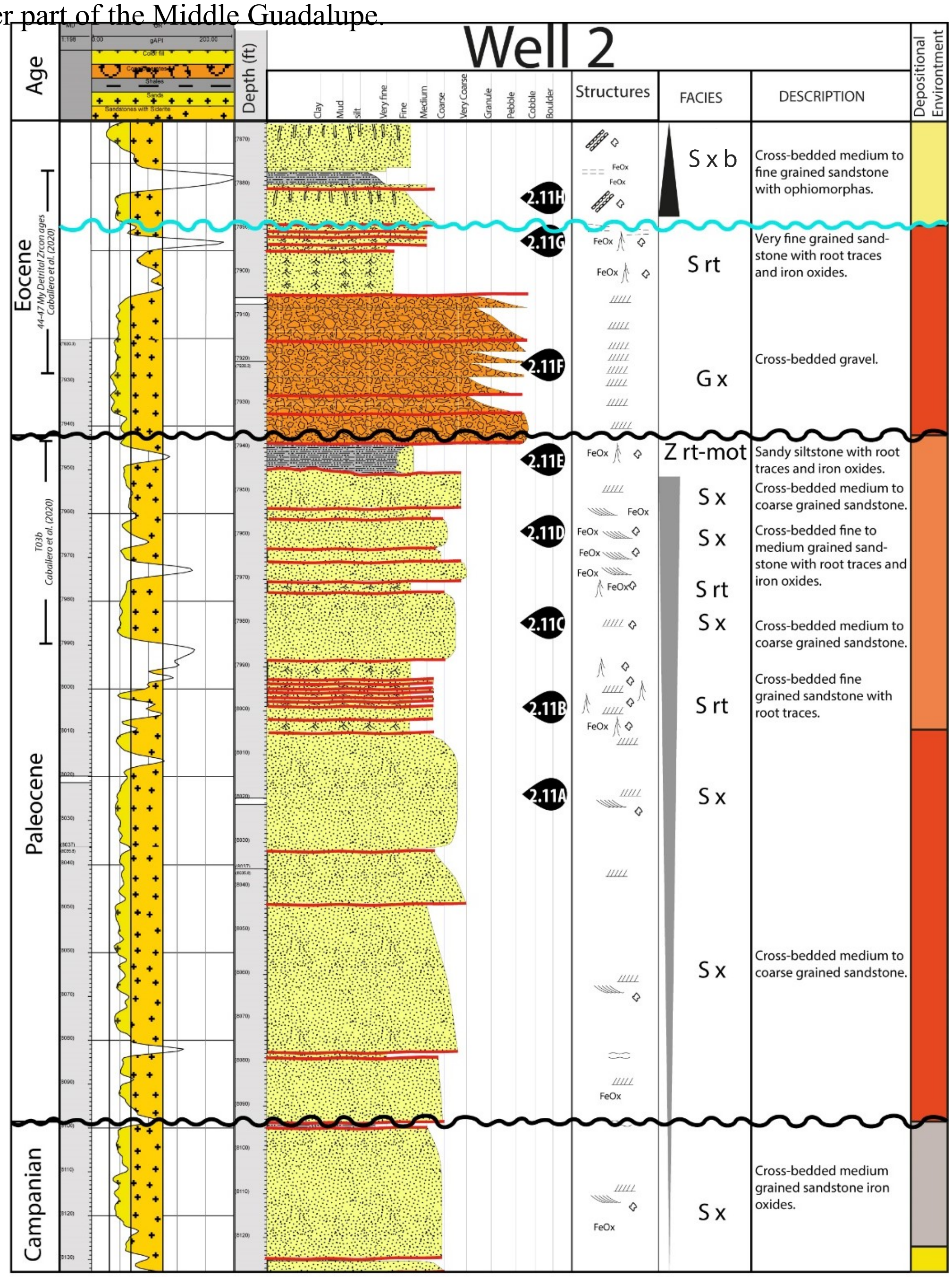


Fig. 2.10. Stratigraphic section from the Well 1. The ages and biozones are based on Caballero et al. (2020) and ECOPETROL (2012).

2.4.2.4. Laminated fine- to coarse-grained sandstones with vertical burrows (S lam b): they can vary regarding the facies association, Fig 2.5D. When it is associated with finer facies, the intervals can be either silty or muddy. In association with coarser-grained facies, they tend to be dominantly sandstones. The thickness ranges from 5 to 30 m. These facies are thicker when associated with facies dominated by coarse grains and tend to be part of prograding successions. Likewise, the beds can present either flaser or wavy lamination, the latter of which is related to prograding successions, while the flaser is present when retrograding patterns are recognized, Fig. 2.6. The recognized ichnofacies were classified as *Ophiomorphas*. It is identified in the Middle and Upper Guadalupe units from the Sagu, Fig. 2.6.

2.4.2.5. Cross-bedded medium-grained sandstones with vertical burrows (S x b): these lithofacies were found among all the sedimentary sections, Fig 2.5E. They can vary up to coarse-grained sandstones, and when it is associated with glauconite and phosphates with a high amount of *Ophiomorphas* the lithofacies tend to be retrograding, Fig. 2.7C/D. The thickness can vary from 5 m to 30 m and the thickest is presented along the Sagu. These lithofacies are present along the upper part of the Middle Guadalupe, and in the middle part of the Upper Guadalupe units along the Sagu. In the wells, they are found in the lower and upper part of the sedimentary log, Figs. 2.8, 2.10, and 2.12. Moreover, they tend to be coarser towards the east, where well 3 is located. See Figs. 2.7C/D, 2.9A/F, and 2.13A/F.

2.4.2.6. Wavy laminated heterolithic siltstones and sandstones with horizontal burrows (Z/S w lam b): the siltstones can be finer reaching muddy size while the sandstones vary from medium to coarse-grained, Fig 2.5G. The thickness is ±3-7 m. These lithofacies are absent in the area of the well and are preserved within the upper part of the Middle Guadalupe rock unit in the Sagu, where some *Thalassinoides* are seen at the base of the beds.

2.4.2.7. Laminated gray siltstones with iron oxides (Z lam): these facies are dominantly siltstones; but in a few beds they are sandy, Fig 2.5I. The interval contains iron oxides, presumably siderite, and they appear either following the bedding (Fig. 2.7E) or in some concretions (Fig. 2.7J). The thickness is about 5-10 m. They are present in the Guaduas and Los Cuervos Formations in the Sagu section and absent in the wells. No prograding or retrograding pattern is recognized.

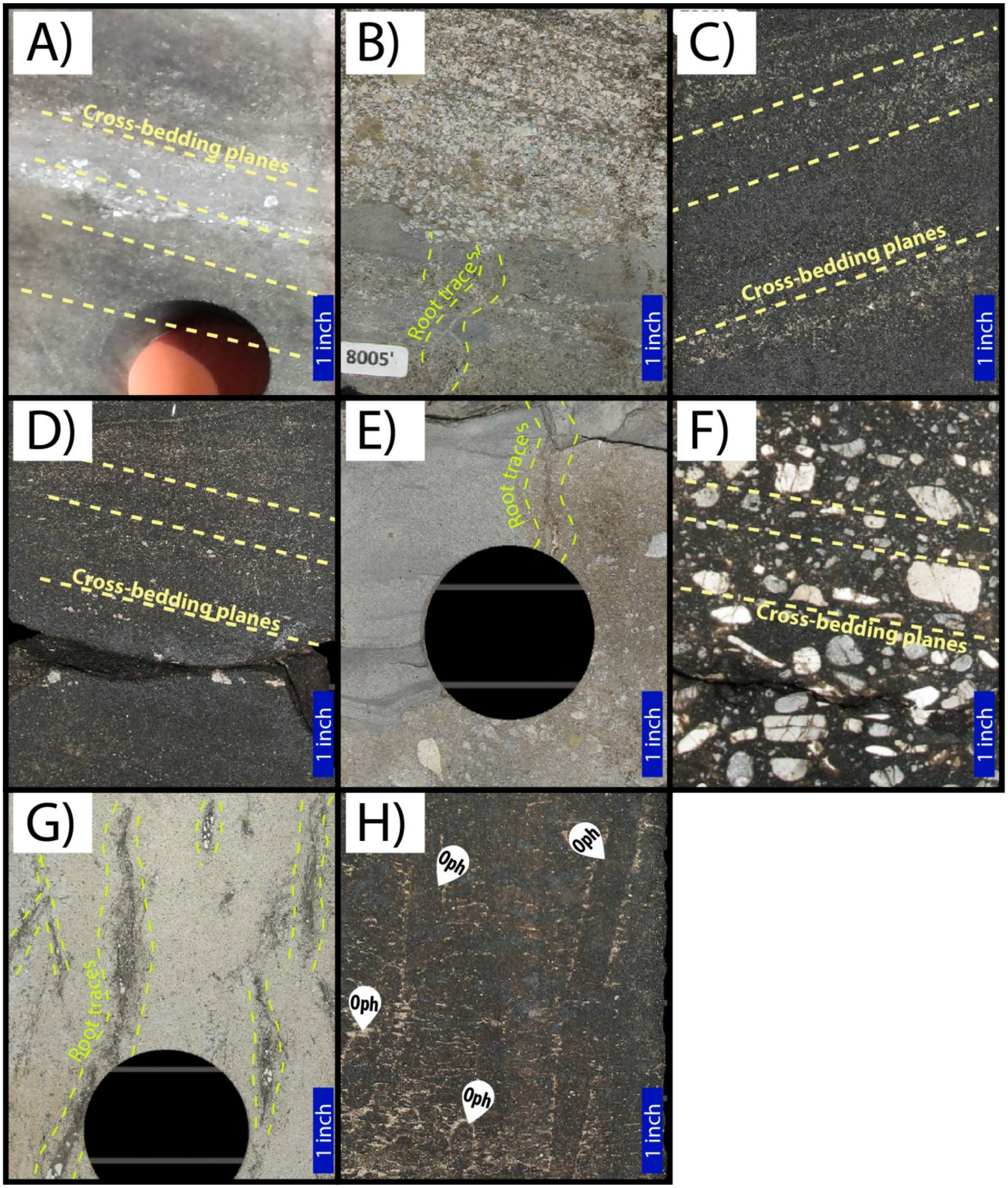


Fig. 2.11. Photoplate of the well 2. A) Cross-bedded medium to coarse-grained sandstones, B) Cross-bedded medium to coarse-grained sandstones with root traces, C) Cross-bedded medium to coarse-grained sandstones, D) Cross-bedded very coarse-grained sandstones, E) Cross-bedded sandy siltstones with root traces and iron oxides, F) Cross-bedded granules, G) Very fine-grained sandstones with root traces, and H) Cross-bedded medium-grained sandstones with Ophiomorphas.

2.4.2.8. Lenticular-bedded gray to reddish siltstones (Z l): these facies can vary in color with the presence of iron oxides, which are present as mots, Fig 2.5O. The siltstones lenses can also be sandier, and orange colored due to oxidation, Fig. 2.7H. Their thickness can range from 1 to 10 m. These lithofacies are only present in the aggrading Barco Formation in the Sagu section, Fig. 2.6.

2.4.2.9. Laminated gray siltstones with plant debris (Z lam org): these lithofacies are prograding and the siltstones become sandier towards the top, see Figs. 2.5J, 2.7I, and 2.7J, where the plant debris disappears, and the facies turn into the Z l with iron oxides. The thickness is near 20-30 m. They dominate in the Los Cuervos Formation of the Sagu Creek, which is absent in the wells.

2.4.2.10. Gray siltstones with root traces and iron oxides (Z rt-mot): the sand grains vary in the lithofacies, Fig 2.5K. For instance, in wells 2 and 3 they are sandier, Figs. 2.11E and 2.13E. The thickness of the facies varies from 3 to 10 m, and they are present along the Los Cuervos Formation in the Sagu, and at 7950 / 8070 ft depth in wells 2 and 3, respectively. They are associated with aggrading successions and can present iron oxides.

2.4.2.11. Bioturbated medium-grained sandstone (S biot): these facies are unique, no sedimentary structure is visible due to the high amount of ichnofacies, based on Buatois & Mángano (2011) those were classified as *Cruziana,* Fig 2.5F. Also, it is only present in the Sagu, in a 1 m tabular bed, Fig. 2.7M and 2.7N, on top of the conglomeratic facies of the Mirador Formation.

2.4.2.12. Cross-bedded medium- to coarse-grained sandstone (S x): these are the most common facies because they are present along the four stratigraphic sections, Fig 2.5H. However, the grain size can vary from medium-fine up to coarse-very coarse, Fig. 2.7F, 2.7G, 2.11A, and 2.13C. The cross-bedding can also vary from trough to planar, though in the wells, it was impossible to see the difference. They can be 10 to 100 m thick. They are present in the Upper Guadalupe and Barco formations in the Sagu, Fig. 2.6, as well as in distinct depths in the wells, Figs. 2.8, 2.10, and 2.12. They are frequently found in prograding intervals. They can be gravelly when associated with gravels and conglomerates, e.g., Fig. 2.9C.

2.4.2.13. Massive fine- to medium-grained sandstones (S m): the grain size is consistent in these facies, Fig 2.5L. They were recognized only in the Sagu, being up to 10 m thick inside the prograding Los Cuervos Formation.

2.4.2.14. Fine- to medium-grained sandstone with root traces (S rt): the variation observed in these facies is related to the sand grain size, which can be either fine or medium, Fig 2.5M. However, in some cases, the rock can show signs of a soft cross-bedding, but as these facies are associated with paleosols, it is common to see sandstones with no sedimentary structures but the root traces, Fig. 2.7M, 2.9B, and 2.11G. Their thickness varies from 1 to up to 20 m and is present within the Barco, Los Cuervos, and Mirador formations from the Sagu, well 1 and well 2, see Figs. 2.6, 2.8, and 2.10.

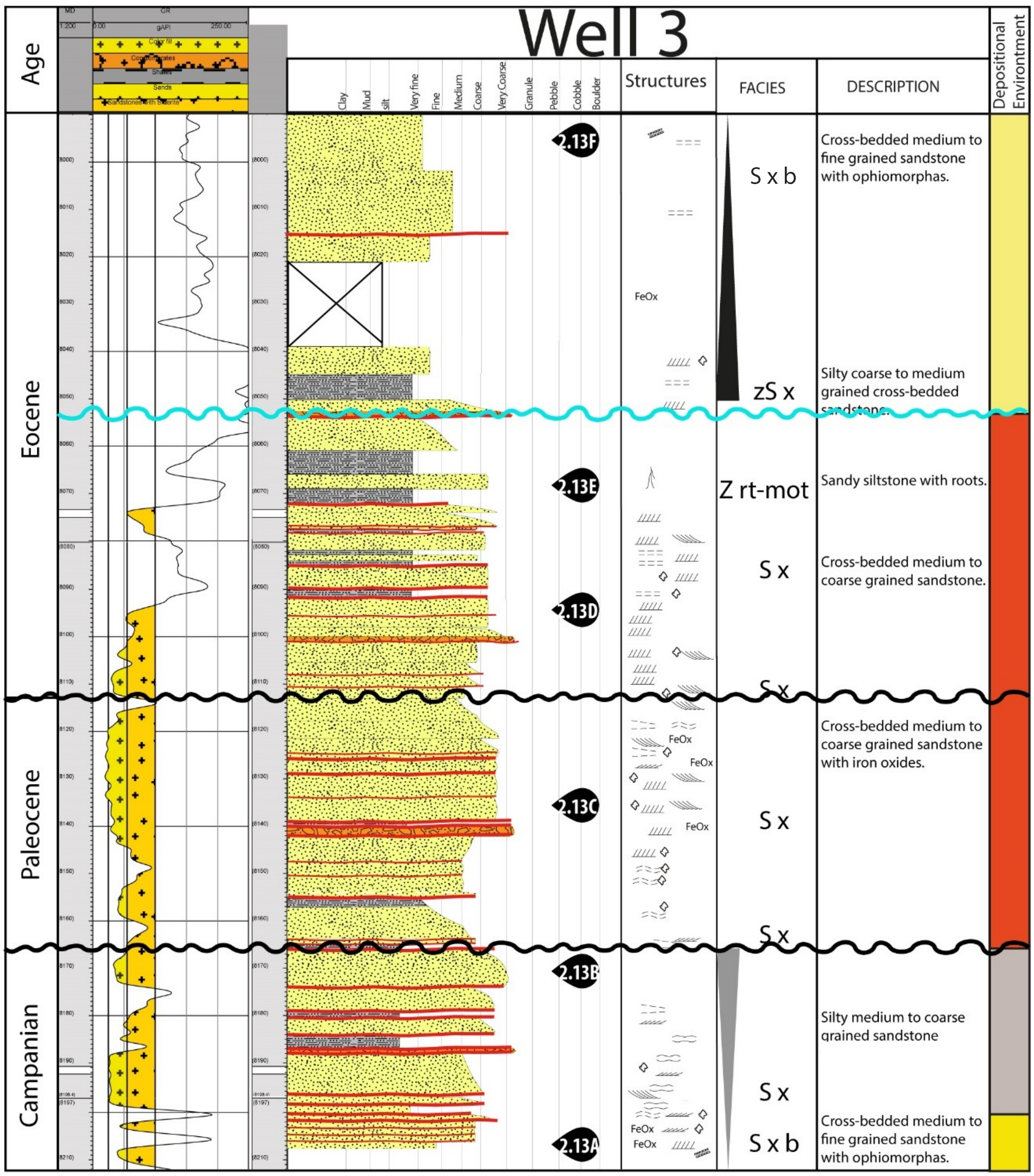


Fig. 2.12. Stratigraphic section from the Well 3. The ages and biozones are based on Caballero et al. (2020).

2.4.2.15. Cross-bedded gravel (G x): the portion of sand grains among the type of cross-bedding (either planar or trough) is variable in these facies. In the Sagu, the trough-cross bedding is clear, Fig. 2.5N, 2.7L, 2.9E, and 2.11F, which becomes clearer when the portion of sand grains increases. This is the most continuous facies of all, with thickness up to 50 m. It is dominant in the Eocene rock units. In the Sagu Creek, the Mirador Fm starts with poorly sorted clasts of up to 28 mm and their composition varies from quartz to gray-black colored sedimentary lithics, Fig 2.7K. However, towards the top of the unit the composition becomes more quarzitic, the sorting shift to moderate, and the amount of sedimentary lithics sharply decreases, and the gradation to coarse- to very coarse-grained sandstones in 10-25 cm sets is more prominent. In wells 1 to 3, the composition of the clasts is mainly quarzitic and the gradation to very coarse-grained sandstones is up to 60 cm, Figs 2.9E, and 2.11E. Likewise, the sorting varies from poorly to moderate towards the top. The Paleocene Gx facies differ from the Eocene due to the clasts are smaller (up to 2.5 mm), mainly quarzitic, and moderate to well sorted.

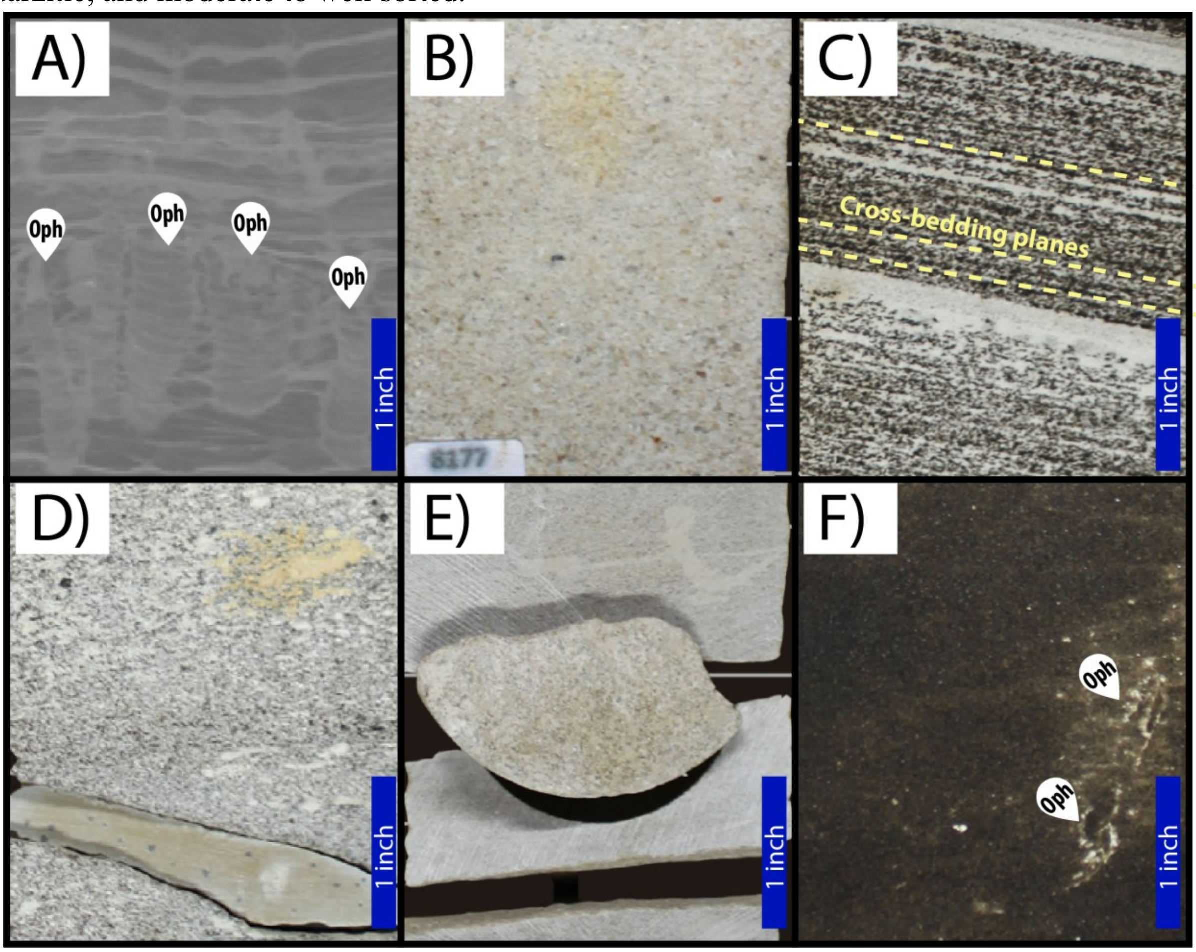


Fig. 2.13. Photoplate of the Well 3. A) Cross-bedded medium to coarse-grained sandstones, B) Cross-bedded medium to coarse-grained sandstone, C) Cross-bedded medium to coarse-grained sandstones, D) Cross-bedded very coarse-grained sandstones, E) Cross-bedded sandy siltstones with root traces and iron oxides, and F) Cross-bedded medium-grained sandstones with ophiomorphas.

2.5. Facies Associations and deposition environments in the Southern Llanos Basin

Following the facies association, the deposition environments were determined based on Boggs Jr. (2006) and Nichols (2009), the significance of the ichnofacies was determined using Buatois & Mángano (2011) and Ekdale et al. (1984), and the implication of the presence of authigenic minerals was analyzed using the theory and principles from Chafetz & Reid (2017), Logvinenko (1982) and Odin & Matter (1981). Subsequently, the sedimentary environments were generalized according to the depositional model built, Fig. 2.4A and 2.4B, aiming for an easier understanding of the shoreline trajectories and further correlation with the regional geology from the late Campanian to early Oligocene. The results are plotted in Table 2.1. The interpretation of the facies associations is:

2.5.1. FA 1:S/M b – (z) S w lam – Z lam b – Z w lam: Inner Shelf facies

They are only present in the Sagu section, where they were recognized along three intervals, Fig. 2.6, and Table 2.1. The S w lam, Z w lam and S/M b belong to the Middle Guadalupe, measuring ±75 m and ±20 m, respectively, Fig 2.6. The Z lam b measures ±50 m and represents the Carbonera (C8), which is mostly comprised of gray to black mudstones and siltstones with *Thalassinoides* and wavy lamination, Fig 2.7O. Some fine-grained and silty sandstones can be found, mostly in the Middle Guadalupe, yet, most of the sandstones in this rock unit are inside the heterolithic successions. The most common sedimentary structures are the heterolithic, wavy and horizontal lamination, indicating the influence of wave currents in an environment when most of the deposition was driven by suspension, as suggested by the dominant lithologies. In addition, their association with *Thalassinoides*, the dominant trace, implies that the deposition took place in moderate to low energy conditions. For this reason, the FA 1 is interpreted to be deposited in an offshore or prodelta environment, and it is generalized to be the uppermost portion of the environment defined as the inner shelf in Fig. 2.4A and 2.4B. This FA1 presents two patterns from bottom to top, it starts being fining-upwards and changes towards the top to a coarsening upwards pattern. The lower and upper contact is usually associated with *S x b, S biot,* and *S lam b* of the FA2 – Lower Shoreface. Therefore, indicating normal transitions. Albeit, a rapid change is preserved in the Carbonera (C8), with the underlying *S biot* only being 1 m thin.

Facies Association	Dominant Lithofacies Code	Lithologic Characteristics	Depositional Context (mechanism of deposition)	Occurrence	Depositional Environment	Simplified environm
FA 1	S/M b	Heterolithic sandstones and mudstones with horizontal burrows (thalassinoides)	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.	In the Sagu three intervals, in the Middle Guadalupe from meter 0 to ±70, from ±110 to ±130, and in the Carbonera (C8). Absent in the Wells.	Offshore / Prodelta	Inner Shelf
	(z)S w-lam	Wavy laminated silty fine-grained sandstones	Low energy setting close to the storm wave base, dominated by tides, and often affected by storm waves			
	Z lam b	Wavy laminated siltstones with horizontal burrows (thalassinoides)	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.			
	S lam b	Laminated fine to coarse-grained sandstone with vertical burrows (ophiomorphas)	Low energy setting proximal to the fair-weather wave base, and often affected by storm waves			
FA 2	S x b	Cross-bedded medium-grained sandstone with vertical burrows (ophiomorphas)	Softground and substrate-controlled. Biogenic reworking in medium energy flow, above the fair-weather wave base.	In the Sagu section three intervals, in the Middle Guadalupe from meter ±70 to ±110 and from ±130 to ±150; and a very thick bed on top	Lower Shoreface / Lower Delta Front	Lower Shoreface
	S biot	Bioturbated medium grained sandstones	Soft ground and substrate-controlled. Biogenic reworking			

			in medium to low energy flow, close to the fair-weather wave base.	conglomerates of Mirador formation. Recognized in the upper part of the Wells.		
	S lam b	Laminated medium to fine-grained sandstone with vertical burrows (ophiomorphas)	Same as above			
	Z/S w lam b	Wavy laminated heterolithic siltstone and sandstone with horizontal burrows (thalassinoides)	Same as above			
FA 3	S x	Through cross-bedded medium to coarse-grained sandstone	High energy regime setting affected by the oscillatory flow-landward transportation of the waves.	Dominant in the Upper Guadalupe and the lower part of the Wells.	Upper Shoreface / Upper Delta Front	Upper Shoreface
	S x b	Trough cross-bedded medium to coarse-grained sandstone with vertical burrows (ophiomorphas)	Softground and substrate-controlled. Biogenic reworking in medium to high energy flow, affected by oscillatory movements of the waves. With K and P enrichment and low sedimentation rates.			
	S lam b	Laminated/flaser-bedding medium to coarse-grained sandstone with vertical	Soft ground and substrate-controlled. Biogenic reworking in medium to high energy flow typical			

		burrows (ophiomorphas)	of plane-bed conditions.			
FA 4	Z lam	Laminated gray siltstone with iron oxides	Aerobic low energy setting with suspension deposition.	Dominant in the Guaduas and Los Cuervos formations in the Sagu. And in the Upper Campanian deposits from the Wells. Interval ±9360 to ±9310 in W1, ±8120 to ±8095 in W2, and ±8200 to ±8172 in W3.	Coastal Plain / Delta Plain / Lacustrine	Coastal Plain
	Z lam org	Laminated gray siltstone with plant debris	Aerobic low energy setting with suspension deposition, with some episodes of increased water level that caused anaerobic temporary conditions.			
	Z rt-mot	Gray siltstone with root traces and iron oxides	Aerobic low energy setting with suspension deposition.			
	S m	Massive fine to medium-grained sandstone	Hyperconcentrated flow during abrupt changes in flow speed from low to high energy.			
	S x	Through cross-bedded coarse-grained sandstone	Same as above			
	S rt	Fine to medium-grained sandstone with root traces	Same as above			
FA 5	S x	Through cross-bedded coarse-grained sandstone	Same as above	Dominant in the Barco and Mirador formations in the Sagu. In	Braided River / Alluvial Fan / Upper and Middle River Courses	Proximal Fluvial

	G x	Cross-bedded gravel	Migration of bedforms related to high turbulent flow energy channels.	the Wells, these are found in the intervals W1: ±9305 to ±9200 and ±9160 to ±9100; W2: ±8095 to ±8015 and ±7940 to ±7890; and W3: ±8165 to ±8050.		
	S rt	Fine to medium-grained sandstone with root traces	Same as above			
FA 6	S x	Cross-bedded (trough or planar) coarse to medium-grained sandstone	Migration of bedforms related to medium flow energy channels.	No dominant interval in Sagu or W3. But one interval in W1 and w2, ±9200 to ±9160, and ±8015 to ±7940, respectively.	Meandering Fluvial / Floodplains / Middle to Lower River Course	Marginal Fluvial
	Z l	Lenticular bedded gray to reddish siltstone	Aerobic low energy setting with suspension deposition.			
	S rt	Medium grained sandstone with root traces	Migration of bedforms related to medium flow energy channels.			

Table 2.1. Lithofacies occurrence and characteristics, facies association, and depositional process interpretation of the Late Campanian to Early Oligocene rock units form the SLLB. Depositional environment interpreted following Boggs (2006), Jones & Jones (2012) and Nichols (2009).

2.5.2. FA 2: Z/S w lam b – S lam b – S biot – S x b: Lower Shoreface facies

Multiple intervals of this association were identified along the Sagu and wells sections. In the Sagu, the *Z/S w lam b, S xb,* and *S lam b* are preserved in the Middle-Upper Guadalupe. While the *S biot* is exclusive from the upper Mirador Fm, see Fig. 2.6. From bottom to top, the intervals from the Sagu are ±35, ± 20, and 1 m, respectively. In the wells, this association is present on top of the studied stratigraphic interval, where *S x b* and *S biot* dominate, Figs. 2.8, 2.10, and 2.12. In general, this association of facies is dominated by medium-grained sandstones with either wavy lamination and only one interval of heterolithic siltstones and mudstones, which indicates variable velocity flow. In addition, the presence and abundance of *Ophiomorphas* indicate deposition above the fair-weather wave base. In the Middle Guadalupe, the presence of glauconite and phosphates reveals shallow-water conditions with restricted sediment supply. Indeed, they are interpreted to be deposited in either lower shoreface or lower delta front conditions, which is generalized as lower shoreface, Table 2.1. However, the content of glauconite and phosphates indicates the dominance of an open shoreline rather than a deltaic system. The successions within the Middle Guadalupe of the Sagu are coarsening upwards, while the middle Eocene intervals from the wells and Sagu are fining upwards instead. This facies association is usually underlaid by *Z lam b* and *Z w lam* (FA1)*,* except for the change of the Eocene units that overlay *G x* and *S rt* (FA 5), Figs 2.6, 2.8, 2.10, and 2.12. The upper contact varies in relationship to the grading, being overlaid by *Z w lam* (FA1) when fining upwards and by *S x* (FA3) when coarsening upwards, Fig 2.6.

Therefore, these facies associations with this facies association are key to understand the types of unconformities recognized, as within the Sagu Creek we determined two types of unconformities. The first one was identified at the bottom of the *S lam b* facies overlaying *Z w lam* deposits between the 130 and 150 m, the upper part of the Middle Guadalupe in Fig 2.6. The second one was recognized on top of the *S biot* facies of the Mirador Fm, underlaying the *Z lam* of the Carbonera C8, at the 500 m of Fig 2.6. Although these unconformable contacts were formed under subaqueous conditions, they developed under different shoreline trajectories. The first one formed during forced regression and is associated with the regressive surface of marine erosion (RSME) according to the criteria exposed by Catuneanu (2002). While the second one was created during a transgression it is overlain by deeper facies. Therefore, following Catuneanu, (2019b) Zecchin et al. (2019) it was established as a transgressive surface of erosion (TSE).

2.5.3. FA 3: S x – S x b – S lam b: Upper Shoreface facies

This association is related to Cretaceous deposits of the Sagu and the wells, e.g., the Upper Guadalupe Formation in the Sagu. The thickness reaches ±80 m in the Sagu, whereas no total thickness was established in the wells due to it is incomplete, yet based on the gamma-ray logs it is estimated in ± 100 m. The *S x* and *S x b* are mainly composed of cross-bedded (trough or planar) medium to coarse-grained sandstones, suggesting medium- to high-energy velocity flow. In the Sagu we recognized *S lam b* which preserves some flaser and wavy lamination. Presumably, the result of periods in which the tides dominated the environment. The abundance of *Ophiomorphas* suggests deposition occurred above the fair-weather wave base, where the daily currents of waves influenced sedimentation. Therefore, they are interpreted to be deposited in the upper shoreface or the upper delta front, which is generalized in the upper shoreface environment, Fig. 2.4A, 2.4B, and Table 2.1. In the Sagu, these facies preserve a fining upwards pattern in the lower part, while the upper part of the facies is coarsening upwards. In wells, they are only coarsening upwards as we checked the upper part of it, Figs 2.8, 2.10, and 2.12. These facies are underlain by *Z/S w lam b* (FA 2) and overlain by *Z lam* and *S x (*FA 4), lower shoreface, and coastal plain deposits, revealing normal transitions related to the trajectories of the shoreline.

2.5.4. FA 4: Z lam – Z lam org – Z rt mot – S m – S rt – S x: Coastal Plain facies

Five intervals preserve these facies, two in the Sagu and one in each Well. In every section, an interval between ±10 to 20 m is seen on top of the Cretaceous deposits. In the Sagu, it corresponds to the Guaduas Formation, while along the wells these facies belong to the Middle Guadalupe. Also, this association is identified in the Los Cuervos Formation in the Sagu. In general, the association is composed of gray laminated siltstones with plant debris and iron oxide (presumably siderite) in some beds, Figs. 2.7E, 2.7L, and 2.7J. However, it changes towards the area of the wells, where cross-bedded medium to coarse-grained quarzitic sandstones dominate the interval, Figs. 2.9A and 2.13B. This evidence suggests deposition in either low- to medium-high velocity or suspension. The latter is related to lacustrine and floodplains environments, with some river channels nearby, where the flow velocity created the trough and planar cross-bedding. The dominant gray color of the siltstones, with some content of plant debris, indicating some preservation of organic matter, Fig 2.5J and 2.7I. Therefore, these facies are interpreted as being related to delta plain, which was simplified as coastal plain because its position in relation to the shoreline is similar. The Cretaceous facies overlay the *S lam b* and *S x b (*FA 3) and underlay the

S x (FA5) that rest on top of the K-T unconformity, see Fig 2.6, 2.8, 2.10, and 2.12. The Paleocene facies are underlain and overlain *G x* and *S x*, respectively (FA 5). Likewise, the top of the Paleocene facies is characterized by *Z rt-mot* and *S rot* facies associated with paleosols formations. The grading of this facies association changes from coarsening- to fining-upwards. In the Sagu, the fining-upwards succession preserves plant debris material, see Fig 2.7I, whereas the coarsening-upwards pattern is characterized by mottling and root traces, see Figs 2.7J and 2.7 K. The fact that these facies are always truncated by an unconformity (Cretaceous-Paleocene and Paleocene-Eocene), and overlain by proximal fluvial facies, indicate that the upper contact of each interval is analogous to the subaerial unconformity (SU) defined by Sloss et al. (1949), see Figs 2.6, 2.8, 2.10, and 2.12.

2.5.5. FA 5:S x – G x – S rt: Fluvial Proximal Facies

This is the most common association of facies along the Paleocene and Eocene rocks from the studied sections. In the Sagu, they correspond to the Barco and Mirador formations, being ± 100 and 50 m, respectively, Fig. 2.6. In wells 1 and 2, two intervals (±30 m and ±10 m) from Paleocene and Eocene also appear Figs. 2.8 and 2.10. However, the Eocene facies are the coarsest-grained, Figs. 2.7K, 2.7L, 2.9E, 2.11E, where gravels and conglomerates are dominant within the *G x*. At the bottom of the beds, poorly- to moderated-sorted units with lithic fragment and angular to subangular clasts are seen, Fig 2.7K, 2.9E, and 2.11F. In well 3, the Paleocene-Eocene facies form only one ±30 m interval, Fig. 2.12, where no significant difference in the grain size or sedimentary structures is defined for the *S x*, Figs. 2.13C and 2.13D. Paleosols (*S rt)* are often found on top of these facies, Figs. 2.7M, 2.11B, and 2.13E. The dominant coarse grain size and the lack of siltstones and mudstones indicate sedimentation in high-velocity energy flow channels with high amalgamation and low chances of forming floodplains. These are characteristic features of braided - anastomosed rivers, as well as alluvial fans. Both are located between the upper and middle course of a river, close to the sediment source and far away from the downstream controls. For this reason, this study generalized it as fluvial proximal facies. The sediment source is interpreted to be the same for the Sagu and the wells as the paleocurrents indicate the sediment source was located southeastwards. They are always overlain by unconformities. However, they are underlain *Z lam org, S rt, S biot,* or *S b,* indicating either normal transitions or abrupt changes. The latter is unique for the middle to late Eocene facies.

2.5.6 FA 6:S x – Z l- S rt: Fluvial Distal Facies

These facies are absent in the Sagu and well 3 but often found along wells 1 and 2. Indeed, they are found in up to ±10 m intervals on top of the Paleocene deposits, Fig. 2.8, and 2.12. It is mainly composed of cross-bedded, very coarse to medium-grained sandstones in medium to thick beds with silty intervals and paleosols, evidencing subaerial exposure, Figs. 2.9D, 2.11C, and 2.11D. The paleosols (*S rt*) preserve abrupt changes in the grain size, Fig 2.11E. These are common characteristics of meandering rivers located in the middle to the lower part of the river course, where despite the sedimentation taking place on the channels (*S x*), the channel amalgamation is reduced, and their abandonment produces the sedimentation of finer sediments as siltstones along their floodplains (*Z l)*. They are under- and overlain by *Gx* (FA 5). Our interpretation coincides with the depositional model proposed to the north by Jaramillo (1999) and Notestein et al. (1944), and also with the paleogeographic restorations by previous studies (e.g., Bayona, 2018; Reyes-Harker et al., 2015).

2.6. Late Campanian to Late Eocene Unconformities

The results indicate that the SLLB was under downstream controls by the Late Cretaceous because the facies from the Campanian and Maastrichtian deposits indicate shallow marine environments, Figs. 2.6, 2.8, 2.10, and 2.12. However, a prograding shallowing upward pattern is clear, and the Paleocene deposits suggest the domain of upstream controls during their deposition. Moreover, the Eocene facies reveal the courses of the rivers rejuvenated at that time and that the sedimentation occurred under high to very high velocity flows, e.g., Mirador Formation facies in the Sagu, Figs. 2.7K and 2.7L. Nonetheless, an abrupt change took place from the late Eocene. Lower shoreface to inner shelf conditions expanded across the SLLB. These changes are separated by unconformities that are diachronous from the Sagu towards the area of the wells, where they are either older or absent, as evidenced by the erosion that removed pre-existing rocks. Following the data, this study identified four unconformities. Two were formed under subaqueous conditions, whereas the other two developed during subaerial exposure.

75°0'0"W

The first unconformity is of the latest Campanian age. It is preserved along the Sagu section (Fig. 2.6). This surface separates lower and upper shoreface facies above and inner shelf deposits below (Fig 2.6), indicating subaqueous conditions during its formation. Our interpretation is that this unconformity is a regressive surface of marine erosion (RSME) that formed during relative sea-level fall and the corresponding lowering of the wave base. Catuneanu 2019b and Plint & Nummedal (2000) indicate this surface forms in lower shoreface conditions by the scouring of waves, and it is the base of forced regression deposits. This wave scouring is interpreted to cause the disappearance of the ophiomorphas and other ichnofacies between the 130 m and 170 m interval of the Sagu section (Fig 2.7A). Its absence along the wells is explained by the fact that the analyzed wells did not reach it or by the fact that it is indeed missing. The biozones in the Sagu Creek indicate this RSME formed during the latest Campanian, Fig 2.6. At this time the area in which the wells are currently located was controlled by coastal plain deposition, indicating there were no favorable conditions for the RSME to be formed. In addition, as this surface expands basinward its correlation should be tracked towards the ECB. The amount of missing time for this surface is not yet understood with the scale of the current data.

The second unconformity is the contact between the Maastrichtian (*Paleocystodinium* and *Proteacidites dehaani* biozones) and the Paleocene (undetermined probably T02 biozone), separating coastal facies below from fluvial facies above, Fig 2.6. The overlaying Paleocene fluvial facies are diagnostic characteristics of a subaerial unconformity (SU), (Catuneanu, 2017, 2019; Catuneanu et al., 2011; Sloss et al., 1949). This unconformity is correlatable towards the wells where it truncates the Campanian deposits, evidencing the expansion of this SU that occurred from the southeast to the northwest. The sedimentary record from well 1 preserves roots trace (Fig. 2.9B), which are typical of subaerial unconformities (SU) Moreover, the age of these rocks suggests a time gap of at least ±10 My in the Sagu section. Across the area of the wells, it increases up to ± 16 Ma.

The third unconformity recognized separates the Paleocene and the middle Eocene rocks. In the Sagu area, the contact between the Los Cuervos Formation and the Mirador Formation preserves this surface (Fig. 2.6 and 2.7k). In the area of the wells, it separates the fluvial facies from the Paleocene and the Eocene (Figs. 2.9C-2.9E, and 2.11D-2.11F). The presence of paleosols on top of the Paleocene (Figs 2.7J and 2.11E) along with the overlain fluvial facies indicate subaerial conditions during its formation. Hence, another SU is identified (Figs. 2.6, 2.8, 2.10, and 2.12). According to Caballero et al. (2020), the succession from Los Cuervos Fm to Mirador Fm probably preserves the biozone sequence established by Jaramillo et al. (2011), passing from T04 to T05 and T06. Those are equivalent to the latest Paleocene, Ypresian, and Lutetian-Bartonian, respectively. However, the deposition of the Mirador Fm in the Sagu Creek is interpretative and the Triassic and Precambrian detrital zircon ages from Carvajal-Torres et al. (2019) do not indicate an estimated age. This study suggests its deposition has occurred between the early to middle Eocene in the Sagu Creek following Jaramillo & Dilcher (2000). In the LLB its deposition started in the early to middle Lutetian, Figs 2.8, 2.10, and 2.12. These data indicate the time gap of this surface is at least ±5 My in the Sagu Creek and up to ±16 My along the LLB.

The last unconformity identified is in the contact between the fluvial facies of the Mirador Formation and at the base of the Carbonera (C8) rock unit. However, the surface is not placed directly below the Carbonera (C8) rock unit, but it is placed below the 1 m thick bed of lower shoreface facies (Fig. 2.6 and 2.7M). In addition, a 1 m interval of reddish to black paleosols (Fig. 2.7M) lies beneath the surface. These two beds are separated by the fourth unconformity, see 500 m point in Fig 2.6. This contact marks the transition from the fluvial facies of the lower to middle Eocene Mirador Formation and the Marine facies of the middle-latest Eocene. The upper part of the Mirador Fm, and the Carbonera (C8). The lack of palynomorphs within the Mirador Formation limits the definition of a lacuna for this surface. Nevertheless, Caballero et al., (2020) indicated no time gap across the Eocene to Oligocene rock deposits, and they classified it as a ravinement surface. Our results match with their interpretation of a ravinement surface, which corresponds to the transgressive surface of erosion (TSE) defined by Nummedal & Swift (1987), formed under subaqueous conditions by the wave scouring related to the retrograding shoreline.

2.7. Discussion

Based on compiled information across the Magdalena Valley and the Eastern Cordillera, Fig 2.14, from different authors, the rock units from the SLLB were correlated according to lithostratigraphic and chronostratigraphic criteria. Table 2.2 summarizes the data collected, showing the general lithologic characteristics, the age, and the environmental interpretations. The results indicate that some of the unconformities extend across the adjacent basins, whereas others are either present along the whole LLB or in the SLLB locally. Following the time gap and correlatability of the surfaces (Fig. 2.14), the magnitude of each one of the unconformities was determined. The data indicate those unconformities formed under subaerial conditions are correlatable across the other segments of the regional basin, e.g., the UMVB, MMVB, and ECB.

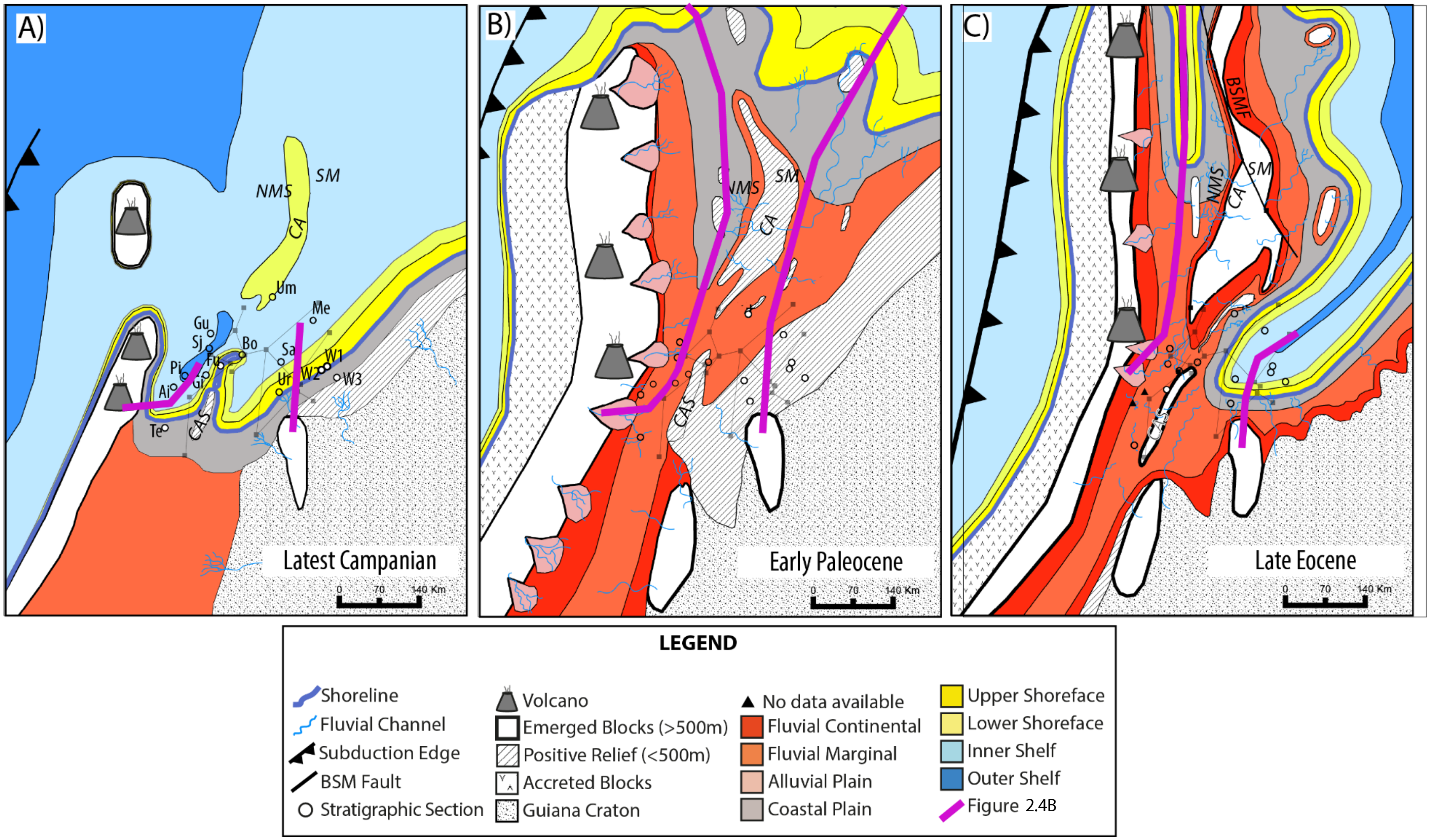


Fig. 2.15. Paleogeographic maps of the Colombian Andes showing three times: A) latest Campanian, B) early Paleocene, and C) earliest Oligocene. The maps expose the change from down-stream controls to up-stream controls in the late Cretaceous-early Paleocene, and the return of down-stream controls to the Llanos Basin by the earliest Oligocene. The stratigraphic sections plotted in each map are the ones plotted in Figure 13, and the net with lines and squares indicates the present-day position. The purple lines show the position of the generalized and idealized clinoform illustrated in Figure 4B, showing that our depositional model must be applied regarding to the position of the sediment source. CAS: Carmen de Apicala Syncline, CA: Cobardes Anticline, NMS: Nuevo Mundo Syncline, SM: Santander Massif, BSMF: Bucaramanga-Santa Marta Fault.

Their time gaps correspond to the sedimentary response to the compressional tectonic regime that affected the basin. On the other hand, the unconformities formed under subaqueous conditions are locally present across the LLB and some part of the ECB. In the case of the regressive surface of marine erosion (RSME), the UMVB and MMVB may have preserved their correlatable basal surface of forced regression.

During the late Maastrichtian and early Paleocene, the influence of the downstream controls came to an end, and the upstream controls dominated. Some studies suggest the Barco Fm deposited under estuarine conditions (e.g., Bayona et al., 2007). Nonetheless, these conditions did not reach the Sagu Creek and the wells. Accordingly, several studies state the dominance of continental palynomorph and the paleogeographic restorations indicate the shoreline was at least 500 Km away (Bayona, 2018; Guerrero & Sarmiento, 1996; Jaramillo, 1999; Mann et al., 2006; Reyes-Harker et al., 2015). Therefore, following the data we determine the early-middle Paleocene was a period in which the upstream controls influenced the sedimentation along the LLB. By the middle-late Paleocene, the downstream controls may have influenced the LLB as indicated by the presence of the coastal plain deposits of the Los Cuervos Fm.

Previous studies stated a foreland basin expanded from the Magdalena Valley in the west to the Llanos Basin in the east. The transition from the under to the overfilled stage occurred as sedimentation outpaced the accommodation due to an increase in sediment supply, resulting in a regression of the shoreline and the development of an extended fluvial network. The subaerial unconformity on top of the Cretaceous rocks in the Sagu creek (Fig. 2.6) and the subaerial unconformity on top of the Campanian rocks in the wells (Fig. 2.8, 2.10, and 2.12) formed during this transition. As shown in Figure 2.14, this surface is cutting older rocks towards the east, and its time gap varies in every basin. The time gap in the SLLB is related to the subaerial exposure caused by a reduction of accommodation in the marginal part of the basin. The increase in the hiatus is explained as the product of the westward propagation of the subaerial exposure that started in the far east.

The correlative disconformity along the ECB preserved between the Cretaceous Guaduas Fm and the Paleocene Cacho Fm has no significant gap. This fact suggests the subaerial unconformity expanded from the west (LLB), resulting in the decrease of the missing time towards the east. Based on Gómez et al. (2005) and Parra et al. (2009) we associate the formation of these unconformities to the flexural profile of the forebulge during orogenic loading episodes. The situation differs from the UMVB and MMVB. Caballero et al. (2013), Cortés et al. (2006), and Sarmiento (2011) indicate the presence of an angular unconformity in the westernmost part segment of the basin. We understand this as evidence of episodes of uplifting and exhumation of the orogen that triggered the formation of an angular unconformity in the westernmost part of the MMVB and UMVB and resulted in the uplift of the forebulge located in the current position of the LLB. The latter also explains the reduction of the accommodation space and the increase of sediment supply as the paleocurrents indicate the sediment source was located eastwards.

According to Parra et al. (2009), erosional unloading took place during the early to middle Eocene. At this time, a SU was formed across the MMVB, the Magdalena Valley Basin Unconformity (MMVU) (Gómez et al., 2003). . Similarly, the SLLB was under subaerial exposure as evidenced by the paleosols preserved on top of the Paleocene rocks (Figs. 2.6, 2.7J, 2.9, 2.8, 2.10, and 2.11E), suggesting an episode in which the accommodation did not increase. The data indicate an association between these events. Additionally, Bayona et al. (2013) demonstrate there is an SU on top of the Paleocene deposits along the ECB, and the associated lacuna is highly variable across the ECB. For instance, in San Juan de Rio Seco and Guaduero in the west, and Paipa and Tunja in the east, the lacuna is clear. Nevertheless, in the proximity of Bogota, the lacuna is null, implying the depocenter may have migrated to the axial part of the ECB.

Multiple chronostratigraphic charts and paleogeographic maps such as those presented by Caballero et al. (2020), Cardona et al. (2018), Cooper et al. (1995), Ramirez-arias et al. (2012), Reyes-Harker et al. (2015), and Sarmiento (2011) coincide with the fact that since the Paleocene the Eastern Cordillera acted as an orographic barrier between the Magdalena Valley and the Llanos. The uplift of the Eastern Cordillera separated the foreland basin into the independent hinterland and foreland basins, respectively, (Caballero et al., 2010; Sanchez et al., 2012) [redacted]. Although the separation that took place may have started since the Paleocene, the stratigraphic surface that marks the initiation of the independent basins was not formed until the late Paleocene to early-middle Eocene. For that reason, this regional SU is defined as a first-order stratigraphic surface that marks the end of the regional foreland basin, and so all the rocks overlying this surface belong to independent basins. This is exposed in the chronostratigraphic chart illustrated in Fig. 2.14, which indicates there is not a clear correlation of the facies since the middle-late Eocene from the MMVB/UMVB in the west to the LLB in the east, as the marine facies of the LLB are not related to the fluvial facies of the UMVB and MMVB.

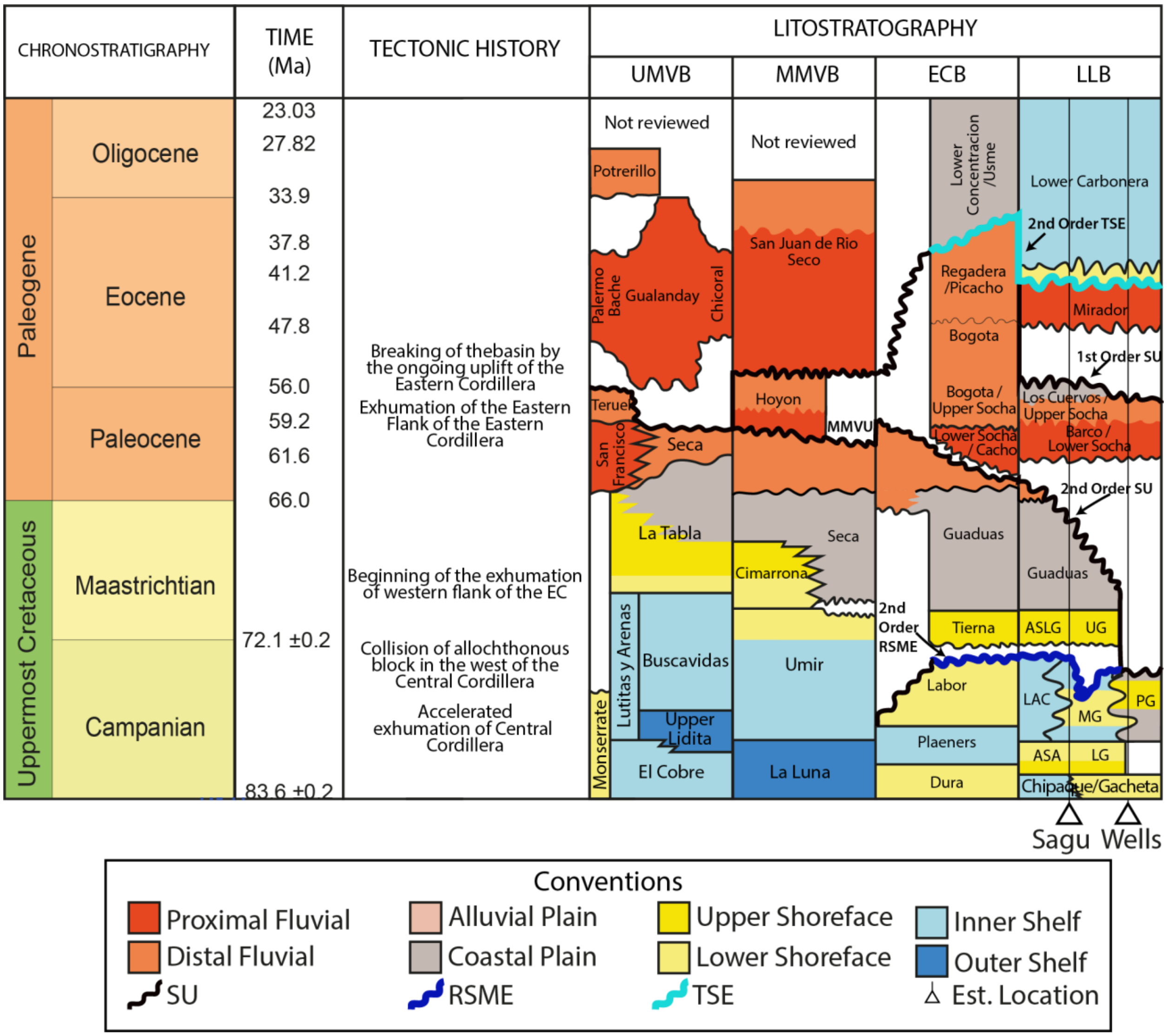


Fig. 2.16. Regional chronostratigraphic chart of the UMVB, MMVB, ECB and LLB depicting the correlation of the facies between the study area and the adjacent basins. MMVU: Middle Magdalena Valley Basin Unconformity, ASLG: Arenitas de San Luis de Gaceno, LAC: Lodolitas de Aguascalientes, ASA: Arenitas de San Antonio, UG: Upper Guadalupe, MG: Middle Guadalupe, LG: Lower Guadalupe, and PG: Palmichal Group.

The case of the subaqueous unconformities is different because the data demonstrate these surfaces tend to be locally preserved along the SLLB. The latest Campanian RSME in the Sagu correlates with an unconformity reported on top of the Middle Guadalupe (Labor and Lodolitas de Aguascalientes) in Medina and Bogota (Guerrero & Sarmiento, 1996; Pérez & Salazar, 1978; and Vergara & Rodriguez, 1997). In these locations, the fine- to coarse-grained sandstones of lower-upper shoreface (Tierna and Areniscas de San Luis de Gaceno) are overlain the deeper facies by a sharp contact. Likewise, the surface connects with the middle to late Maastrichtian SU that truncates the Campanian in the area of the wells. During the formation of this surface, the regional foreland basin extended from west (UMVB and MMVB) to east (LLB) (Horton et al., 2010). The major tectonic event reported is the collision of allochthonous blocks in the west of the paleo-Central Cordillera by Villagómez & Spikings (2013) but, the specific timing remains unclear as this event occurred between ±75 Ma to ± 70 Ma. At this time, the paleo-Central Cordillera along with the uplifting blocks from the east acted as sediment sources (Bayona, 2018). That explains the increase in the sedimentation rate by the late Campanian that triggered the forced regression resulting in the RSME and SU.

Moreover, our data show that the TSE on top of the Mirador Formation in the Sagu, and the Eocene fluvial facies of the wells, locally formed along the LLB and maybe part of the ECB, where coastal plain facies of the Concentration Formation overlies the fluvial facies of the Picacho-Regadera Formation. The surface formed when the exhumed western flank of the ECB separated the foreland basin, creating the Llanos Foreland Basin and the Hinterland Magdalena Valley (Bayona et al. 2013; Caballero et al. 2010; Horton et al. 2010; and Silva et al. 2013). At that time, the ECB and the LLB were connected (Ochoa et al., 2012). Although this TSE marks the initiation of a marine transgression that caused an abrupt change in the facies (e.g., Fig. 2.7M, 2.7N, and 2.7O), its formation occurred under continuous tectonism that enhanced the accommodation, (Parra et al., 2010). This retrogradation of the shoreline is supported by the presence of *cruziana* and *thalassinoides* ichnofacies in the middle Eocene and earliest Oligocene rocks, Figs 2.7N and 2.7O. The first-order change took place between the late Paleocene and the middle Eocene when subaerial exposure occurred along all the basins, and the sedimentation decreased due to negative accommodation. Subsequently, the sedimentation renewed with the deposition of the Mirador Formation in the middle to late Eocene, which was interpreted to be deposited in the first stages of the separation of the basins and, so it belongs to the new first-order sequence. Therefore, the magnitude of the TSE is second-order.

The understanding of these surface still requires finding their correlatable surface in several depocenters as the Caguan-Putumayo Basin, Northern Llanos Basin, Lower Magdalena Valley Basin, and Cocuy-Tablazo basin. We suggest analyzing the same interval along these areas for further studies. The data in these locations will provide insightful and key information to improve the understanding of how the surfaces expanded and what triggered their formation. Our data indicate that to the south (Caguan-Putumayo basin) their correlative surface must be another subaerial unconformity with a substantial hiatus. In the case of Cocuy-Tablazo and Northern Llanos Basin, we predict a similar arrangement with presumably a minor hiatus. Along the Lower Magdalena Valley Basin, marine conditions prevailed for a longer period and the unconformities identified in this study may not be present. Nonetheless, surfaces such as the correlative conformity or the basal surface of the forced regression may have been preserved. However, these hypotheses should be further constrained.

Finally, similar conditions of multiple unconformities preserved are commonly found in analog basins. As an example, Gómez et al. (2019) report the presence of unconformities that were partially or entirely correlated basin-wide. Following our results, the extension of these surfaces can be controlled by the magnitude and influence of the tectonic setting in which they were formed. For instance, the RSME of the Sagu creek, formed during a correlatable forced regression episode but its extension is restricted to the ECB (axial part and eastern flank) due to its entire absence along the LLB. However, the complexity of the regional setting also influences the formation and propagation of unconformities. In some scenarios, the transition from the under- to the overfilled stage is not marked by an unconformity (e.g., Zagros basin), but with a transitional contact (Pirouz et al., 2017). Therefore, our results represent a proxy to the understanding of complex sedimentary records such as the Oriente, Himalayan, and Neuquen foreland basins where several unconformities can be tracked basin-wide (Baby et al., 2013, 1999; Barragan & Baby, 2003; Bhatia et al., 2014; Yinfu et al., 2010).

2.8. Conclusions

(I) The late Campanian-early Oligocene siliciclastic sedimentary facies of the SLLB preserve two general patterns. In summary, progradation took place from the late Campanian to the middle Eocene and retrogradation from the middle-late Eocene to the early Oligocene. Likewise, the sedimentary record allowed the recognition of distinct changes in the facies. Some of those are separated by either abrupt change of facies or unconformable contacts with the latter being formed under subaqueous or subaerial conditions.

(II) Four significant unconformities were recognized along the Sagu creek. Some are preserved in the area of the wells, but some others are not. Two of them were formed under subaqueous conditions, whereas the other two formed under subaerial conditions. Their superimposition controls their absence around the wells. A clear example is the latest Campanian RSME, which is absent in the locality of the wells due to the superimposition of the middle to late Maastrichtian to early Paleocene SU that reworked and truncates the Campanian rocks in wells 1, 2, and 3.

(III) The magnitude and extension of these unconformities are related to their type and their relation to tectonism. For instance, the middle Maastrichtian to early Paleocene SU from the Sagu and wells correlates with a similar unconformity reported across the UMVB, MMVB, and ECB, which marks the change from coastal-distal to distal-proximal fluvial deposition. This shift corresponds to the transition from the under- to the overfilled stage of the regional foreland basin that existed at that time. This change occurs when sedimentation outpaces accommodation and enhances the formation of fluvial networks across the entire basin (Catuneanu, 2004, 2019a; Nemčok et al., 2005). Therefore, this SU represents a second-order stratigraphic surface that may be mapped basin-wide.

(IV) Similarly, the late Paleocene to middle Eocene SU from the Sagu and the wells were correlated across the adjacent basins. Indeed, it is synchronic to the MMVU defined by (Gómez et al., 2005). The regional extension of this surface is explained due to it formed during erosional unloading, which may have been triggered by the termination of the foreland basin (Horton et al., 2010; and Parra et al., 2009). Thus, it corresponds to a first-order stratigraphic surface. Its diachroneity is probably associated with the basin architecture at that time. The fact that the reported time gap of this SU in the easternmost MMVB and along the ECB (e.g., Bayona et al., 2013) is negligible suggesting that the depocenter migrated eastwards during the overfilled stage in the Paleocene.

(V) The latest Eocene to earliest Oligocene TSE formed after the first-order tectonic change occurred and, so its presence is restricted to the LLB and ECB, which according to previous authors, were connected at that time (e.g., Ochoa et al., 2012). For that reason, no similar stratigraphic surface is preserved in the UMVB or MMVB.

(VI) The absence and presence of an unconformity are controlled by the magnitude of the tectonism and to the tectonic setting. For instance, the RSME located in the Sagu creek was formed when the foreland basin extended regionally. Although it is absent along the UMVB, MMVB, and part of the ECB, the corresponding basal surface of the forced regression must be preserved in those areas. On the contrary, the TSE formed during the late Eocene to early Oligocene in the Sagu and wells area has no equivalent across the UMVB and the MMVB due to it formed when the regional foreland was separated into two different basins.

(VII) These results contribute to the understanding of how the stratigraphic record preserves evidence of the major and minor tectonic events during all the stages of the basin evolution and establish the relationship between the tectonic history and the different unconformities in the sedimentary record. Our methodology and results can be applied to analog complex basins.

Basin	Location	Author	Formation	Age	General Description	Environmental Interpretation		Correlation to the study area
						Prev Studies	This Study	
Upper and Middle Magdalena Valley	Piedras	Guerrero et al. (2000) and Bayona (2018)	Seca	Maastrichtian to Middle	Gray mudstones with minor interbedding of glauconitic sandstones and coals towards the lower part. While at the upper part reddish siliciclastic sandstones are dominant.	The lower part is Coastal, the upper part is a flood/alluvial plain.	Lower part: Coastal Plain Upper Part: Marginal Fluvial	N/A Study area indicates a period of erosion and no deposition during this time.
			La Tabla	Early to Middle Maastrichtian	Coarsening-upward fossiliferous litharenites and sandy biospartites, conglomeratic sandstones, and pebble conglomerates toward the top.	Lower part: shallow ramp to shoreface Upper Part: Upper Shoreface to Coastal	Lower part: Lower to Upper Shoreface Upper Part: Upper Shoreface to Coastal Plain	Coastal Plain deposits from Guaduas in Sagu. No record in the Wells area.
			Buscavidas	Late Campanian to Early Maastrichtian	Coarsening-upward biomicrites and impure (muddy) biomicrites with foraminifera.	Shallow marine ramp	Inner shelf	Shoreface facies from Upper Guadalupe and lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.

er and Middle Magdalena Valley

arvajal et al. (1993), Yepes (2001) and Garzon et al. (2012)

			Upper Lidita	Middle to Late Campanian	Laminated biomicrites and cherts with scarce thin to medium beds of phosphatized bio- and intra-micrites.	Deep carbonate ramp	Inner shelf	Inner shelf facies of the lower part of the Middle Guadalupe in Sagu. Upper and Shoreface deposits in the Wells (restricted info).
			Gualanday	Eocene	Conglomerates interbedded with reddish to gray mottled claystones and mudstones.	Braided fluvial channels	Continental fluvial	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
	Aico		Seca	Late Maastrichtian to Middle Paleocene	Reddish mottled claystones with conglomeratic levels. In the upper part, gypsum and calcite are present in a succession of sandstones with some plant debris.	Continental to marginal	Marginal fluvial	Late Maastrichtian: N/A Study area indicates a period of erosion and no deposition during this time. Paleocene: Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			La Tabla	Early to Middle Maastrichtian	Coarsening upwards succession of massive, flaser laminated and cross-bedded medium-grained to coarse sandstones. Presence of marine microfossils.	Littoral	Lower to upper shoreface	Coastal Plain deposits from Guaduas in Sagu. No record in the Wells area.

arvajal et al. (1993), Yepes (2001) and Garzon et al. (2012)

Age

er and Middle Magdalena Valley

			Buscavidas	Latest Campanian to Early Maastrichtian	Dominant siltstones with sporadic intervals of thin wavy heterolithic successions between mudstones and very fine-grained sandstones. Horizontal burrows. The upper part becomes sandier as the heterolithic are most common and the sandstones are medium to fine-grained. A high content of marine microfossils.	Shallow marine, near the fair and storm weather wave base.	Inner shelf	Shoreface facies from Upper Guadalupe and lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
			Upper Lidita	Late Campanian	Black to dark chert interbedded with siltstones and porcelanites. A high content of marine microfossils.		Outer shelf	Lower shoreface and inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.

er and Middle Magdalena Valley

Lamus et al. (2013); Bayona et al. (2013) and Bayona (2018)

	Guaduero		San Juan de Rio Seco	Middle Eocene to Early Oligocene	Very fine to coarse-grained sandstones and conglomeratic sandstones and conglomerates.	Continental braided to meandering rivers and floodplains	Continental to marginal fluvial	Mirador formation and Carbonera C8 in the Sagu. In the wells, it correlates with the Eocene facies association 5 and with the Oligocene lower shoreface facies.
			Seca	Maastrichtian to Middle	Gray and reddish mottled mudstones with some very fine to medium sandstones beds.	Floodplains, paleosols, and fluvial deposition	Lower part: Coastal Plain Upper Part: Marginal Fluvial	N/A Study area indicates a period of erosion and no deposition during this time.

er and Middle Magdalena Valley	**Guaduero**	Lamus et al. (2013); Bayona et al. (2013) and Bayona (2018)	Umir	Campanian to Early-Middle Maastrichtian	The transition from marine siliciclastic mudstones, siltstones, chert, and carbonates to marginal siliciclastic mudstones and sandstones with some carbonates.	Shallow marine with fan deltas to the coastal plain	Inner shelf to lower shoreface and coastal plain	Shoreface facies from Upper Guadalupe and lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well. The lower part of Umir Fm correlates with the Lower Guadalupe described by Martinez (2016) in Sagu.
	San Juan de Rio Seco		San Juan de Rio Seco	Middle Eocene to Early Oligocene	La Cruz member: cross-bedded coarse conglomeratic sandstones. Almacigos member: mudstones dominated with very thick beds of cross-bedded coarse-grained sandstones. Armadillos member: cross-bedded medium to coarse-grained sandstone.	Alluvial plain and braided and meandering rivers	Lower part: continental fluvial Upper part: marginal fluvial	Mirador formation and Carbonera C8 in the Sagu. In the wells, it correlates with the Eocene facies association 5 and with the Oligocene lower shoreface facies.

er and Middle Magdalena Valley
966); Gomez et al. (2003); Bayona et al. (2013); Lamus et al. (2013) and
(1996) **San Juan de Rio Seco**

				Hoyon	Middle Paleocene to Early Eocene	Cross-bedded conglomerates in the lower part, and horizontal laminated and matrix-supported conglomerates in the upper part. The upper part contains more mudstone intervals.	Alluvial fans	Lower part: continental fluvial Upper part: marginal fluvial	Lower part: Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells. Upper part: Los Cuervos formation in the Sagu. Facies association 6 in Wells 1 and 2, while Well 3 indicates erosion/non-deposition.
				Seca	Middle-Late Maastrichtian to	Intercalation of gray mudstones with cross-bedded medium to coarse-grained sandstones that turn conglomeratic towards the top.	Floodplains, paleosols, and fluvial deposition	Lower part: Coastal Plain Upper Part: Marginal Fluvial	N/A Study area indicates a period of erosion and no deposition during this time.
				Cimarrona	Early to Middle Maastrichtian	Coarsening upwards succession from medium-fine grained sandstones with foraminifera to conglomeratic sandstones with gastropods, bivalves, and ammonites.	Shallow marine with fan deltas to the coastal plain	Lower part: Upper shoreface Upper part: Coastal plain	Coastal Plain deposits from Guaduas in Sagu. No record in the Wells area.

er and Middle Magdalena Valley	San Juan de Rio Seco		Umir	Campanian to Early Maastrichtian	Dominant mudstones with foraminifera, bivalves, and ammonites. The presence of thick to very thick fine to very fine wavy laminated sandstones with calcareous concretions is prominent in the upper part.	Shallow marine	Inner shelf and the uppermost is a transition to lower and upper shoreface.	Shoreface facies from Upper Guadalupe and lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
	Tesalia	Veloza et al. (2008) and Ferreira et al. (2002)	Potrerillo	Oligocene	Laminated reddish, greenish, and yellowish mudstones and siltstones with some very thick beds of conglomerates.	Flood plains	Marginal fluvial	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
			Palermo/Bache	Middle Eocene	Lower Part: Coarsening upwards succession from cross-bedded very coarse-grained sandstones with siltstones lenses; to gravelly conglomerates with very coarse-grained sandstones lenses. Upper Part: Mudstones with lenses and very thick beds of gravelly very coarse-grained sandstones, with plant debris. Some calcareous sandstones are registered in the middle part.	Lower part: fluvial channels Upper part: floodplains	Lower part: Continental fluvial Upper part: marginal fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.

er and Middle Magdalena Valley	Tesalia	Veloza et al. (2008) and Ferreira et al. (2002)	Teruel	Late Paleocene	Very coarse-grained sandstones with gravel clasts and siltstones.	Fluvial to coastal plain	Marginal fluvial	Los Cuervos formation in the Sagu. Facies association 6 in Wells 1 and 2, while Well 3 indicates erosion/non-deposition.
			San Francisco	Early Paleocene	Reddish to gray mottled sandy siltstones with pant debris and roots; paleosols and thick to very thick beds of gravelly coarse-grained sandstones.	Fluvial	Continental fluvial	Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			Monserrate	Campanian	Wavy laminated or flaser bedded clayey sandstones with bioturbation and phosphates; with thick intervals dominated by fossiliferous horizontal bedded dark mudstones. These facies are locally calcareous.	Offshore to nearshore	Lower shoreface to inner shelf	Lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies in the lower part of each well.
	Girardot	De Porta (1966) and Acosta et al. (2002)	Potrerillo	Oligocene	Coarsening upwards bed succession of claystones to gravelly coarse-grained sandstones interbedded with claystones.	Alluvial plains to braided fluvial	Continental fluvial	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.

er and Middle Magdalena Valley	Girardot	De Porta (1966) and Acosta et al. (2002)	Chicoral	Middle Eocene	Coarsening upwards succession from cross-bedded medium to coarse-grained sandstones interbedded with claystones; to conglomerates and sandstones separated by thick intervals of claystones.	Alluvial to flood plains	Continental fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.
			Seca	Late Maastrichtian to Middle Paleocene	Lower part: fine-grained sandstones interbedded with gray mudstones. Upper part: Reddish mudstones with siltstones with plant debris and sporadic fine-grained quarzitic sandstones.	Delta plain to meandering rivers	Lower part: Coastal Plain Upper Part: Marginal Fluvial	Late Maastrichtian: N/A Study area indicates a period of erosion and no deposition during this time. Paleocene: Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			La Tabla	Early to Middle Maastrichtian	Coarsening upwards succession from medium-fine grained sandstones with foraminifera to conglomeratic sandstones with gastropods, bivalves, and foraminifera replaced with calcite. Gypsum is reported.	Shoreface to the coastal plain	Lower to upper shoreface	Shoreface facies from Upper Guadalupe. No Maastrichtian record from the Wells area.

per and Middle Magdalena Valley	**Girardot**	De Porta (1966) and Acosta et al. (2002)	Nivel de Lutitas y Arenas	Campanian to Early Maastrichtian	Horizontal laminated and sporadic wavy laminated calcareous siltstones with foraminifera and ichnofossils, interbedded with calcareous mudstones. Some beds of fine to very fine-grained sandstones are registered, as well as gypsum layers.	Calcareous shelf	Inner shelf	Shoreface facies from Upper Guadalupe and lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
Eastern Cordillera Basin and Foothills	**Medina**	Guerrero y Sarmiento (1996), Parra et al. (2010), Jaramillo (1999) and Jaramillo and Dilcher (2000)	Carbonera C8 / San Fernando	Early Oligocene	Dark-gray to greenish mudstone. Occasional minor bioturbation. Limited interbeds of trough cross-laminated sandstone. Local micro foraminiferal linings and dinoflagellates.	Transitional environment, lakes, prodelta or estuaries	Inner shelf	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
			Mirador / Areniscas de El	Lower to Middle Eocene	Massive and cross-bedded conglomeratic and coarse sandstones with the occurrence of gravelly conglomeratic beds.	Braided fluvial channels	Continental fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.

			Upper Socha / Arcillas de El	Upper Paleocene	Light grey, purple, and green claystones and siltstones with plant debris and occasional fine to medium cross-bedded sandstones. The lower part registers bioturbation and some brackish palynomorphs.	Flood plains and channel fills from Coastal/Deltaic plain	Coastal plain	Los Cuervos formation in the Sagu. Facies association 6 in Wells 1 and 2, while Well 3 indicates erosion/non-deposition.
Eastern Cordillera Basin	Medina	ento (1996), Parra et al. (2010), Jaramillo (1999) and Jaramillo and Dilcher (2000)	Lower Socha	Early Paleocene	Cross-bedded medium to coarse and occasionally conglomeratic sandstones with some intervals of reddish to gray siltstones and mudstones with plant debris.	Braided fluvial channels and floodplain deposits in continental setting	Continental fluvial	Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			Guaduas	Middle to Late Maastrichtian	Gray siltstones with plant debris interbedded with thin to very thin quarzitic very fine-grained sandstones; and gray to black carbonaceous mudstones with plant debris.	Swap, lakes, and bays. Coal seems associated with estuaries	Coastal plain	Coastal Plain deposits from Guaduas in Sagu. No record in the Wells area.
			Arenitas de San Luis	Early to Middle Maastrichtian	Dominant medium to coarse-grained sandstones with cross-bedding, bivalves, horizontal burrows, and wavy lamination. The lower part contains a ±15 m heterolithic succession.	From top to bottom: foreshore to Lower Shoreface.	Lower part: Lower to Upper Shoreface Upper Part: Upper Shoreface	Shoreface facies from Upper Guadalupe. No Maastrichtian record from the Wells area.

Eastern Cordillera Basin	**Medina**	errero y Sarmiento (1996), Parra et al. (2010), Jaramillo (1999) and amillo and Dilcher (2000)	Lodolitas de Aguascalientes	Middle to Late Campanian	Dominant black mudstones with some intervals of very fine sandstones with phosphorous, gastropods, rhizocorallium, bivalves, and horizontal burrows.	Deposition below the fair and storm weather wave base.	Inner shelf	Lower shoreface and inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
			Arenitas de San Antonio	Early to Middle Campanian	Fine to medium-grained sandstones with horizontal burrows, phosphorous and glauconite, and some intervals of black mudstones and heterolithic.	Lower to upper shoreface	Lower to upper shoreface	No checked in the area. But according to Martinez (2016), it is correlatable with Lower Guadalupe in the Sagu area.
	Umbita	Bayona et al. (2013) and Ulloa et al. (1975)	Concentracion	Early Oligocene	Gray to reddish and greenish siltstones and claystones interlayered with sandstones and some conglomerates.	Coastal and marginal swamps	Coastal plain	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
			Picacho	Middle to Late Eocene	Conglomeratic medium to coarse-grained feldspathic sandstones with conglomeratic lenses and often interbedded with claystones.	Fluvial	Continental fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.

Eastern Cordillera Basin	Bayona et al. (2013) and Ulloa et al. (1975)	**Umbita**	Upper Socha	Late Paleocene to Early Eocene	Dominant claystones and siltstones interbedded with fine to medium-grained sandstones.	Fluvial	Marginal fluvial	Los Cuervos formation in the Sagu. Facies association 6 in Wells 1 and 2, while Well 3 indicates erosion/non-deposition.
			Lower Socha/Cacho	Middle Paleocene	Medium to coarse and often conglomeratic quarzitic sandstones with an interval of interbedded sandstones and siltstones in the middle part of the unit.	Fluvial	Continental fluvial	Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			Guaduas	Middle Maastrichtian to	Dark to gray claystones and siltstones intercalated with fine to medium-grained sandstones that are often conglomeratic in the upper part. Very thick coal seams are reported in the middle part of the unit.	Littoral to continental marine	Lower part: Coastal Plain Upper Part: Marginal Fluvial	N/A as Sagu and Wells area under erosion.
			Tierna	Early Maastrichtian	Fine to coarse-grained quarzitic sandstones interbedded with dark to black lutites.	Shallow marine to deltaic	Upper shoreface	Shoreface facies from Upper Guadalupe and coastal plain deposits from Guaduas in Sagu. No Maastrichtian record from the Wells area.

Eastern Cordillera Basin	Umbita	Bayona et al. (2013) and Ulloa et al. (1975)	Labor	Late Campanian	Fine to grained quarzitic sandstones interbedded with dark to black lutites.	Shallow marine	Lower shoreface	Lower shoreface and inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies in the lower part of each well.
			Plaeners	Middle Campanian	Siliceous siltstones, lutites, and very fine to fine-grained sandstones.	Shallow marine	Inner shelf	No checked in the area. But according to Martinez (2016), it is correlatable with Lower Guadalupe in the Sagu area.
	Bogota	Vergara y Rodriguez (1997), Acosta et al. (2002) and Bayona et al. (2010)	Usme	Early Oligocene	Massive to cross-bedded coarse to medium-grained sandstones with gray to reddish and often mottled massive mudstones.	Swamps, floodplains, and channels deposition	Coastal plain	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
			Regadera	Middle to Late Eocene	Horizontal-, cross-bedded and massive medium to coarse-grained sandstones often mottled with massive mottled to reddish mudstones. Some intervals have roots, indicating paleosols.	Channel fills and floodplains	Continental fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.

Sarmiento (1992), Vergara y Rodriguez (1997); Acosta et al. (2002) and Bayona et	**Eastern Cordillera Basin**	**Bogota**	Bogota	Late Paleocene to Early Eocene	Horizontal to trough cross-bedded medium to coarse-grained sandstones, often wavy laminated, interbedded with gray to reddish, and mottled massive mudstones and siltstones. Presence of tuffs.	Swamps, floodplains, and channel deposition, close to areas with volcanism.	Marginal fluvial	Los Cuervos formation in the Sagu. Facies association 6 in Wells 1 and 2, while Well 3 indicates erosion/non-deposition.
			Cacho	Middle Paleocene	Horizontal-, cross-bedded and massive medium to coarse-grained sandstones often mottled, interbedded with gray massive mudstones. In some parts heterolithic sedimentation.	Swamps, floodplains, channels deposition.	Continental fluvial	Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
			Guaduas	Middle Maastrichtian to Early Paleocene	Lower part: Massive coarse to medium-grained sandstones interbedded with laminated and massive mudstones. This interval contains Coal seams. Heterolithic intervals. Upper part: Massive coarse to medium-grained sandstones interbedded with reddish to mottled mudstones and heterolithic deposits.	Lower part: coastal plain and fluvial channels Upper part: fluvial and floodplains	Lower part: Coastal Plain Upper part: Marginal Fluvial	N/A as Sagu and Wells area under erosion.
			Tierna	Early Maastrichtian	Thick beds of cross-bedded sandstones with a few thin to medium beds of siltstones and mudstones that disappear towards the top. Phosphatic nodules, fish bones, glauconite, and horizontal ichnofacies (skolithos and cruziana).	Littoral	Upper shoreface	Shoreface facies from Upper Guadalupe and coastal plain deposits from Guaduas in Sagu. No Maastrichtian record from the Wells area.

Eastern Cordillera Basin	**Bogota**	ez & Salazar (1978), Sarmiento (1992), Vergara y Rodriguez 97), Acosta et al. (2002) and Bayona et al. (2010)	Labor	Late Campanian	Thick to very thick beds of clayey fine to medium-grained sandstones with sporadic phosphatic nodules, fish bones, and ichnofacies (often horizontal). These intervals are separated by very thin beds of claystones and mudstones.	Shallow marine, between the fair and storm weather wave base.	Lower Shoreface	Lower shoreface and inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
			Plaeners	Middle Campanian	Siliceous siltstones and claystones, lutites, and very fine-grained sandstones interbedded with mudstones and siltstones. This interval is highly fossiliferous (e.g., fish bones) but with low content of ichnofacies. Horizontal and wavy lamination is dominant.	Shallow marine	Inner shelf	No checked in the area. But according to Martinez (2016), it is correlatable with Lower Guadalupe in the Sagu area.
	Fusa	Acosta & Ulloa (2001) and Bayona et al. (2003)	Unit III/Bogota	Late Eocene to Early Oligocene	Decametric sequences of massive, sandy light gray to red mottled mudstones interbedded with metric sequences of medium to thick beds of fine to medium-grained sublitharenites, litharenites, and subarkoses to the top.	Alluvial to the coastal plain	Coastal plain	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.

			Unit II/Cacho	Middle Eocene	Fining-upward successions of green to gray, fine to medium-grained sandstones interbedded with light gray, massive, and sandy mudstones. Sandstones are dominantly massive and ripple-wavy laminated at the bottom; through cross-bedding in isolated cosets.	Coastal plain	Continental fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.
			Unit I/Guaduas	Early to Middle Paleocene	Green, wavy-laminated mudstones with an excellent record of the plant's remains. Thin to medium beds of ripple-laminated, fine-grained iron-rich quartz arenites dominate at the bottom. The middle to the top is dominated by coarsening upwards sequences or interbedded mudstones.	Coastal plain	Marginal fluvial	Barco formation in the Sagu creek and the Paleocene facies association 5 in the Wells.
Eastern Cordillera Basin	**Fusa**	osta & Ulloa (2001) and Bayona et al. (2003)	Labor	Late Campanian	Fine to medium-grained sandstones in thick to very thick beds.	Littoral to sublittoral	Lower Shoreface	Lower shoreface and inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.
			Plaeners	Middle Campanian	Thin beds of siliceous siltstones with foraminifera interbedded with gray mudstones.	Littoral to sublittoral	Inner shelf	No checked in the area. But according to Martinez (2016), it is correlatable with Lower Guadalupe in the Sagu area.

Eastern Cordillera Basin	**Uribe**	Buchely et al. (2015) and Buchely (2015)	San Fernando	Oligocene	Gray siltstones and mudstones with plant debris interbedded with thin beds of medium to coarse-grained quarzitic cross-bedded sandstones.	Lacustrine	Coastal plain	Marine facies with thalassinoides from the Carbonera C8 in the Sagu, and lower shoreface facies with ophiomorphas from the Wells.
			Mirador*	Eocene*	Conglomerates, medium-coarse grained quarzitic conglomeratic sandstones, and siltstones in sub tabular to tabular beds.	Braided fluvial	Continental -Marginal fluvial	Conglomeratic facies of the Mirador formation in Sagu and the intervals with the Eocene facies association 5 in the Wells.
			Palmichal Gp.	Campanian	Dominant fine to medium-grained sandstones with horizontal bedding and some wavy bedding. The succession contains very thick beds of conglomerates with cross-bedding, as well as some beds of gray siltstones.	Delta plain	Upper shoreface to the coastal plain	Lower shoreface to inner shelf deposits from Middle Guadalupe in Sagu. In the Wells, it is correlatable to the upper shoreface and coastal facies identified in the lower part of each well.

Table 2.2. Lithofacies occurrence and characteristics, facies association, and depositional process interpretation of the Late Campanian to Early Oligocene rock units form the SLLB. Depositional environment interpreted following Boggs (2006), Jones & Jones (2012) and Nichols (2009).

2.9. References

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Chapter 3: First-order stratigraphic boundaries of the Late Cretaceous – Paleogene retroarc foreland basin in Colombia

ABSTRACT

The present-day Magdalena Valley, Eastern Cordillera, and Llanos Basin were part of a regional multiphase basin that started as an extensional basin in the Jurassic, was transformed into a retroarc foreland basin in the Late Cretaceous, and subsequently separated into a hinterland and a foreland basin during the Eocene. The purpose of this study was to establish the stratigraphic boundaries formed during the first-order changes that marked the beginning and the end of the lifespan of the retroarc foreland basin. In the initial stage, the lateral extent along the dip of the foreland basin was approximately 300-470 km. The Magdalena Valley, Eastern Cordillera, and westernmost Llanos Basin comprised the major depocenters of the basin. However, the western flank of the Eastern Cordillera and most of the Llanos Basin were uplifting. A late Campanian first-order maximum regressive surface preserved at the base of the retrograding marine facies of the Upper Lidita, Buscavidas and Umir, Guadalupe, and Palmichal units, is the lower boundary of the retroarc foreland sequence. This surface does not extend across the whole basin. In the uplifting areas, subaerial unconformities truncate the middle Campanian rocks. These surfaces compound the lower first-order boundary and its diachroneity is controlled by the northward migration of the orogen. The Teruel, Hoyon, Bogota, Cacho, Socha, Barco, and Cuervos formations are truncated by a regional first-order subaerial unconformity formed during orogenic unloading that marks the termination of the foreland basin in the Eocene. Therefore, it is the upper boundary of the first-order sequence.

Keywords: Campanian, Paleocene, sequence stratigraphy, composite surface, tectonic changes.

3.1.Introduction

Regionally, Colombia is in an active tectonic margin due to the interaction of the South American, Caribbean, and Nazca plates (Colleta et al., 1990; Cooper et al., 1995; Dengo & Covey, 1993). This interplay caused the uplift of the three ranges (Western, Eastern, and Central) and also the separation of a Late Cretaceous-Paleogene regional basin into multiple basins (Gómez et al., 2005; Gómez et al., 2003; Horton et al., 2010; Parra et al., 2010; Saylor et al., 2012). The regional basin started as a continental rift from the earliest Cretaceous, it became a retroarc basin by the Late Cretaceous and was separated by the uplift of the Eastern Cordillera during the Paleogene (Bayona et al., 2020, 2013; Cediel et al., 2011; Horton et al., 2010; Nie et al., 2010; Pindell & Erikson, 1994; Sarmiento, 2001; Zapata et al., 2019). As a result, different multiphase basins with around 140 Ma of sediment record preserve a complex structural evolution.

Colleta et al. (1990), Cooper et al. (1995), Dengo & Covey (1993), and Villamill (1999) promoted regional geological models regarding the uplift and exhumation of the Central and the Eastern cordilleras. The concepts introduced by those authors were complemented within the following decade by Bayona et al. (2007), Cortés (2006), Horton et al. (2010), Mora et al. (2006), Mora et al. (2008), Mora et al. (2010), Parra et al. (2010), Santos et al. (2008) and Sarmiento (2001). They calibrated the timing of uplift of the Eastern Cordillera and presented some analysis of the sedimentology and basin-fill history during the Cretaceous and part of the Cenozoic. More recently, these works have been summarized and complemented in a series of paleogeographic maps and geological models presented by (Bayona, 2018; Bayona et al., 2020; Cardona et al., 2018; Cediel et al., 2011; Martínez & Roncancio, 2011; Montes et al., 2019; Reyes-Harker et al., 2015; and Sarmiento, 2001, 2011).

The timing of the major tectonic events from the Campanian to the Paleogene is understood (e.g., Bayona et al., 2013; Caballero et al., 2010; Gómez et al., 2005; Moreno et al., 2011; Parra et al., 2012a; and Villagómez & Spikings, 2013). The geological model defined by Gómez et al., (2005ab) and Parra et al., (2010) state the foredeep of the regional foreland basin extended from the Magdalena Valley to the west to the Llanos Foothills to the east, with the Llanos Basin being the forebulge. In terms of sequence stratigraphy, multiple authors (e.g., Caballero et al., 2017; Caycedo Garcia & Catuneanu, 2018; Föllmi et al., 1992; Guerrero & Sarmiento, 1996; Guerrero et al., 2000; Naranjo et al., 2017; Ramon & Fajardo, 2006) have recognized numerous sequence

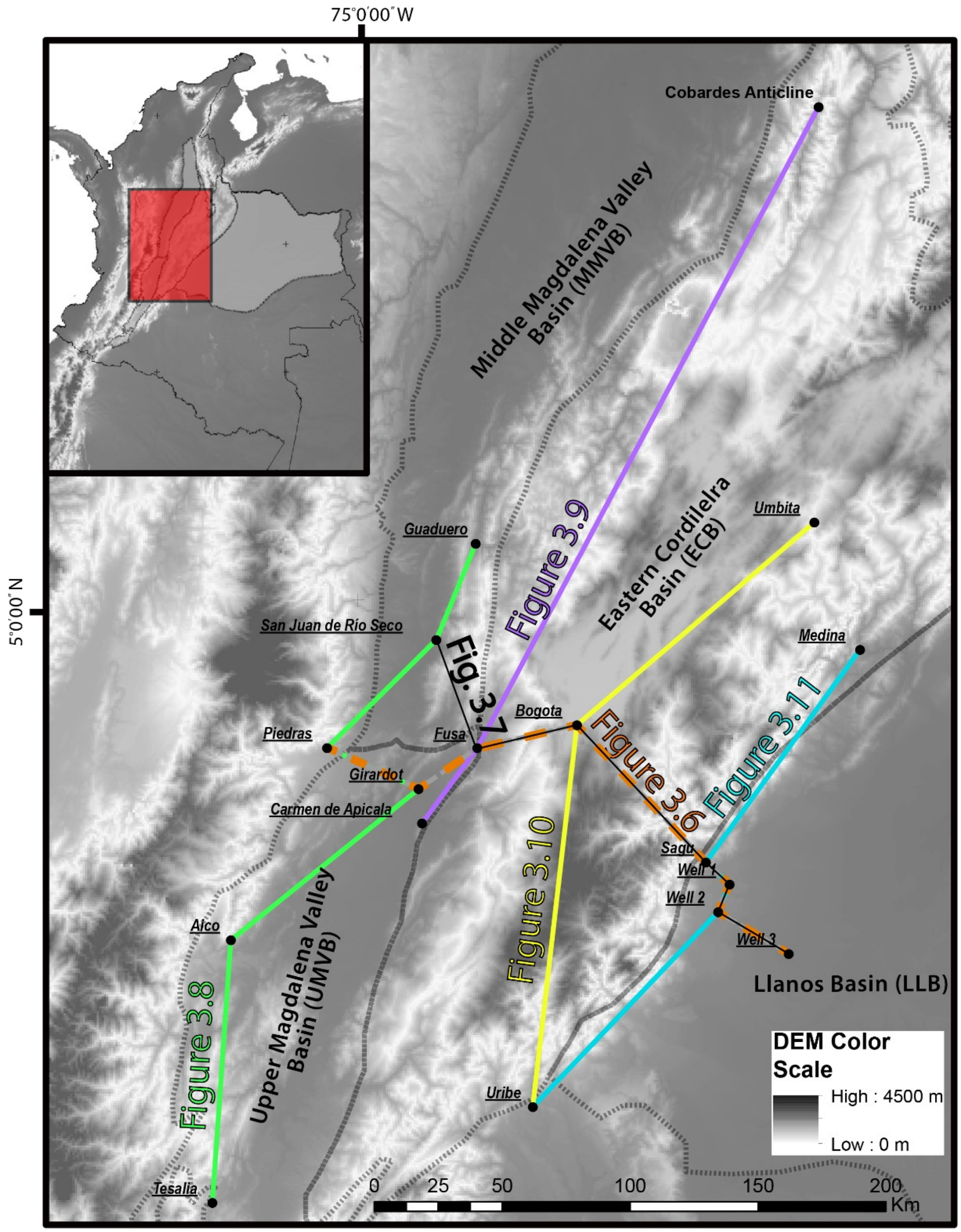


Fig. 3.1. Location of the study area in the central part of Colombia. UMVB: Upper Magdalena Valley Basin, MMVB: Middle Magdalena Valley Basin, ECB: Eastern Cordillera Basin, LLB: Llanos Basin. The reviewed authors are: Guadero: Bayona et al., (2013), De Porta, (1965), and Lamus et al., (2013); Umbita: Bayona et al., (2013) and Ulloa & Rodríguez, (1975); San Luis de Gaceno: Guerrero & Sarmiento, (1996), Jaramillo, (1999) and Parra et al., (2010); San Juan de Rio Seco: Bayona et al., (2013), Gómez et al., (2003) and Lamus et al., (2013); Bogota: Bayona et al., (2010), Pérez & Salazar, (1978), Sarmiento, (1992), Vergara & Rodriguez, (1997); Sagu: This study and Martínez, (2016); Wells 1-3: This Study; Piedras: Guerrero et al., (2000); Girardot: Acosta et al., (2002) and De Porta, (1966); Fusa: Bayona, (2018) and Bayona et al., (2003); Tesalia: Jiménez et al., (2012) and Veloza et al., (2008); Aico: Carvajal et al., (1993), Garzon et al., (2012) and Yepes, (2001b); Uribe: Buchely, (2015) and Buchely et al., (2015).

stratigraphic surfaces across the Upper and Middle Magdalena Valley (UMVB and MMVB), Eastern Cordillera Basin (ECB), and the Llanos Basin (LLB). The majority of the sequence stratigraphic surfaces recognized are local and not related to tectonic changes (e.g., Vergara et al., 1997). Therefore, these surfaces do not represent the initiation or termination point of the foreland basin, which is a compound surface that comprises the forebulge unconformity (Catuneanu, 2004, 2018). Hence, the purpose of this study is to determine the stratigraphic response to the first-order changes that mark the beginning and termination of the regional retroarc foreland basin in the study area, Fig 3.1.

This study includes three new stratigraphic sections from the Llanos Basin built from well data (cores and logs), Fig 3.1. The area was strategically selected because it was the marginal part of the extensional regional basin and became the forebulge of the regional foreland basin (Bayona, 2018; Gómez et al., 2005; Parra et al., 2010). So, the tectonic changes may have resulted in unconformities (e.g., forebulge unconformity) preserved within the sedimentary record. Those stratigraphic sections were correlated towards the UMVB, MMVB, ECB, and Llanos Foothills using 14 stratigraphic sections from several authors, Fig 3.1. The first step was the definition of the chronostratigraphic chart following the reported biozones. This process is described in Carvajal-Torres et al., (2021).

Furthermore, the recognition of changes in the accommodation and sedimentation was determined by the identification of variations in grain size, sedimentological structures, lithology, authigenic minerals, microfossils, and ichnofacies. The analysis was carried out independently in each section prior to correlation. Paleontological data was used to determine the timeframe and isochrones at every location. In addition, UPb ages of detrital zircons, heavy minerals distribution, petrographic studies, and paleocurrents direction were reviewed to establish the sediment sources and estimate the distribution of the fluvial channels. For instance, Bayona et al. (2013, 2008), Carvajal-Torres et al. (2019), and Lamus et al. (2013) demonstrated that during the Cretaceous-Paleocene, the sedimentary source of most of the ECB and LLB was closer to the Magdalena Valley due to the lack of unstable minerals in the sedimentary record. Likewise, their reported high population of Precambrian detrital zircons indicates a dominant sediment source of that age.

The results were plotted in paleogeographic palinspatically restored maps that summarize the timelines correlations from the latest Campanian to early Oligocene. Data from numerous authors (e.g., Cardona et al., 2018; Mann et al., 2006; Montes et al., 2019) have been used to constrain the palinspastic restorations. The sequence stratigraphic analysis and nomenclature were done following Catuneanu (2017, 2019a, 2020). The results indicate the transition from extensional to compressive regime resulted in a compound first-order stratigraphic surfaces composed of a

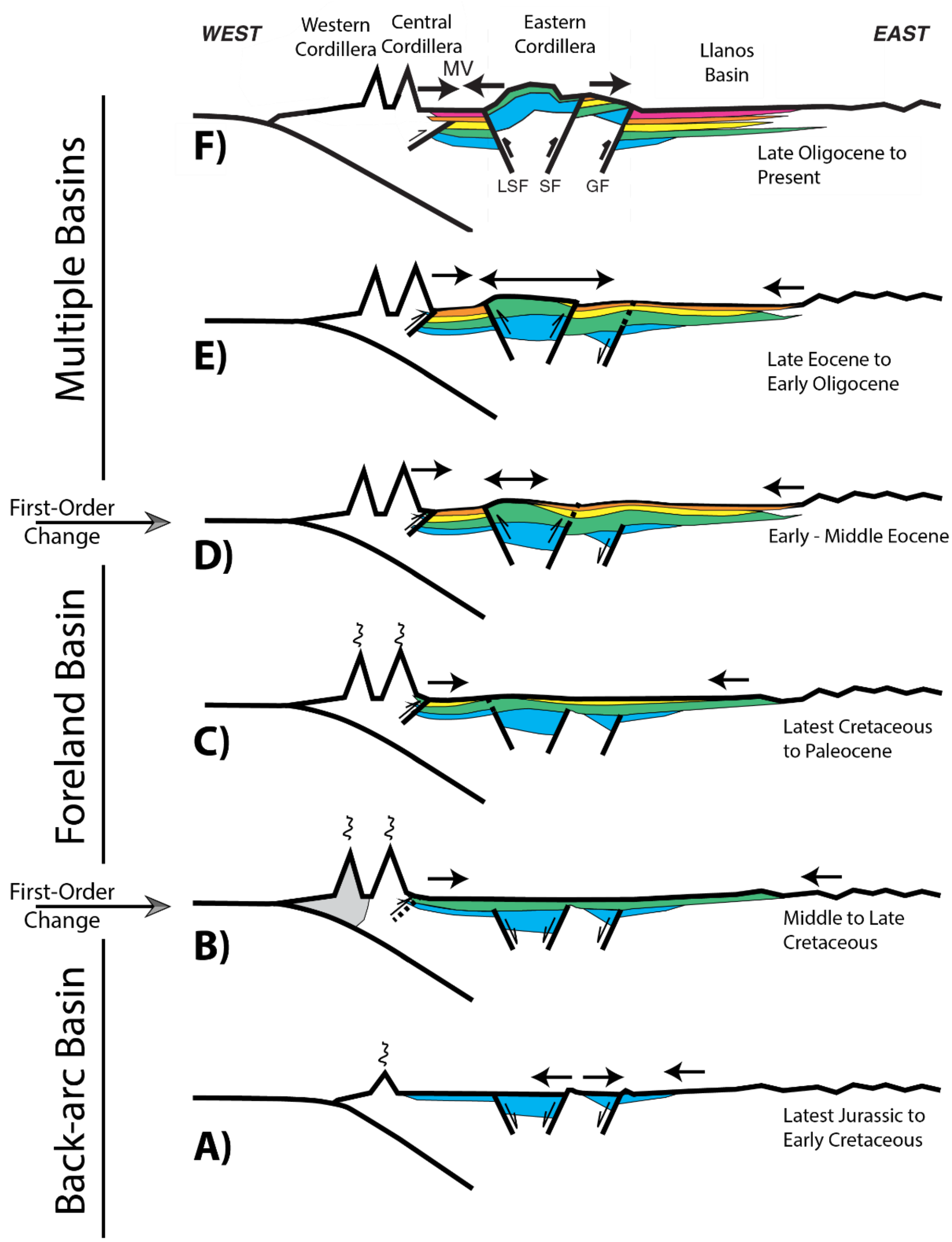


Fig. 3.2. Tectonic evolution of the Colombian Andes. After Horton et al. (2010a)

maximum regressive surface (MRS) and two subaerial unconformities (SU). Two hypotheses were evaluated to understand the formation of the forebulge unconformity. The first corresponds to the forebulge located in the Llanos Basin, while the second examines the location of the forebulge across the western flank of the ECB. The new data incorporated from Sagu creek and the Llanos basin contributed to define the extension of the retroarc foreland basin deposits, the basin architecture, and the diachroneity of the basin-fill history. Moreover, the results suggest that the transition from the retroarc foreland basin to the current geological setting that occurred during the Eocene is marked by a first-order subaerial unconformity that extends along the Colombian territory.

3.2.Geodynamic Framework

The tectonics of the Northern Andes is controlled by the interaction of the Nazca, South-American, and Caribbean plates. Their interaction produced the exhumation of the Western, Central, and Eastern Cordillera, and also transformed the basins that existed from the Late Jurassic to the Paleocene (Bayona et al., 2013; Horton et al., 2010). During the Cretaceous, subduction of the Caribbean plate under the South-American plate accompanied by a diachronous accretion of oceanic terranes from the west, resulting in the uplift and exhumation of the continent, triggering the closure of an existent extensional basin. The fact that older accreted terranes are in the southern part of Colombia is understood to be related to the northeastern movement of the subducting plate (Pindell & Kennan, 2009). Thermochronological data from Villagómez & Spikings (2013) along the Central Cordillera reveal that the exhumation of the continent started in the Early Cretaceous in the southwestern part of Colombia. While ± 400 km towards the northeast, the onset of the exhumation took place during the Late Cretaceous to Early Paleocene.

The accreted terrains were part of an oceanic volcanic arc developed during the Late Jurassic to Early Cretaceous in the back-arc basin (Spikings et al., 2015; Villagómez & Spikings, 2013). Their collision and further accretion triggered the exhumation of the Central Cordillera (Villagómez, 2010) due to an increase in the uplift rate and formed a retroarc foreland basin to the east (Gómez et al., 2005). The exhumation of the Central Cordillera prompted a rise in the terrigenous sediment supply into the basin. Therefore the sedimentation conditions in the platform diachronically switched from chemical precipitation to siliciclastic detritus during the uppermost Campanian to Early Maastrichtian. Bayona (2018) and Bayona et al., (2020) recognized this contact as the ‘xenoconformity’ defined by Carroll (2017). Data reveal this contact is younger northwards (e.g., Bayona et al., 2013; Garzon et al., 2012).

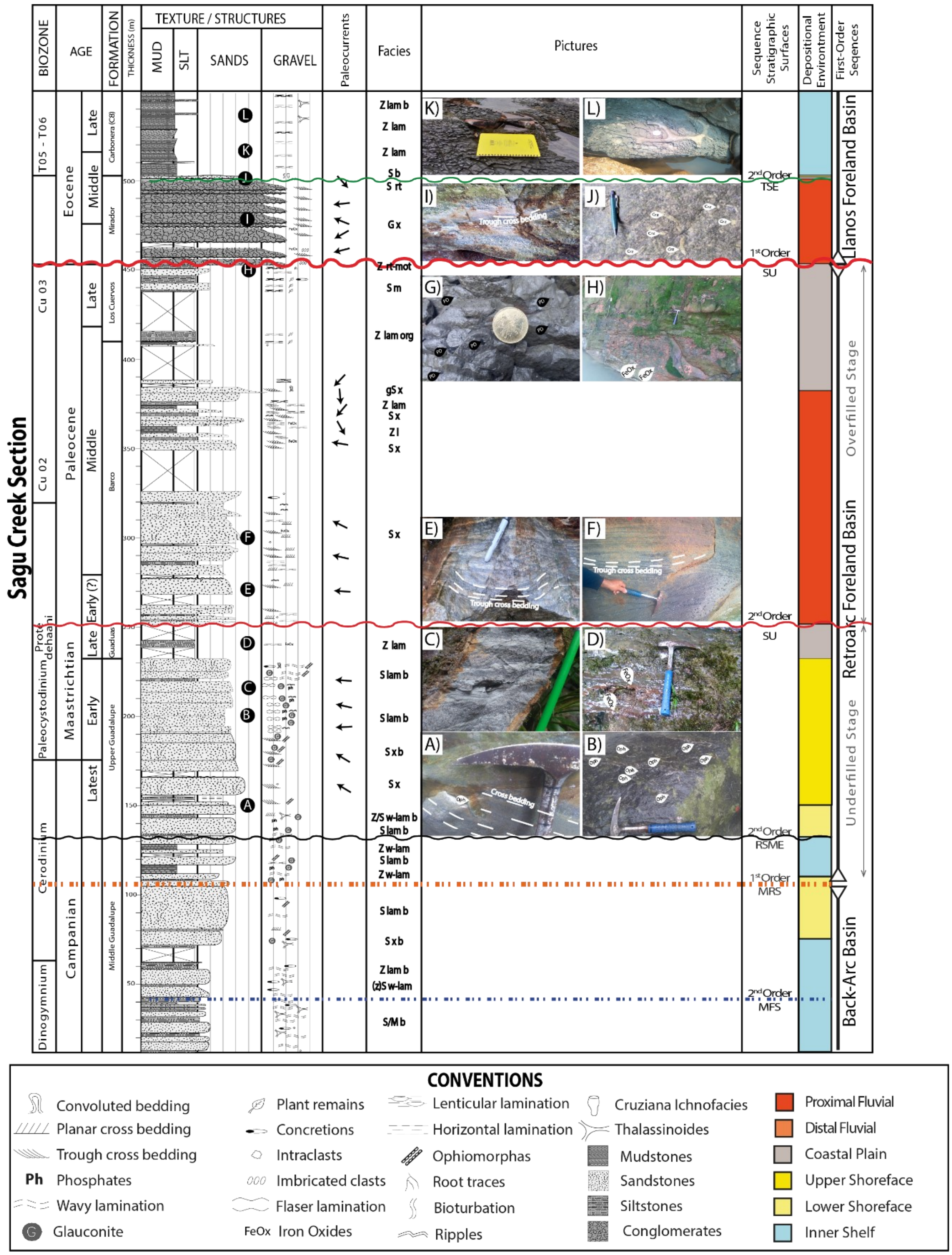


Fig. 3.3. Stratigraphic column from the Sagu creek. See facies codes description in Table 3.1 and faces association in Table 3.2. MFS: Maximum flooding surface; MRS: Maximum regressive surface, RSME: Regressive surface of marine erosion; TSE: Transgressive surface of marine erosion; and SU: Subaerial unconformity.

During the latest Campanian to Paleocene, the Central Cordillera was one of the sediment sources for the Magdalena Valley (Upper: UMVB and Middle MMVB), Eastern Cordillera (ECB), and Llanos basin (LLB). Their westernmost sedimentary record indicates an increase in volcanic and metamorphic Mesozoic grains (Bayona et al. 2013, Caballero et al. 2010, Horton et al. 2010, Moreno et al. 2011b; Nie et al. 2012). At this time, the ongoing subduction and associated terrain accretion caused the deformation that resulted in the uplift of the western flank of the Eastern Cordillera (Bayona et al. 2013; Moreno et al., 2013; Sánchez et al. 2012). This positive relief disconnected the western (UMVB and MMVB) and eastern (ECB and LLB) depocenters into different basins during the Paleocene to Eocene (Bayona et al., 2013; Ochoa et al., 2012; Reyes-Harker et al., 2015), which is recognized as a first-order change in the tectonic setting. From late Paleogene to Neogene the ongoing compression resulted in the folding and faulting of the ECB, and the formation of the present-day geological setting (Mora et al., 2013; Moreno et al., 2011; Ramirez-arias et al., 2012), Fig 3.2.

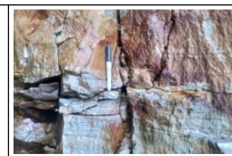
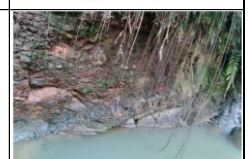
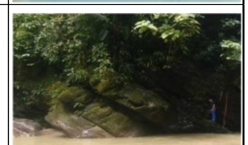
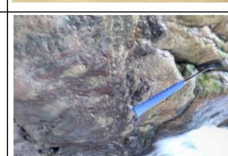
3.3.Data and Methods

We incorporated well data (cores, logs, and drilling reports) from three wells in the LLB, Fig 3.1. This data was provided by the Geological Survey of Colombia (SGC). The Campanian age of the rock units in the Sagu and the wells was defined following the *Cerodinium-Dinogyminium* biozone from Caballero et al. (2020), ICP - Ecopetrol (2014), and Martínez (2016). The presence of Maastrichtian rocks in the Sagu Creek was established due to the *Paleocystodinium* and *Proteacidites dehaani* biozones from Vergara & Rodriguez (1997). The timing of the Paleocene and Eocene rock units along the Sagu and wells was identified according to Caballero et al. (2020), Guerrero & Sarmiento, (1996), Parra et al. (2009), and Vergara & Rodriguez (1997). Likewise, the time gap of the unconformities was determined using the results from Caballero et al. (2015), Carvajal-Torres et al. (2019), De La Parra (2009), and ICP - Ecopetrol (2014), which defined that the lacuna of the Cretaceous-Paleocene and Paleocene-Eocene, was about ±5-10My and ±12My, respectively. The stratigraphic sections of the Sagu and wells are presented in Figs. 3.3 and 3.4.

Following Farrell et al. (2012), we defined the lithofacies, Table 3.1. Subsequently, their associations were specified, see Table 3.2. A detailed facies analysis can be found in Carvajal-Torres et al. (2021). Furthermore, we defined a simplified depositional model to establish the depositional environment of each facies association, Fig 3.5, and Table 3.2. This model indicates the relation between the orogen and the shoreline and summarizes the accumulation conditions. In addition to the Cretaceous-Paleocene and Paleocene-Eocene unconformities, we included the late Campanian and middle Eocene unconformities from Caballero et al. (2015, 2020) and Carvajal-Torres et al. (2021). Based on Catuneanu (2017, 2019), Catuneanu et al. (2011), and MacEachern et al. (2012) we determined a 1) late Campanian regressive surface of marine erosion (RSME), 2) the Cretaceous-Paleocene and Paleocene-Eocene boundaries as subaerial unconformities (SU), and 3) the middle to late Eocene transgressive surface of erosion (TSE), Fig 3.3. The late Campanian RSME is absent in the wells, Fig 3.4.

Dominant Lithofacies Code	Lithologic Characteristics	Picture
S/M b	Heterolithic sandstones and mudstones with horizontal burrows (thalassinoides)	
(z)S w-lam	Wavy laminated silty fine-grained sandstones	
Z lam b	Wavy laminated siltstones with horizontal burrows (thalassinoides)	
S lam b	Laminated fine to coarse-grained sandstones with vertical burrows (ophiomorphas)	
S x b	Cross-bedded medium-grained sandstone with vertical burrows (ophiomorph te	
S biot	Bioturbated medium-grained sandstones	
Z/S w lam b	Wavy laminated heterolithic siltstone and sandstone with horizontal burrows (thalassinoides)	

Table 3.1. Lithofacies associations and depositional context interpretations.

S x	Through cross-bedded medium to coarse grained sandstone	
Z lam	Laminated gray siltstone with iron oxides	
Z lam org	Laminated gray siltstone with plant debris	
Z rt-mot	Gray siltstone with root traces and iron oxides	
S m	Massive fine to medium-grained sandstone	
S rt	Fine to medium-grained sandstone with root traces	
G x	Cross-bedded gravel	
Z l	Lenticular bedded gray to reddish siltstone	

Continued Table 3.1.

Facies Association	Dominant Lithofacies Code	Depositional Context (mechanism of deposition)	Occurrence	Simplified environment
FA 1	S/M b	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.	In the Sagu three intervals, in the Middle Guadalupe from meter 0 to ±70, from ±110 to ±130, and in the Carbonera (C8). Absent in the Wells.	Inner Shelf
	(z)S w-lam	Low energy setting close to the storm wave base, dominated by tides and often affected by storm waves		
	Z lam b	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.		
	S lam b	Low energy setting proximal to the fair weather wave base, and often affected by storm waves		
FA 2	S x b	Softground and substrate-controlled. Biogenic reworking in medium energy flow, above the fair weather wave base.	In the Sagu seciton three intervals, in the Middle Guadalupe from meter ±70 to ±110 and from ±130 to ±150; and a very thick bed on top conglomerates of Mirador	Lower Shoreface
	S biot	Soft ground and substrate-controlled. Biogenic reworking in medium to low energy flow, close to the fair weather wave base.		
	S lam b	Same as above		
	Z/S w lam b	Same as above		
FA 3	S x	High energy regime setting affected by the oscillatory flow-landward transportation of the waves.	Dominant in the Upper Guadalupe and in the lower part of the Wells.	Upper Shoreface
	S x b	Softground and subtrate-controlled. Biogenic reworking in medium to high energy flow, affected by oscillatory movements of the waves. With K and P enrichment and low sedimentation rates.		
	S lam b	Soft ground and substrate-controlled. Biogenic reworking in medium to high energy flow typical of plane-bed conditions.		
FA 4	Z lam	Aerobic low energy setting with suspension deposition.	Dominant in the Guaduas and Los Cuervos formations in the Sagu. And in the Upper Campanian deposits from the Wells. Interval ±9360 to ±9310 in W1, ±8120 to ±8095 in W2, and ±8200 to ±8172 in W3.	Coastal Plain
	Z lam org	Aerobic low energy setting with suspension deposition, with some episodes of increased water level that caused anaerobic temporary conditions.		
	Z rt-mot	Aerobic low energy setting with suspension deposition.		
	S m	Hyperconcentrated flow during abrupt changes in flow speed from low to high energy.		
	S x	Same as above		
	S rt	Same as above		
FA 5	S x	Same as above	Dominant in the Barco and Mirador formations in the	Contiental Fluvial
	G x	Migration of bedforms related to high turbulent flow energy channels.		
FA 6	S x	Migration of bedforms related to medium flow energy channels.	No dominant interval in Sagu or W3. But one interval in W1 and w2, ±9200 to ±9160, and	Marginal Fluvial
	Z l	Aerobic low energy setting with suspension deposition.		
	S rt	Migration of bedforms related to medium flow energy channels.		

Table 3.2. Facies association and depositional environment interpretation.

After the independent interpretation of depositional environments, multiple chronostratigraphic correlations were built to achieve a better understanding of the regional context., Fig 3.1, 3.6, 3.7, 3.8, 3.9, 3.10 and 3.11. Based on Qayyum et al. (2017, 2015) and Wheeler (1959), we first correlated the isochrones from the list of the authors reviewed per location with the those found in the Sagu and wells. That list is presented in Table 3.3. Afterward, we correlated the unconformities. As stated by Carvajal-Torres et al. (2021), the subaqueous unconformities from the Sagu and wells were limited to the Llanos Basin and part of the ECB. Nonetheless, the Cretaceous-Paleocene and Paleocene-Eocene SU were successfully correlated across the adjacent depocenters. The lacuna varied in each location. For instance, Bayona et al. (2013) exposed that in Bogota that time gap is almost null, whereas in Umbita and San Juan de Rio Seco it is at least ±2My. We also the biostratigraphic gaps and numerical methods from Caballero et al. (2015), Caballero et al. (2020), Contreras et al. (2010), De La Parra (2009), Gómez et al. (2003), Jaramillo (1999), Jaramillo et al. (2011), Vergara & Rodriguez (1997), and Yepes (2001a). Their data is highly effective and relative age changes were identified. Nonetheless, we understand that those lacunas are subject to further calibration.

Finally, we correlated the chronostratigraphic units following the facies associations and depositional environments, interpreting the transitions when they changed laterally, and no information was in between. The results are plotted in Figs 3.6, 3.7, 3.8, 3.9, 3.10, and 3.11. Also, we identified a contact between prograding facies below and retrograding facies above of the late Campanian in most of the sections. Therefore, we interpret a maximum regressive surface (MRS). In the Sagu section, it marks the contact between a ≈ 30 m FA 2 (lower shoreface deposits) and the overlaying ≈ 20 m FA 1 (inner shelf deposits), see *S lam b* and *Z w-lam* contact in Fig 3.3. This MRS is absent in the sections from Fusa, Carmen de Apicala, and the wells, as a synchronous SU truncates the middle to late Campanian strata.

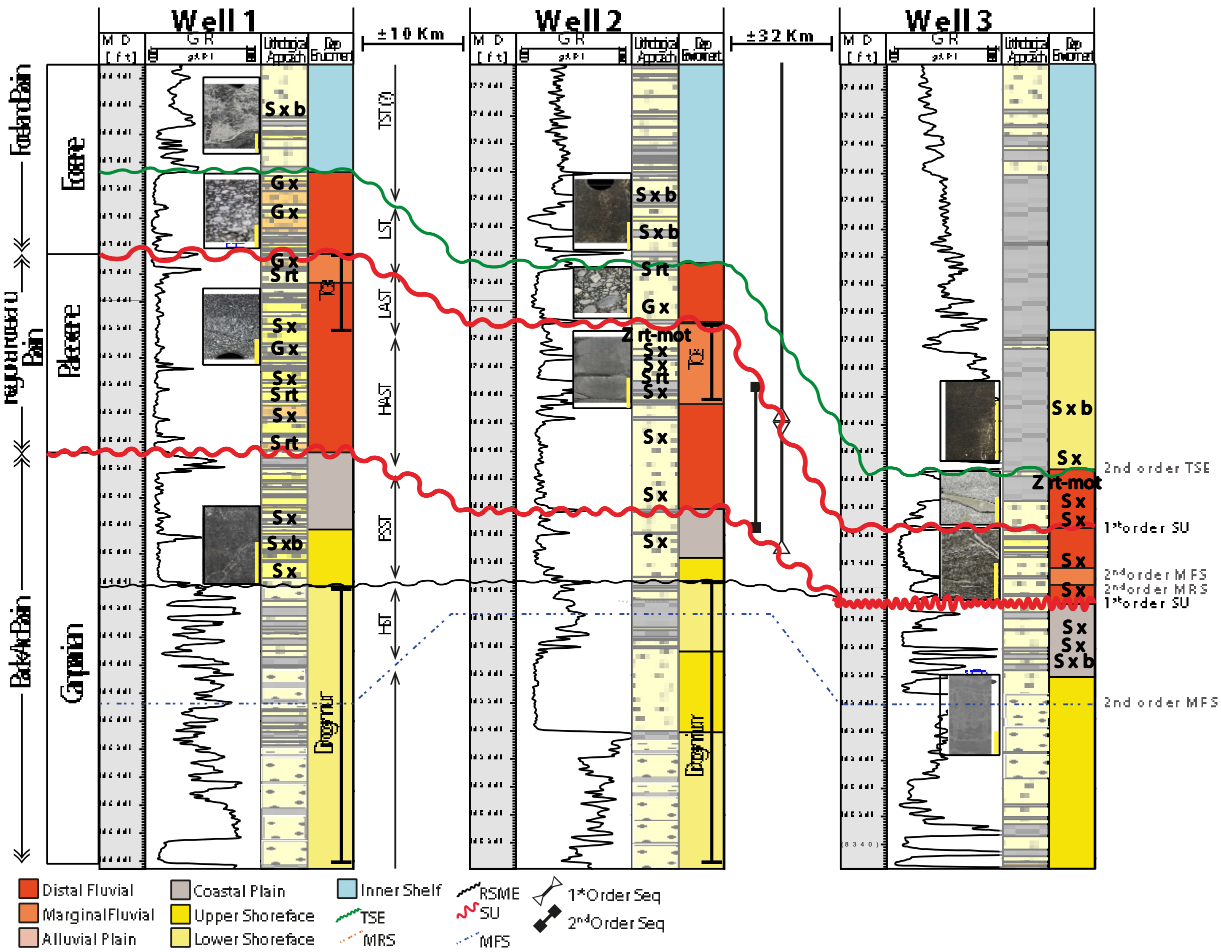


Fig. 3.4. Stratigraphic section from the wells 1 to 3 with its corresponding correlation. See facies codes description in Table 3.1.

To determine the hierarchy of these surfaces we analyzed their relationship with the major and minor tectonic events that occurred since the late Campanian to the earliest Oligocene, which is the estimated lifespan of the retroarc foreland basin (e.g., Gómez et al., 2005; Horton et al., 2010; Mora et al., 2010; Moreno et al., 2011a; Parra et al., 2009; Villagómez, 2010; Villagómez & Spikings, 2013). Moreover, the basin architecture was estimated based on the sedimentary thickness of the units during the two stages of the basin (underfilled and overfilled). The latter were outlined following the principles from Catuneanu (2019), in which in a sedimentary basin connected to the global ocean the underfilled accommodation occurs below the sea level. Otherwise, it takes place within the overfilled accommodation.

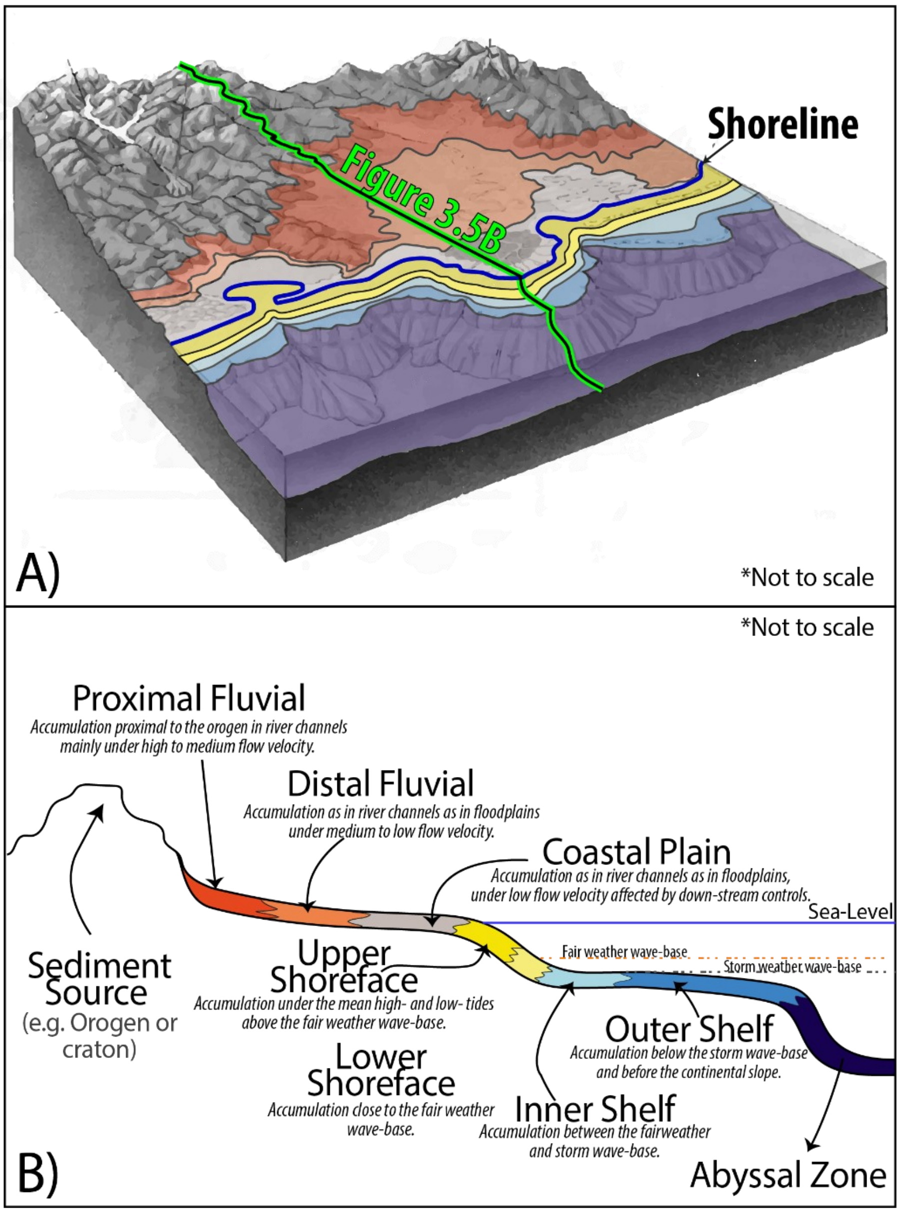


Fig. 3.5. Generalized depositional model.

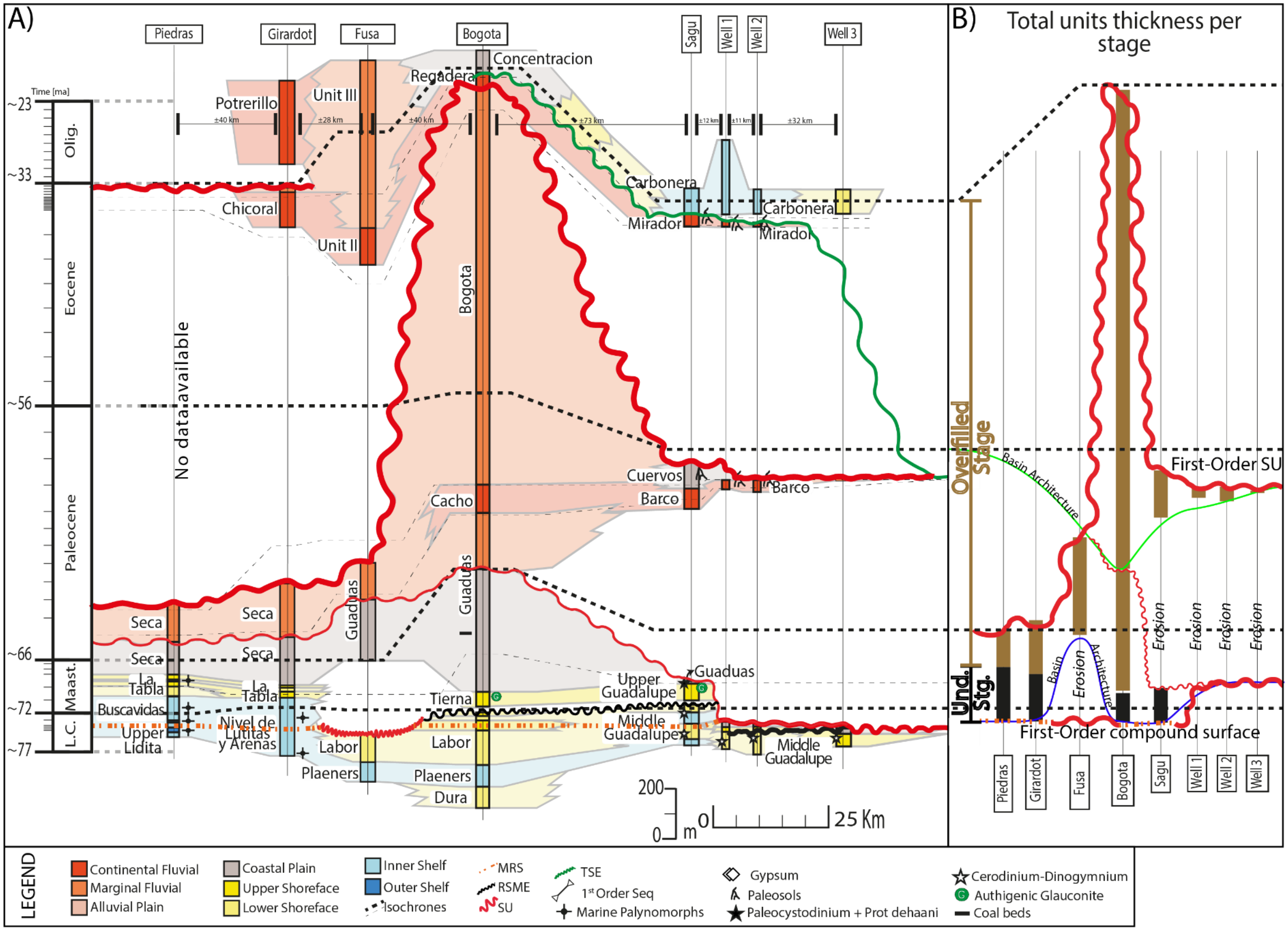


Fig. 3.6. Chronostratigraphic correlation from the MMVB to the LLB. Location in Fig 1. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion; Und Stg: Underfilled Stage. The thickness of the unconformities represents its hierarchy and magnitude

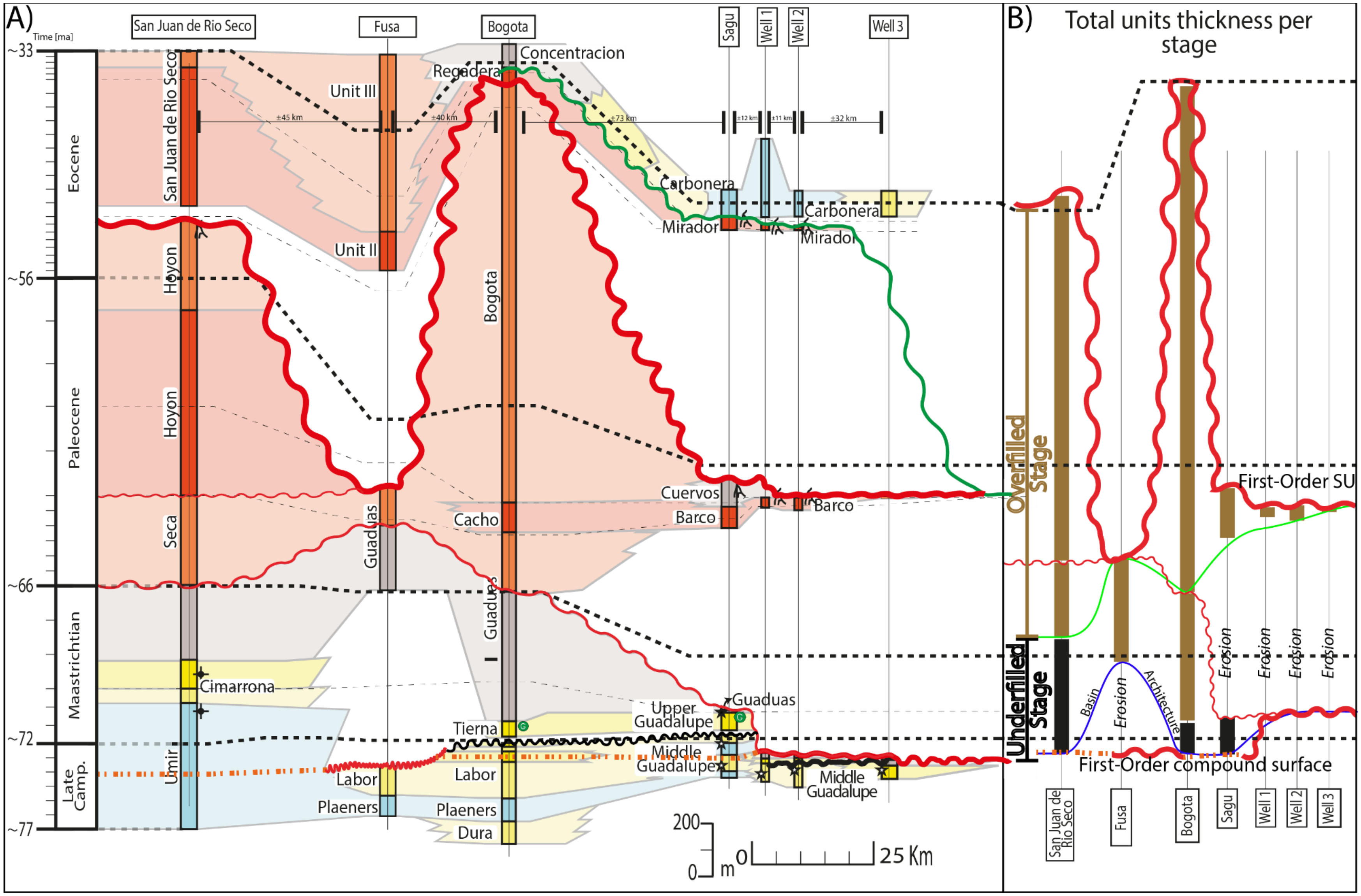


Fig. 3.7. Chronostratigraphic correlation from the MMVB to the LLB. Location in Fig 1, conventions in Fig 6. The thickness of the unconformities represents its hierarchy and magnitude. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion. The thickness of the unconformities represents its hierarchy and magnitude

Fig. 3.8. Chronostratigraphic correlation from the UMVB to the MMVB. Location in Fig 1, conventions in Fig 6. The thickness of the unconformities represents its hierarchy and magnitude. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion. The thickness of the unconformities represents its hierarchy and magnitude.

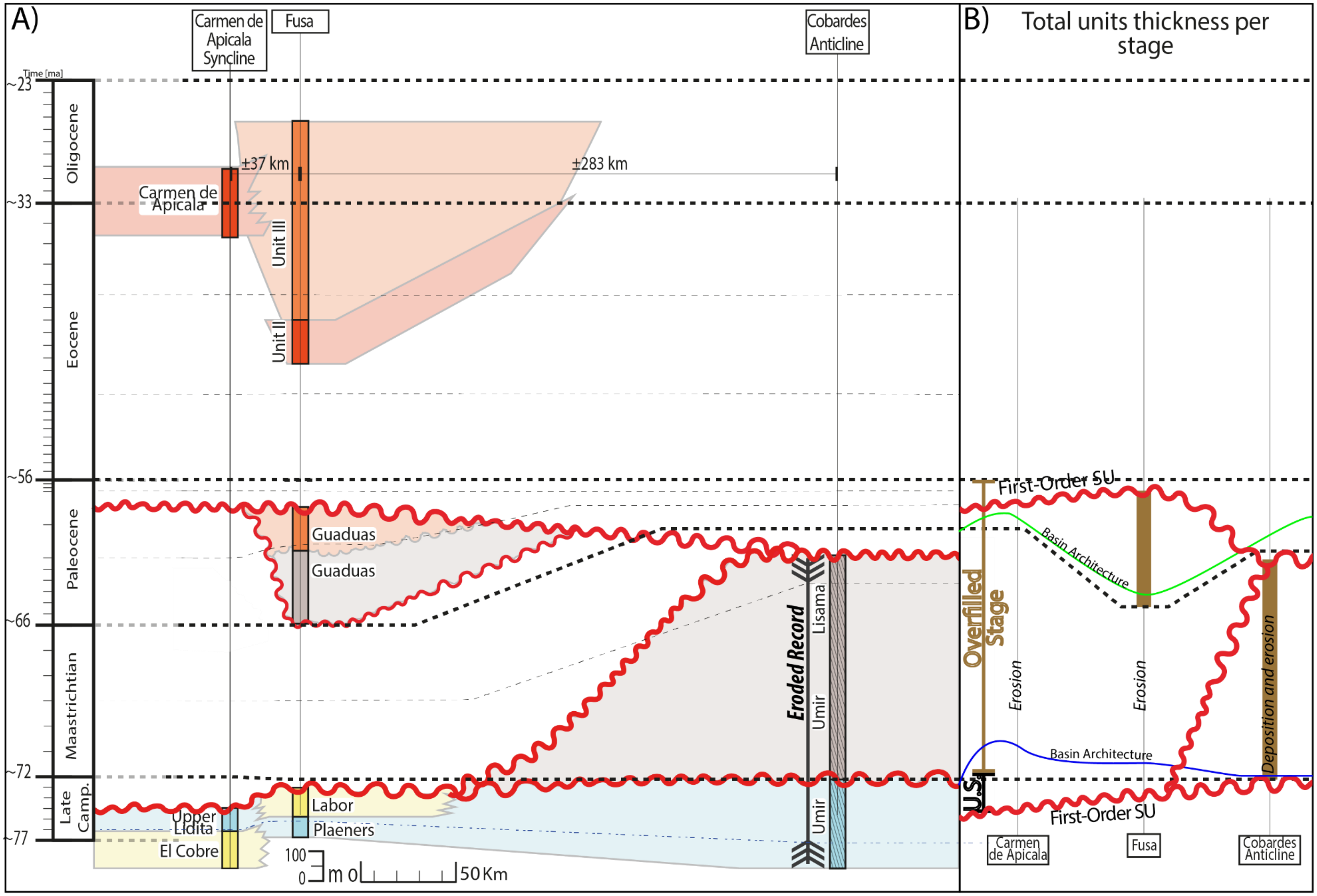


Fig. 3.9. Chronostratigraphic correlation across the western flank of the ECB. Location in Fig 1, conventions in Fig 6. The thickness of the unconformities represents its hierarchy and magnitude. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion; US: Underfilled Stage. The thickness of the unconformities represents its hierarchy and magnitude.

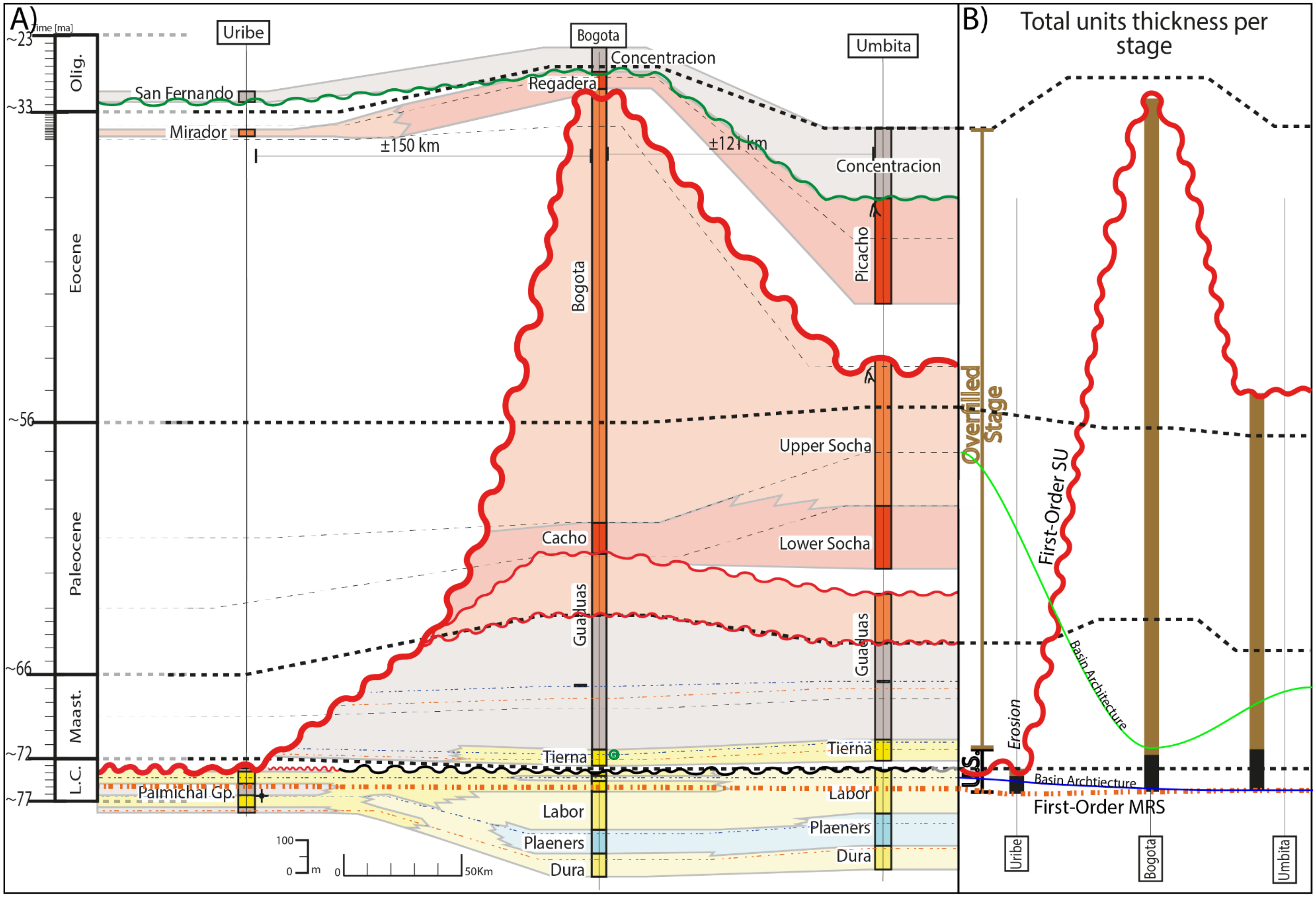


Fig. 3.10. Chronostratigraphic correlation from Uribe to Umbita (along the axial part of the ECB). Location in Fig 1, conventions in Fig 6. The thickness of the unconformities represents its hierarchy and magnitude. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion; US: Underfilled Stage. The thickness of the unconformities represents its hierarchy and magnitude.

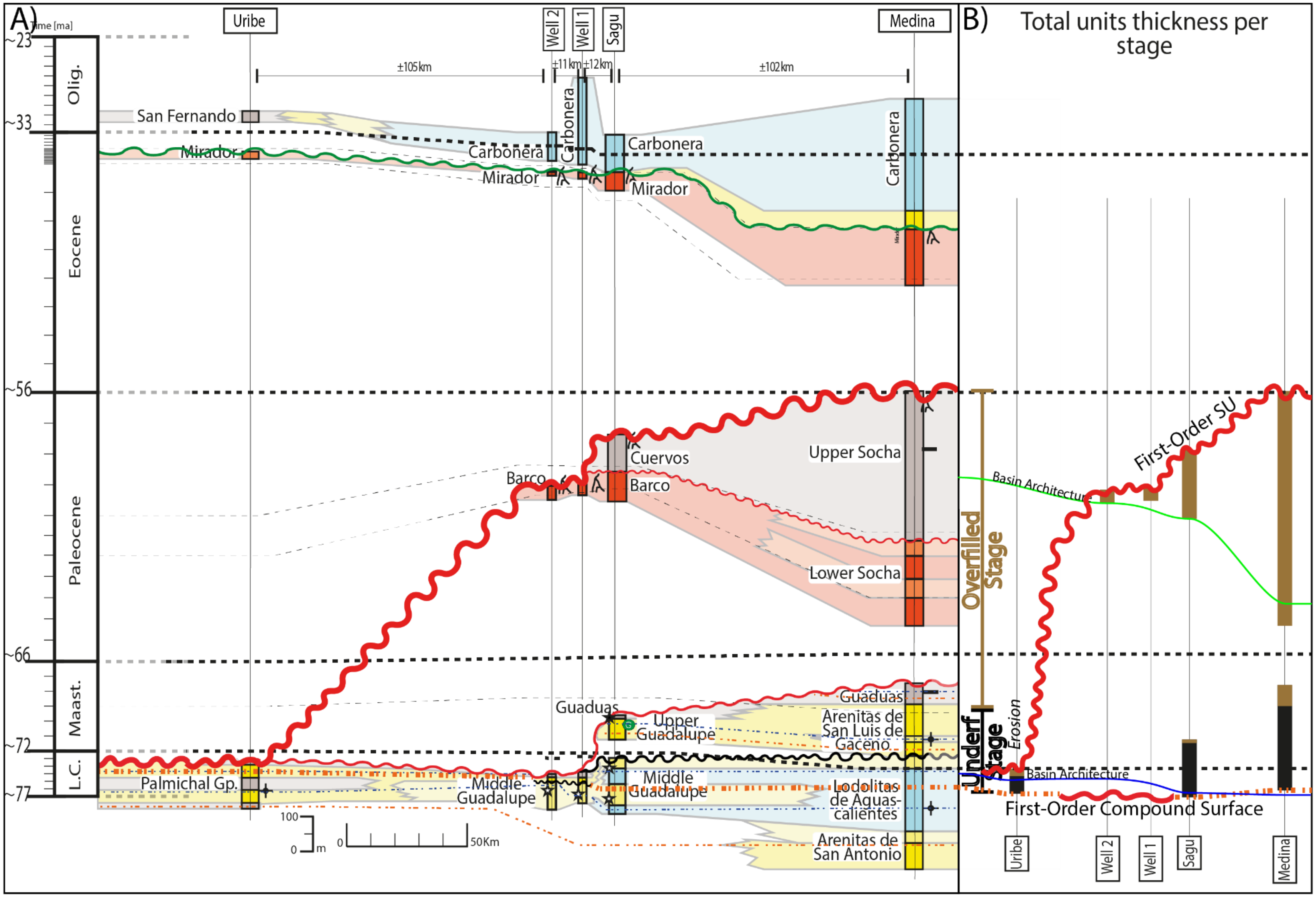


Fig. 3.11. Chronostratigraphic correlation along the LLB. Location in Fig 1, conventions in Fig 6. The thickness of the unconformities represents its hierarchy and magnitude. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion. The thickness of the unconformities represents its hierarchy and magnitude.

3.4.Foreland Basin Fill History

Several studies have identified stratigraphic surfaces such as unconformities (e.g., Gómez et al., 2005; and Ramon & Rosero, 2006), and maximum flooding surfaces (MFS) (e.g., Caballero & Naranjo, 2015, 2017; Caballero et al, 2020), even so, their relationship with the regional tectonic framework is not considered. Indeed, the changes in the eustatic sea level are contemplated by some authors (e.g., Garzon et al., 2012) as the primary factor driving transgressions and regressions. Detailed studies focused on the timing of the structures (e.g., Mora et al., 2010, 2013; and Silva et al., 2013) demonstrated the active tectonism also exerted control in the movement of the shoreline. Changes in the tectonic setting caused the first-order changes in the study area, Fig 3.2, and defined the lifespan of the regional foreland basin.

The lithostratigraphy and facies of the Colombian territory are illustrated and described by multiple authors (e.g., Vergara & Rodriguez, 1997). This study compiles their reports and includes new data from the southern part of the Llanos Basin to exhibit the regional distribution of the facies and their relationship with the tectonic framework. Figures 3.3 and 3.4 expose the new data incorporated and figures 3.6 to 3.11 illustrate the chronostratigraphic correlations across the Colombian territory. Following, we present a series of palinspatically restored maps constructed based on Bayona (2018), Cediel et al. (2011), Mann et al. (2006), Martínez & Roncancio (2011), Reyes-Harker et al. (2015), and Sarmiento (2001), see figures 3.12 to 3.16. They highlight the basin architecture and the tectonic framework during the first-order changes and the facies distribution during the different stages of the basin evolution.

3.4.1. Upper Campanian

The uplift of the paleo-Central Cordillera and the accretion of the oceanic terranes in the study area took place in the late Campanian (Mora et al., 2020; Villagómez, 2010; Villagómez & Spikings, 2013). As a result, the extensional basin ended due to the exhumation of the continent, (Fig 3.2). The prograding sediments overlying the Middle Campanian MFS, (Fig 3.3-3.6), indicate a regression of the shoreline across the whole study area. The lithological evidence is preserved within the transition from the Upper Lidita to Buscavidas, and within the lowermost part of the Umir formation along the UMVB and MMVB, where outer shelf facies are overlain by inner shelf facies, Fig 3.8. In Aico, it resulted in a decrease of marine palynomorphs (Garzon et al., 2012; Yepes, 2001a), Fig 3.8. Likewise, the Middle Guadalupe formation (Labor unit in ECB), preserves upper shoreface facies within a lower shoreface facies succession, (Fig 3.10). In the Llanos foothills, the Middle Guadalupe (Lodolitas de Aguascalientes in Medina) exposes lower shoreface facies within inner shelf facies, (Figs 3.3, 3.6, and 3.11). Indeed, the late Campanian rocks from the Medina section indicate a reduction in the marine palynomorphs and an increase in continental and terrestrial microfossils (Guerrero & Sarmiento, 1996).

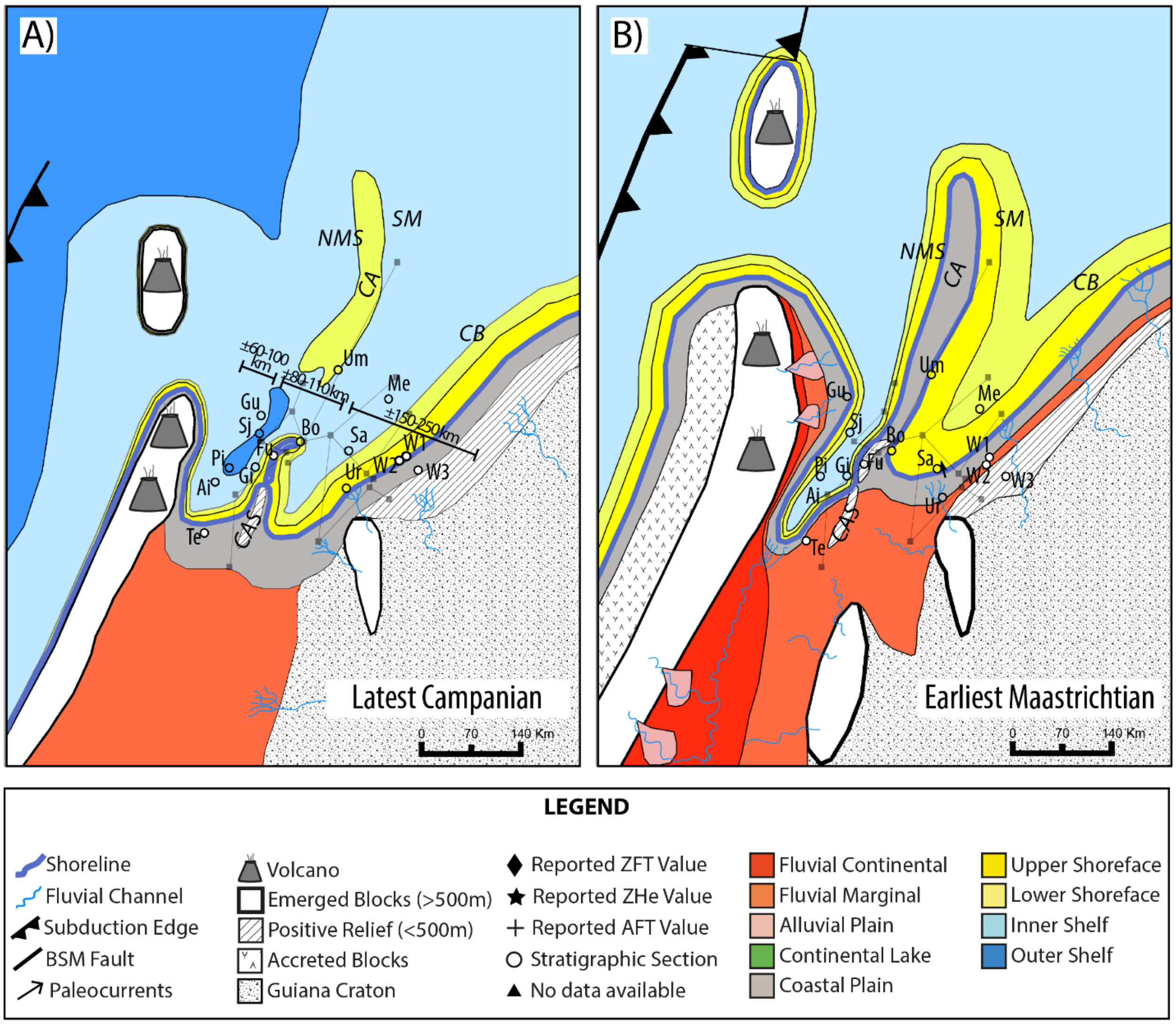


Fig. 3.12. Palinspatically restored paleogeographic maps for A) Latest Campanian and B) Earliest Maastrichtian. Abbreviations: Te: Tesalia, Ai: Aico, Pi: Piedras, Gi: Girardot, Fu: Fusa, Bo: Bogota, Sj: San Juan de Rio Seco, Gu: Guadero, Sa: Sagu, Me: Medina, Um: Umbita, Ur: Uribe, W1/2/3: Well 1-3; *CAS*: Carmen de Apicala Syncline, *NMS*: Nuevo Mundo Syncline Area, *CA*: Cobardes Anticline Area, *SM*: Santander Massif Area, *CB*: Cocuy Area. The original positions are represented by the gray squares.

In the LLB, there are no strata from the Late Campanian, Fig 3.4. The stratigraphic section from the wells suggests the presence of an unconformity on top of the upper shoreface to coastal plain middle-late Campanian rocks, wells 1 to 3 in Figs 3.4, 3.6, and 3.11. According to the biostratigraphy from ECOPETROL (2012) and ICP - Ecopetrol (2014), the missing record corresponds to the late Campanian to early-middle Paleocene, Figs 3.4, 3.6, and 3.11. Similarly, in Tesalia, Fusa, and the Carmen de Apicala sections, an unconformity is recognized, Fig 3.6, 3.7, and 3.9. According to the palinspastic map, the location of the available wells and Tesalia were at the distal part of the basin, Fig 3.12A. On, the other hand, the present-day sections of the Fusa and Carmen de Apicala were located within an uplifting block within the basin, Fig 3.12A. The estimated lateral extension of this uplifting block is ±80-110 km, Fig 3.12A.

At the end of the Campanian, the exhuming block was surrounded by two depocenters, Fig 3.9a, the Magdalena (UMVB and MMVB) Valley to the west, and the area from the ECB (at least from the axial part) to the LLB in the east. They extended ≈60-100 km and ≈150-250 km, respectively. Figure 3.12A. Figure 3.6B and 3.7B illustrate estimated basin architecture from west to east during the late Campanian to Maastrichtian (the underfilled stage). The data indicate an emerging block located in the western part of the ECB, Fig 3.6B, 3.7B, and 3.12A.

3.4.2. Early Maastrichtian

The orogenic advance continued at this time. Provenance analysis (e.g., Lamus et al., 2013 and Nie et al., 2010) demonstrates that the uplifting Central Cordillera started to be a sediment source by this time ¶(Valencia-Gómez et al., 2020; Villagómez & Spikings, 2013). In addition, the basin registers a change from carbonatic to siliciclastic deposition. In Aico and Tesalia, the southernmost areas, this change took place in the uppermost Campanian (e.g., Garzon et al., 2012). Although the shoreline moved northwards the downstream controls still governed along the study area. The progradation of the shoreline produced subsequent erosion (either subaqueous or subaerial) in some areas. Wells 1-3 continued under subaerial exposure, whereas the strata from the Sagu preserve shallow marine deposition overlain inner shelf facies. The contact between these facies is unconformable. A coetaneous similar unconformity is reported in Bogota and Umbita areas, Figs 3.6A and 3.10A.

The distribution of the facies evidences the ongoing exhumation of the western ECB, where shallower facies are registered, Fig 3.10A and 3.12B. However, the end of the Early Maastrichtian is characterized by retrograding facies in the adjacent depocenters. The increased portion of microfossils and finer sediments reported in the UMVB and MMVB (e.g., Guerrero et al., 2000), and the increase in glauconite and phosphates in the LLB (e.g., Guerrero & Sarmiento, 1996), are diagnostic of a transgression. The thickness of the sedimentary record of the Early Maastrichtian in the MMVB and UMVB is ± 110-150 m, while the ECB and LLB record ± 80-90 m.

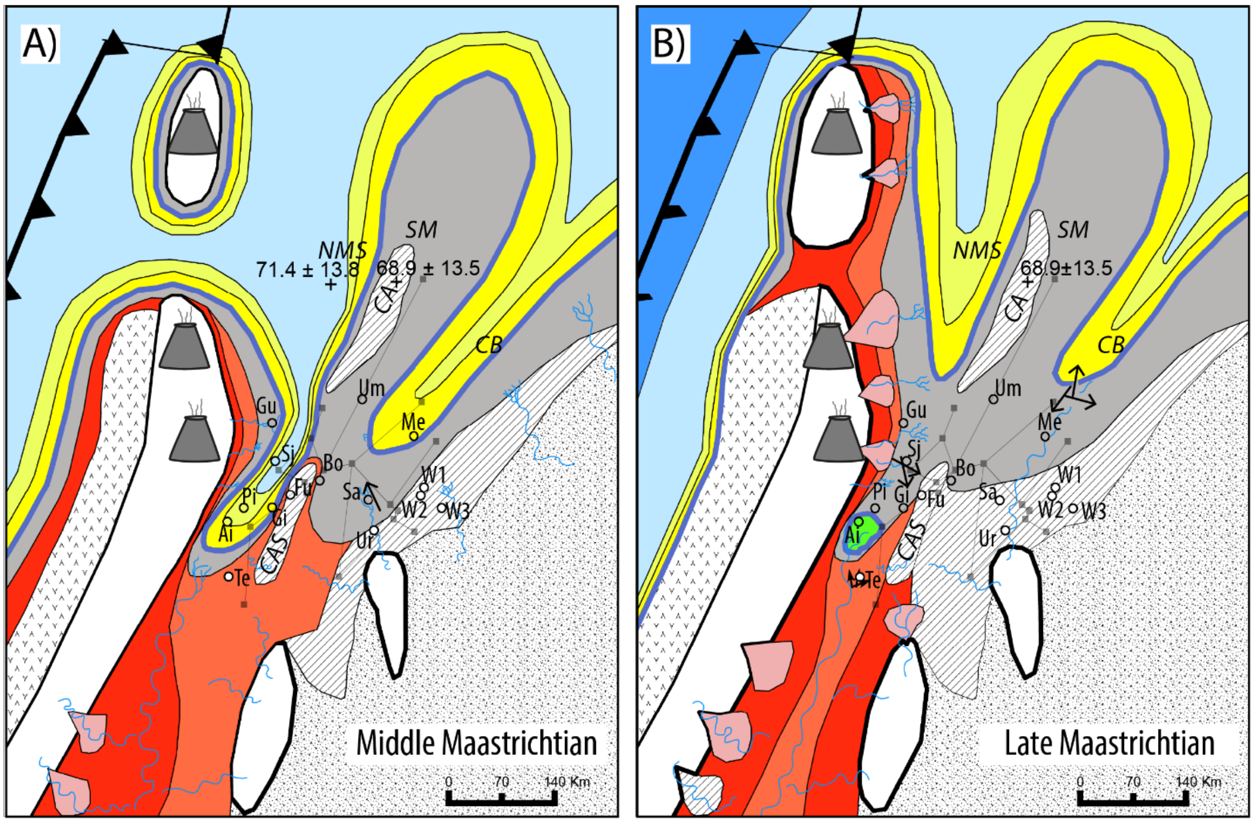


Fig. 3.13. Palinspatically restored paleogeographic maps for A) Middle Maastrichtian and B) Late Maastrichtian. Abbreviations: Te: Tesalia, Ai: Aico, Pi: Piedras, Gi: Girardot, Fu: Fusa, Bo: Bogota, Sj: San Juan de Rio Seco, Gu: Guadero, Sa: Sagu, Me: Medina, Um: Umbita, Ur: Uribe, W1/2/3: Well 1-3; *CAS*: Carmen de Apicala Syncline, *NMS*: Nuevo Mundo Syncline Area, *CA*: Cobardes Anticline Area, *SM*: Santander Massif Area, *CB*: Cocuy Area. Conventions in Fig 12. The original positions are represented by the gray squares.

3.4.3. Middle Maastrichtian

Multiple facts evidence the advanced stage of the compressional basin (a retroarc foreland basin). First, the south to the north exhumation of the western ECB, Fig 3.8a. Thermochronological data from distinct authors (e.g., Caballero et al., 2013a; Mora et al., 2020 and Silva et al., 2013a) indicate the northwestern part of the ECB uplifted at least since the Middle Maastrichtian, Fig 3.13A. Second, the increase in the accommodation space in the MMVB, UMVB, and ECB, which is demonstrated in the sediment thickness, Fig 3.4, ±200 m and ±110 m, respectively. Third, the start of the Central Cordillera as a sediment source, and fourth, the increased sedimentation rate.

The latter is understood to trigger the progradation of the facies regarding the accommodation space. The facies indicate a northwards movement of the shoreline. In the UMVB and MMVB, the sedimentation was still under marine conditions. In contrast, the ECB and LLB were dominated by coastal plain deposition, and the regression of the shoreline led to subaerial exposure of the Uribe and Sagu areas. Nevertheless, an increase in marine microfossils (foraminifera and dinoflagellates) across the UMVB and MMVB (e.g., Garzon et al. 2012 and Tchegliakova, 1996), in addition to numerous exploitable coal beds from the Guaduas Fm in the backbulge (Bayona et al. 2013 and G. Sarmiento, 1992); reveal the occurrence of a transgression of the shoreline in the Middle Maastrichtian.

3.4.4. Late Maastrichtian

This period represents the starting point of the overfilled stage of the foreland basin. Although the sediment thickness (±220 m in the UMVB - MMVB, and ± 120 m in the ECB-LLB) suggests an increase in accommodation, the sediment derived from the Central Cordillera (e.g. San Juan de Rio Seco and Guadero in Bayona et al. 2013) enhanced the sediment supply along the basin and favored a northwards progradation of the shoreline. Coastal plain and marginal facies expanded along the study area, (Fig 3.8b).

The presence of gypsum layers in the Aico area demonstrates that the regression of the shoreline produced brackish water bodies (lacustrine environments) in the southern part of the UMVB. In the ECB, sedimentation only occurred near Bogota and Umbita as the other areas were under subaerial exposure, Fig 3.13B. The exhuming western ECB block grew and extended northwards. Thermochronometers from Silva et al. (2013a) reveal exhumation in the Santander Massif, though it was not a sediment source at this time neither had control in the fluvial channels.

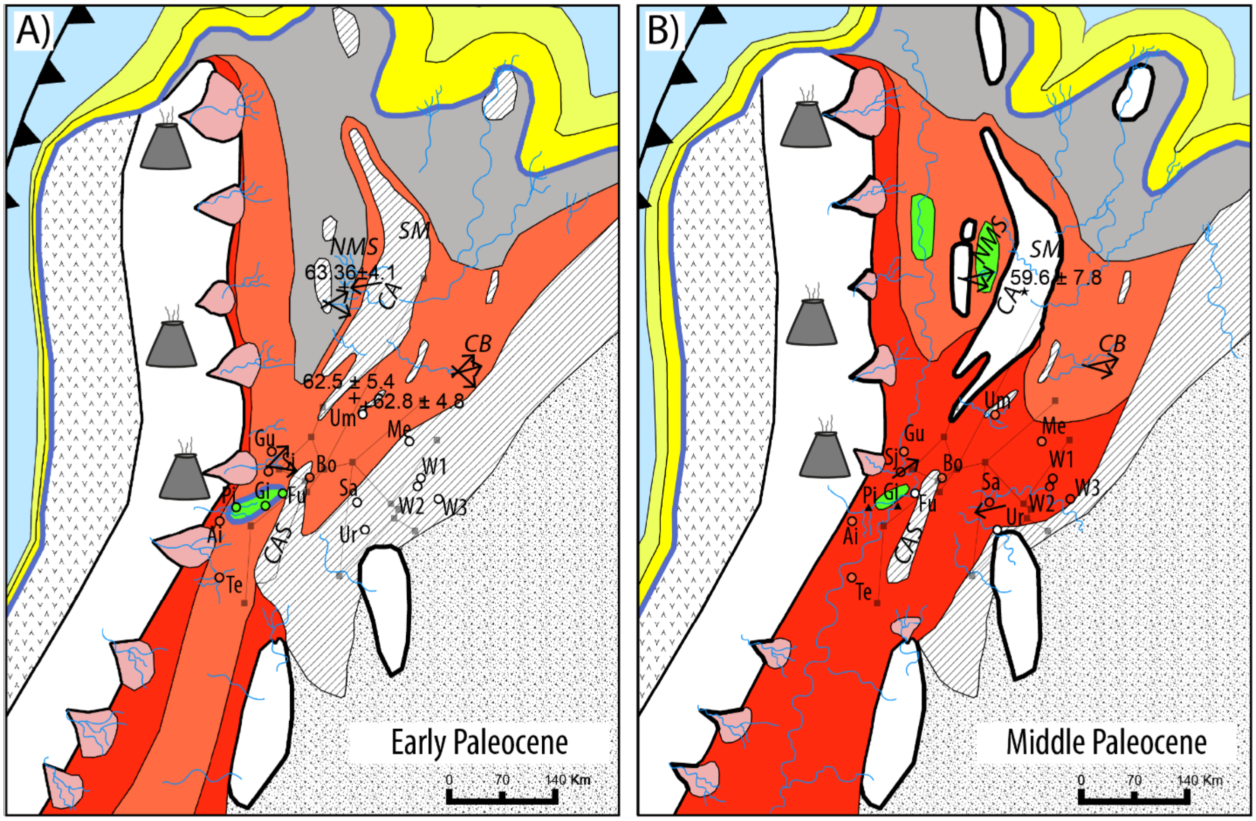


Fig. 3.14. Palinspatically restored paleogeographic maps for A) Early Paleocene and B) Middle Paleocene. Abbreviations: Te: Tesalia, Ai: Aico, Pi: Piedras, Gi: Girardot, Fu: Fusa, Bo: Bogota, Sj: San Juan de Rio Seco, Gu: Guadero, Sa: Sagu, Me: Medina, Um: Umbita, Ur: Uribe, W1/2/3: Well 1-3; *CAS*: Carmen de Apicala Syncline, *NMS*: Nuevo Mundo Syncline Area, *CA*: Cobardes Anticline Area, *SM*: Santander Massif Area, *CB*: Cocuy Area, *BSMF*: Bucaramanga Santa Marta Fault. Conventions in Fig 12. The original positions are represented by the gray squares.

3.4.5. Early Paleocene

The increased portion of unstable minerals in San Juan de Rio Seco (Bayona et al. 2013) evidences proximity to the orogen. The outcomes of this orogenic advance are 1) the more prominent topographic relief in the western ECB, 2) the creation of a fluvial network across the study area, and 3) migration of the southern part of the exhuming block of the western ECB, (Figs 3.9 and 3.14A). The stratigraphy of the study area characterized by the dominant fluvial facies indicates the shoreline was even farther north due to the ongoing regression. Despite the active tectonic activity (Bayona et al., 2013; Mora et al., 2020), the proximity of the orogen, and the topography created in the western ECB, the fluvial systems did not have enough energy, and except for San Juan de Rio Seco, most of the facies are floodplain dominated with a low amalgamation of the channels.

The contact between the fluvial facies and the underlying coastal to marginal facies of the late Maastrichtian is diachronous, indicating the sedimentation was not continuous. The sedimentation rate decreased in relationship with the late Maastrichtian. In the UMVB and MMVB, this contact is paraconformable, (Fig 3.8). Instead, the earliest Paleocene was a period of subaerial exposure and subsequent erosion in most of the ECB and LLB, (Figs 3.10 and 3.11). In these areas, a SU truncates the coastal to marginal facies of the late Maastrichtian. It becomes older southeastwards.

Basin	Location	Author
Upper and Middle Magdalena Valley	Piedras	Guerrero et al. (2000) and Bayona (2018)
	Aico	Carvajal et al. (1993), Yepes (2001) and Garzon et al. (2012)
	Guaduero	Lamus et al. (2013); Bayona et al. (2013) and Bayona (2018)
	San Juan de Rio Seco	De Porta (1966); Gomez et al. (2003); Bayona et al. (2013); Lamus et al. (2013) and Tchegliakova (1996)
	Tesalia	Veloza et al. (2008) and Ferrerira et al. (2002)
	Girardot	De Porta (1966) and Acosta et al. (2002)
Eastern Cordillera Basin and Foothills	Medina	Guerrero y Sarmiento (1996), Parra et al. (2010), Jaramillo (1999) and Jaramillo and Dilcher (2000)
	Umbita	Bayona et al. (2013) and Ulloa et al. (1975)
	Bogota	Perez & Salazar (1978), Sarmiento (1992), Vergara y Rodriguez (1997), Acosta et al. (2002) and Bayona et al. (2010)
	Fusa	Acosta & Ulloa (2001) and Bayona et al. (2003)
Llanos Basin	Uribe	Buchely et al. (2015) and Buchely (2015)

Table 3.3 List of the reviewed literature for every location plotted in figure 1.

Thermochronometers near the Umbita area (e.g. Silva et al. 2013) unveil the uplift and exhumation of new blocks. Likewise, in the south, sedimentation is renewed in the Fusa section. These factors suggest a migration of the uplifting block driven by the ongoing subduction and the eastwards orogenic advance, (Fig 3.14A).

3.4.6. Middle Paleocene

The unceasing compression related to the subduction in the west led to the exhumation of intracontinental blocks in the MMVB, Fig 3.9b. For instance, the exhuming blocks across the MMVB documented by Caballero et al. (2013) and Parra et al., (2012). These acted as a local sediment source (Moreno et al. 2011), as shown by the paleocurrent directions in Figure 3.9b. The tectonism also created new accommodation, which is evident due to the renewed sedimentation, excluding the Uribe section. The resulting time gap is ± 2 My (Bayona et al., 2013). In comparison to the previous period, the sedimentary record is approximately twice thicker in the UMVB, MMVB, ECB, and LLB, (Figs 3.6, 3.7, 3.8, 3.10, and 3.11). Despite the new accommodation, the high amalgamated channels dominated facies indicates the sedimentation was related to higher energy fluvial channels and suggests a very high sediment supply rate.

Paleocurrents from the UMVB, MMVB, ECB, and Sagu demonstrate the Central Cordillera, the exhuming western ECB, the Guiana Craton, and the intracontinental highs were supplying sediments to the basin. Their continuous exhumation enhanced the energy and transport capacity of the fluvial channels and triggered an increase in the sediment supply. As a result, the aggradation of the facies took place in the study area. The facies distribution exposed in Figures 3.6 and 3.7 are analogous to the overfilled stage of a foreland basin presented by DeCelles & Giles, (1997), DeCelles, (2012), and Nemčok et al. (2009), so it indicates the regional foreland basin was on its final stage.

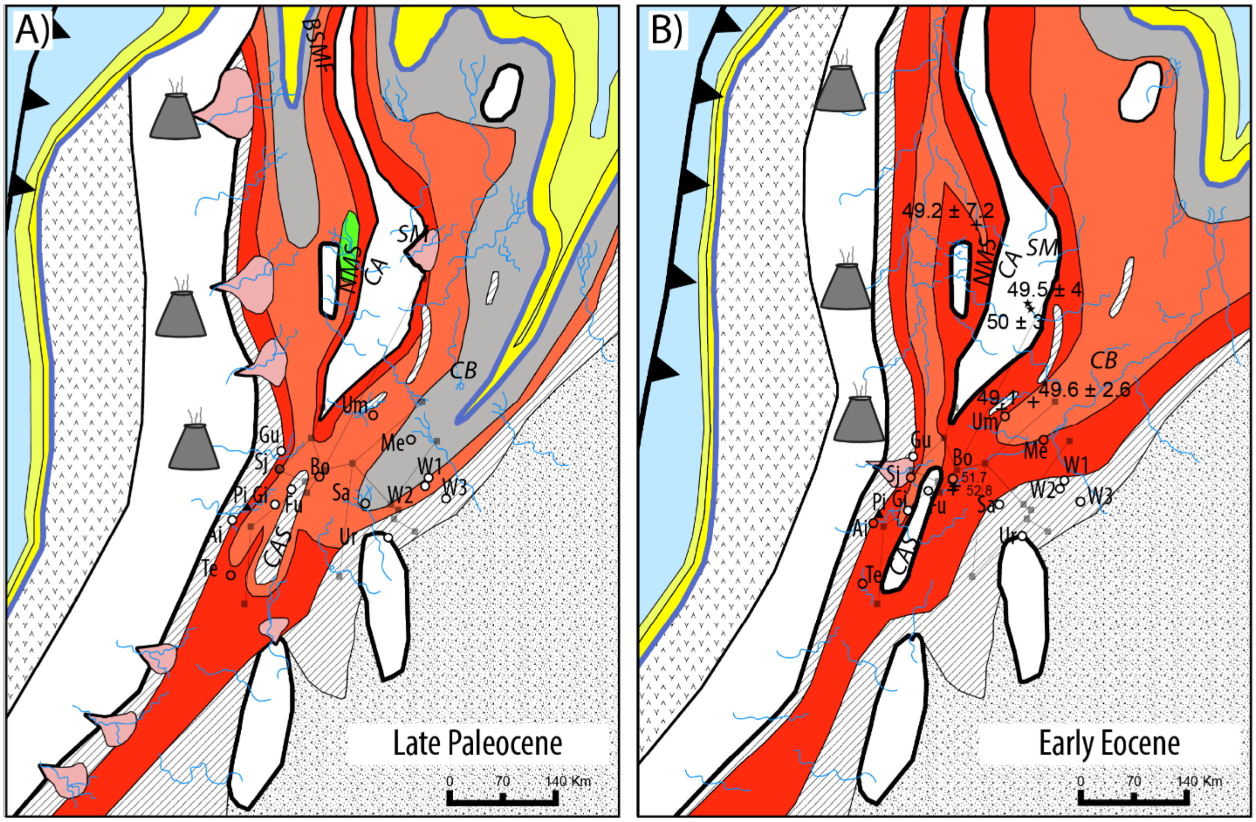


Fig. 3.15. Palinspatically restored paleogeographic maps for A) Late Paleocene and B) Early Eocene. Abbreviations: Te: Tesalia, Ai: Aico, Pi: Piedras, Gi: Girardot, Fu: Fusa, Bo: Bogota, Sj: San Juan de Rio Seco, Gu: Guadero, Sa: Sagu, Me: Medina, Um: Umbita, Ur: Uribe, W1/2/3: Well 1-3; *CAS*: Carmen de Apicala Syncline, *NMS*: Nuevo Mundo Syncline Area, *CA*: Cobardes Anticline Area, *SM*: Santander Massif Area, *CB*: Cocuy Area, *BSMF*: Bucaramanga Santa Marta Fault. Conventions in Fig 12. The original positions are represented by the gray squares.

3.4.7. Late Paleocene

Multiple authors (e.g., Cardona et al. 2018, Cortés et al. 2006 and Tesón et al. 2013) affirm the Late Paleocene was a period with significant tectonic activity. Their data show an increase in the magmatic activity in the Central Cordillera, maximum shortening and exhumation of the western ECB, and an eastwards expansion of the ongoing deformation. Albeit, sedimentation was not evenly distributed along the basin, the Late Paleocene deposits are characteristically very thick, Figs. 3.6 to 3.11. This thickness is the result of new accommodation in the study area.

Regardless, fluvial facies extended across most of the study area, and the fact that some regions register subaerial exposure indicates the shoreline did not reach this latitude, Fig 3.15A. Bayona (2018) and Bayona et al. (2013) determined that rock units from this period register the highest sedimentation rate since the latest Campanian. Moreover, Jaramillo & Dilcher (2000) detect an increase in the temperatures that affected the biodiversity in the Late Paleocene. Therefore, the active tectonism, the increased sediment supply, the vegetation, and the climate during the Late Paleocene restrained the study area under the upstream controls.

However, the UMVB, MMVB, and ECB areas preserve a significant change in the facies. In the UMVB and MMVB, the facies exhibit a shift from high-amalgamated fluvial deposits to low-amalgamated fluvial deposits; the contact between those facies is transitional and conformable, Fig 3.8. Additionally, Ayala-calvo et al. (2009) and Caballero (2010) identified coastal plain facies in the north part of Colombia and marginal lacustrine facies in the Nuevo Mundo Syncline, respectively, documenting downstream controls to the north of the study area, Fig 3.10a. On the other hand, brackish palynomorphs in the Medina section (Guerrero & Sarmiento, 1996) and carbonaceous material in the Sagu Creek unveil the existence of a coastal to marginal facies in the backbulge, (Fig 3.6). These relatively synchronous changes indicate an increase in the relative sea level and a transgression of the shoreline in the Late Paleocene. Presumably, triggered by tectonism which was the major controlling factor. Nonetheless, the shoreline did not reach the study area.

3.4.8. Early Eocene

Multiple changes took place in this period. First, the cease in sedimentation and subsequent subaerial exposure produced the formation of paleosols reported by various authors (e.g., De Porta 1966 and Jaramillo 1999). As a result, a regionally diachronous correlatable SU was formed. Figures 3.3 to 3.6 reveal that this SU becomes younger northwards. Second, an increase in the temperature (Jaramillo & Dilcher 2000; Jaramillo, 2019). Third, the sedimentation rate is the lowest registered since the Maastrichtian, excluding the Bogota area.

Lastly, numerous authors have claimed the initiation of a tectonic quiescence in the middle Eocene (e.g., Mora et al., 2013; Gómez et al., 2005). Based on all these changes, previous studies (e.g., Reyes-Harker et al., 2015) recognized this period as the endpoint of the regional foreland basin. The diachroneity of this surface describes how the foreland basin ended from south to north.

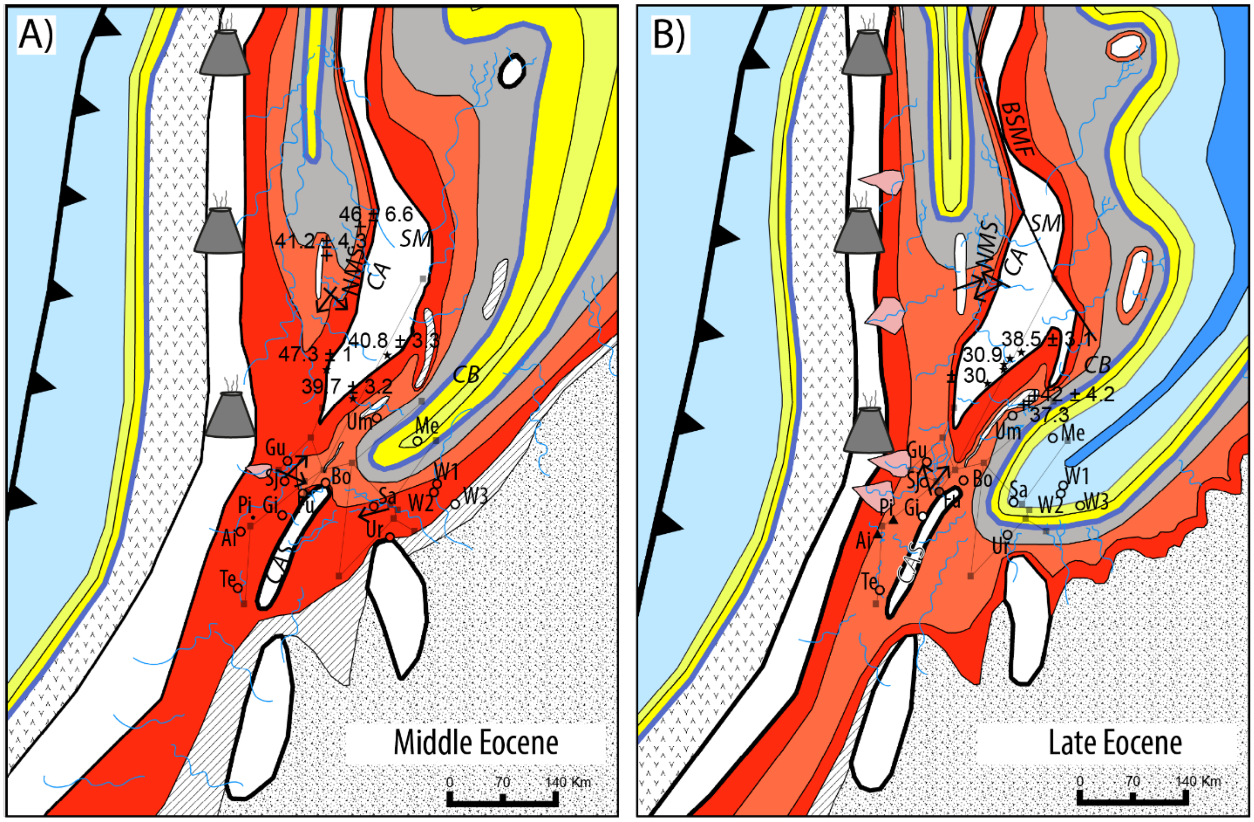


Fig. 3.16. Palinspatically restored paleogeographic maps for A) Late Paleocene and B) Early Eocene. Abbreviations: Te: Tesalia, Ai: Aico, Pi: Piedras, Gi: Girardot, Fu: Fusa, Bo: Bogota, Sj: San Juan de Rio Seco, Gu: Guadero, Sa: Sagu, Me: Medina, Um: Umbita, Ur: Uribe, W1/2/3: Well 1-3; *CAS*: Carmen de Apicala Syncline, *NMS*: Nuevo Mundo Syncline Area, *CA*: Cobardes Anticline Area, *SM*: Santander Massif Area, *CB*: Cocuy Area, *BSMF*: Bucaramanga Santa Marta Fault. Conventions in Fig 12. The original positions are represented by the gray squares.

3.4.9. Middle Eocene

Tectonic quiescence dominated during the Middle Eocene (Gómez et al. 2005, Mora et al., 2013; Parra et al. 2009 and Reyes-Harker et al. 2015). Although, areas such as the Nuevo Mundo Syncline were under tectonic activity (Caballero et al., 2010). Thermochronological data from Caballero et al. (2013) and Silva et al. (2013) unveil the uplift of the western part of the ECB. The sediments of the adjacent areas contain unstable minerals, young peaks in detrital zircon ages, and immature continental fluvial deposits (Bayona et al. 2013, Carvajal-Torres et al., 2019 and Parra, 2015).

At the end of this period, the sedimentation renewed at a very low rate. Figures 3.3 to 3.6 show the high amalgamated channel fluvial dominated deposition. These continental fluvial facies extended along the study area. However, shoreface deposits identified by Guerrero & Sarmiento, (1996) and Jaramillo & Dilcher, (2000) in the Medina area indicate a renovation of the downstream controls at the end of this period, Fig 3.11a. Likewise, the fluvial facies from the Mirador formation in the Sagu creek are overlain by a 1 m thick bed of lower shoreface deposits, Fig 3.3. This proximity to the shoreline is not recorded within the sedimentary record from the UMVB to the MMVB, Fig 3.11a, it implies the disconnection of the facies from west to east.

3.4.10. Late Eocene

It appears that by this time the Bucaramanga-Santa Marta strike-slip fault was active (Cardona et al. 2018). This compressional regime also caused the eastwards migration of the deformation in the ECB and subsequent erosion of the Concentracion Fm (Ochoa et al. 2012). Therefore independent depocenters (Villamil, 1999) were created, the Magdalena Valley in the west and the Llanos Basin in the east. Each one of those depocenters continued receiving sediments from the Eastern Cordillera. Thermochronological data and provenance analysis from Bayona et al. (2013), Caballero et al. (2013), Horton et al. (2010), Mora et al. (2010a), Moreno et al., (2011), Nie et al. (2010), Sánchez et al. (2012) and Silva et al. (2013) indicate that the Paleogene and Cretaceous rocks were under erosion during the Early Oligocene.

At this time, the Central Cordillera and Eastern Cordillera bounded from the west to the east of the Hinterland basin in the Magdalena Valley, Fig 3.2. Low-amalgamated channels fluvial facies dominated in the south, Fig 3.11b. In the Nuevo Mundo Syncline, the deposition took place in a coastal to proximal fluvial facies (Caballero, 2010). While the Llanos Basin, bounded in the west by the Eastern Cordillera, was under marine deposition, Fig 3.11b. The coastal facies in the Uribe section, evidence the proximity of the shoreline.

3.5.First-Order Retroarc Foreland Sequence

The collision and accretion of oceanic blocks to the Central Cordillera triggered its exhumation leading to the closure and termination of the Late Jurassic to Early Cretaceous extensional basin, so prompted the initiation of a retroarc foreland basin in the Cretaceous (Gómez et al., 2005; Horton, Parra, et al., 2010; Villagómez & Spikings, 2013), Fig. 3.2. From the late Eocene to the

Early Oligocene, this retroarc foreland basin ended. Subsequently, two independent basins were created, the hinterland Magdalena Valley Basin and the foreland Llanos Basin (e.g., Moreno et al. 2011). Despite the understanding of the geological evolution, the stratigraphic response is yet to be understood. Based on the facies architecture and stratigraphic evidence in the Sagu Creek and the wells 1-3 combined with the reported data from several authors such as sediment structures, authigenic minerals, microfossils distribution, gamma-ray, and biostratigraphy, Table 3.3, we identified the bounding surfaces of this first-order sequence.

According to Allen & Allen (2005), Catuneanu (2019b), and Nemčok et al. (2013), once the retroarc foreland initiates, the foredeep area subsides and hosts deep marine retrograding facies, whereas shallow marine deposition occurs in the backbulge. While the forebulge area uplifts and is subject to either subaerial or subaqueous conditions forming the forebulge unconformity. This unconformity underlies the first-order foreland sequence and its diachroneity is the result of the diachronic exhumation of the forebulge (Catuneanu 2004). In cases such as the Western Interior Basin, dynamic subsidence creates accommodation across the forebulge area and renders shallow marine deposition (Miall et al. 2008).

In the case of study, once the exhumation of the Central Cordillera started, two areas were exposed. First, the western flank of the ECB was diachronically exposed from south to north. In the south, multiple authors (e.g., Caicedo et al., 2002, 2000; and Ramon & Rosero, 2006) recognized an unconformity in the Prado and Carmen de Apicala synclines, (Figs 3.12 to 3.16). Therefore, indicating exhumation and erosion from the Campanian to the Paleogene, (Figs 3.12 to 3.14). The overlaying fluvial continental facies from the Paleogene and the Neogene are diagnostic to classify it as a SU. Bayona et al. (2003) identified a similar unconformity in the Fusa section. The time gap associated implies that the exhumation and erosion occurred from the latest Campanian until the latest Maastrichtian - earliest Paleocene. Then, the sedimentation was resumed with marginal fluvial conditions, Figs 3.6 to 3.9. North to the study area, the Cobardes Anticline started to uplift during the middle Maastrichtian, Fig 3.13A. The sedimentation did not resume ever since and Jurassic rocks are exposed in the core of the structure, (Julivert, 1970). The data indicate a traceable SU from south to north with a younger northwards pattern, Fig 3.9.

Second, most of the LLB was also under subaerial exposure from the late Campanian to the Paleocene, Figs 3.12 to 3.14. Similarly, the unconformity is underlain fluvial facies from the Barco formation and is classified as a SU, Figs 3.4 and 3.11. Once the compressional regime triggered the formation and uplift of the Central Cordillera in the late Campanian, the basin experienced a reduction of accommodation. Subsequently, a progradation of the shoreline took place. Additionally, this compression resulted in a lithospheric flexure that exhumed most of the LLB. In terms of sequence stratigraphy, those events formed a maximum regressive surface (MRS) and a subaerial unconformity (SU). As they were formed during tectonic changes, we define these surfaces are first-order stratigraphic surfaces.

The evidence in the depocenters is more difficult to identify, albeit the stratigraphic response to the transition from the back-arc to retroarc foreland basin is comparable to analogous areas from the southern Andes. In the Patagonian Andes, Fildani & Hessler (2005) and Wilson (1991) demonstrate progradation takes place during the transition from the back-arc (i.e., Zapata Formation) to the retroarc foreland (Punta Rosa Formation). The facies in the latter eventually retrograde once the maximum regressive surface is formed. Correspondingly, the late Campanian deposits in the study area expose a progradation pattern and a subsequent retrogradation pattern. In the MMVB and UMVB, the evidence is preserved within the transition from Upper Lidita to Buscavidas and lowermost Umir formations. A decrease in marine palynomorphs and an increase in continental microfossils mark the contact between the underlain prograding pattern and the retrograding succession above. An example of that can be observed in the Aico and Piedra's sections (Garzon et al., 2012; Guerrero et al., 2000; Yepes, 2001a, 2001b).

Likewise, a prograding pattern is identified across the ECB and the westernmost ECB (including the foothills). In the ECB the change is evident within the transition from the Plaeners to the Labor units from the Middle Guadalupe, Fig 3.10. In the Sagu creek, the change is preserved in the Middle Guadalupe. Figure 3.3 illustrates how the finer sediments and thalassinoides disappear towards the top while thicker beds of coarse material dominate and ophiomorphas appear within the lower part of the Middle Guadalupe. The latter being overlain by a 20 m succession of heterolithic with glauconite and phosphorite. In the Medina area, the Lodolitas de Aguascalientes registers an increase in the content pollen that coincides with an increase in sandy portion and the presence of shallow marine fossils and ichnofossils (Guerrero & Sarmiento, 1996).

Following the criteria from Helland-Hansen & Martinsen (1996), we classify this surface as a maximum regressive surface (MRS). The south to north extension throughout the depocenters is illustrated in figures 3.8, 3.10, and 3.11. The low-resolution isochrones impede the constraining of the exact age of this MRS. Nonetheless, the data indicate this surface is relatively younger in Guaduero than in Tesalia, Fig 3.8, and relatively younger in Medina than in Sagu, Fig 3.10. From west to east the surface connects with the first SU formed in the western ECB and the LLB, Figs 3.6 and 3.7. Hence, this MRS is hierarchically classified as of first-order, and along the SU bound the overlying deposits of the first-order foreland basin sequence.

During the latest Maastrichtian to the earliest Paleocene, fluvial environments expanded across the basin as the shoreline moved northwards, Figs 3.8b and 3.9a. At that time, deposition occurred across the UMVB, MMVB, ECB, and westernmost ECB, Figs 3.13B to 3.14A. Subsequently, the sedimentation resumed in areas like Fusa and Tesalia. According to Nemčok et al. (2005), this facies architecture coincides with the change from the underfilled to the overfilled stage of a foreland basin, which is truncated by a SU formed during the Late Paleocene to the Early Eocene, Figs 3.6 to 3.11. The time gap of this SU varies along the basin, although it increases southwards and eastwards. Various studies (e.g., Parra et al. 2009) detected a period of tectonic quiescence in the middle Eocene that is associated with orogenic unloading and the subsequent end of the retroarc foreland basin. For that reason, we establish this SU as the first-order upper boundary of the first-order foreland basin sequence. Sediments under or overlaying this sequence belong to different basins and do not share a genetic relationship.

3.6.Discussion

The understanding of the lifespan of the retroarc foreland basin is fundamental not only to comprehend its evolution but also to recognize and accurately correlate the stratigraphic sequences genetically related along the Northern Andes. For instance, some of the principal hydrocarbons reservoirs in the Llanos Basin were deposited in the retroarc foreland basin, so their correlation across the basin requires the recognition of stratigraphic surfaces. The data from Wells 1-3 reveal subaerial conditions in the southern LLB, which affected the extension of these reservoirs in this part of the basin. However, the first step is to identify the boundaries of the first-order foreland basin, in which the Magdalena Valley (UMVB and MMVB), the ECB, and westernmost LLB were the major depocenters. While the western part of the ECB and most of the ECB were exhumed under subaerial exposure. The data indicate the lower boundary of this sequence is compounded by an MRS and two SU formed during the late Campanian. In the Sagu section, we recognized a first-order MRS that is connected to a SU present in wells 1-3. The upper limit is a regional SU dated from the latest Paleocene to early-middle Eocene, both boundaries are diachronous.

The data indicates the diachroneity is the result of the allogenic controls during basin evolution. In the case of the lower boundary, the diachronic exhumation of the Central Cordillera started in the south and subsequently spread northwards Figs 3.8, 3.12, and 3.13. It explains the younger northward pattern reflected within the sedimentary record. The lower first-order boundary is younger northwards, Fig 3.4-3.6. Although the resolution of the biostratigraphic and paleontological data is limited, and this pattern is relatively established in the depocenters, the data from the unconformities contributed to identifying the timing. In Fusa and Carmen de Apicala areas the time gap indicates subaerial exposure during the late Campanian, while the thermochronological data from the Cobardes Anticline (e.g., Caballero, Parra, & Andres, 2010; Silva et al., 2013; Siravo et al., 2018), implies exhumation and uplift since the middle Maastrichtian. The northwards advance of the subduction and the orogen led to this diachroneity.

Based on the sedimentary thickness and the facies association, we separated the sediments deposited during the underfilled and overfilled stages, Figs 3.6B, 3.7B, 3.8B, 3.9B, 3.10B, and 3.11B. The separation of the strata was carried out following the criteria from Catuneanu (2019a, 2019b) and MacEachern et al. (2012). As the foreland basin was connected with the global sea level (Bayona, 2018; Bayona et al., 2020; Mann et al., 2006), all the strata deposited below the sea level was categorized to the underfilled stage, and all the sediments deposited above the sea level belong to the overfilled stage. The resulting estimated basin architecture indicates the accommodation increased from south to north in the depocenters, Figs 3.8, 3.10, and 3.11. From west to east, the lateral extension of the western depocenter, the uplifting western ECB block, and the eastern depocenter are ±60-100 Km, ±150-250 Km, and ±80-110 Km, respectively. Figures 3.6 and 3.7 illustrate the estimated basin architecture that unveils a clear uplifting block in the western part of the ECB and exposes the positive relief from the LLB that resulted in the subaerial exposure. To explain the formation of the unconformities in the western ECB and along the area of the wells, we evaluated two hypotheses. The first one implies the presence of the forebulge in the western flank of the ECB, and the second one indicates the location of the forebulge across the LLB. The latter supports the statement from Gómez et al. (2005), Gómez et al. (2003) and Parra et al. (2009).

In the first scenario, the estimated lateral extension supports the interpretation of a foredeep across the UMVB and MMVB, a forebulge through the western ECB, and a backbulge along the ECB and westernmost LLB. The thickness of the underfilled stage sediments from the presumable foredeep doubles the one deposited in the potential backbulge area, Figs 3.6 and 3.7. While, the thickness of the overfilled deposits indicates that most of the sediment was deposited nearby Bogota and San Juan de Rio Seco, Fig 3.7. Moreover, the deposition renewed around the western flank of the ECB (forebulge), see Fusa in Figs 3.6, 3.7, and 3.9. In this model, we understand these facts as the eastward migration of the fluvial deposition, and the interplay between the lithospheric flexural profile and the basin architecture. Nevertheless, the presence of a forebulge unconformity along the western flank involves a larger difference in sedimentary thickness between the foredeep and backbulge. In addition, the eastwards migration of the forebulge entails a reduction of the sedimentary thickness in the proximal areas (Catuneanu, 2004; DeCelles & Giles, 1997). In contrast, the data reveal an increase in the sediment thickness in the proximal areas such as Bogota, Figs 3.6, 3.7, 3.13, and 3.14.

On the other hand, the scenario proposed by Gómez et al., (2005), implies that the thickness of the underfilled deposits decreases eastwards, and the eastwards migration of the forebulge resulted in the movement of the fluvial facies in the same direction. Based on the data, this study recognizes the eastwards reduction of the thickness of the strata from the underfilled stage, see Figs 3.6 and 3.7. Additionally, the new data incorporated from the wells 1 to 3, prove that sedimentation renewed after a period of subaerial exposure from the late Campanian to early-middle Paleocene, Figs 3.3 and 3.14. Our data and interpretation coincide with Parra et al. (2009). The renewed sedimentation in the LLB was the result of the eastwards migration of the foreland basin that caused an episode of rapid subsidence. Likewise, this hypothesis concurs with the models presented by Catuneanu (2004), DeCelles & Giles (1997b), and Nemčok et al. (2009).

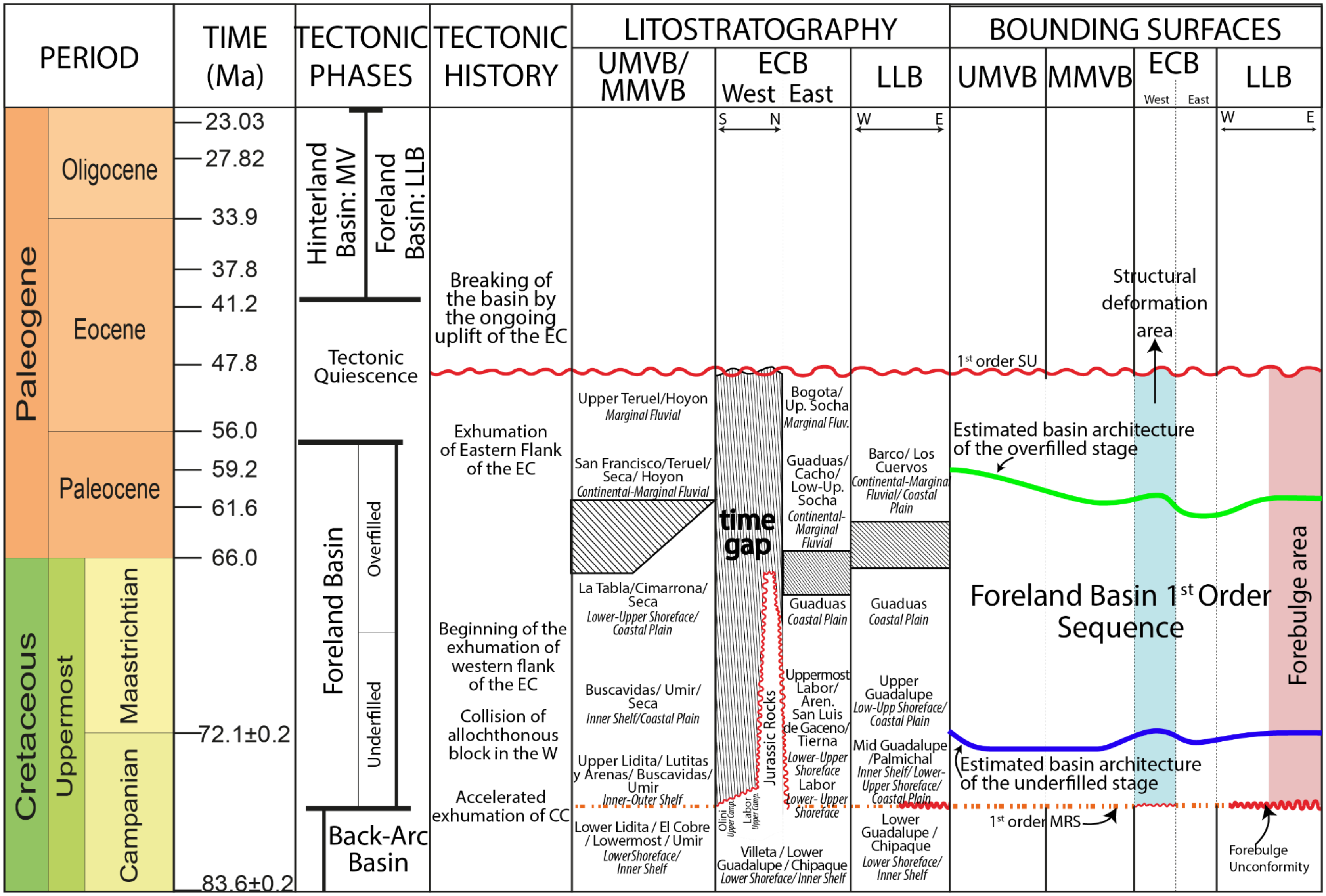


Fig. 3.17. Sequence stratigraphic framework of the UMVB, MMVB, ECB and LLB for the Middle Campanian to Middle Eocene. See the diachroneity of the unconformity along the western part of the ECB. Additionally, see how the forebulge unconformity connects towards the depocenter throughout a first-order MRS, forming the composite first-order lower boundary of the foreland sequence. The upper boundary formed during the Early Eocene due to a period of tectonic quiescence.

The upper boundary, formed during an orogenic unloading event, is highly diachronous. Although, the multiple allogenic controls and the basin architecture, differing from the previous first-order change, produced a more complex surface. The correlations with the newly incorporated data from the Llanos Basin indicate the upper boundary is relatively older westwards, Figs 3.6 and 7, demonstrating the foreland basin was in the overfilled stage, and so the depocenter moved eastwards. Indeed, the deposits recognized in the new data from Sagu and the wells 1-3 unveil the depocenter migrated westwards from the Campanian to Maastrichtian (during the underfilled stage), albeit it migrated eastwards during the Paleocene (in the overfilled stage). This fact clarifies the reason for the discontinued and renewed sedimentation in these areas and the presence of the forebulge in the east. Our analysis suggests this diachroneity is also related to the tectonic stages of orogenic loading and unloading proposed by Parra et al. (2009). They controlled the basin architecture.

The first-order MRS limits the prograding facies deposited during the last stage of the extensional basin. Following the sedimentary record from Sagu and the wells, we recognized forced and normal regressive deposits associated with the termination of the extensional basin. The latter is missing in the area of the wells due to a SU formed during a forced regression. Hence, the lower first-order boundary is a compound surface resulted from the combination of an MRS and a SU. The missing sedimentary record in the wells is understood as the subaerial exposure during the superimposing forced regressions driven by the lithospheric flexure.

Following the new data from the Sagu section, we recognized early Maastrichtian deposits due to the presence of *Paleocystodinium* within the upper shoreface deposits a few meters above the first-order MRS, Fig 3.3. Likewise, the samples from Vergara & Rodriguez (1997) indicate the presence of *Proteacidites dehaani, Echitriporites suescae, Gabonisporites vigorouxi,* and *Ulmoideipites krempii*. Those associated with middle-late Maastrichtian times by Contreras et al. (2010), De La Parra (2009), Muller et al. (1987), and Yepes (2001a) across the Colombian territory. The high content of authigenic glauconite and phosphates indicates a retrogradation occurred, Fig 3.3. Moreover, this surface in the Sagu is correlatable with a maximum flooding surface (MFS) across the early Maastrichtian deposits in the other depocenters, Figs 3.6 to 3.11. Yet, multiple studies indicate these phosphates and glauconite are reworked across the ECB (e.g., Bayona et al., 2013). They are truncated by a subaerial unconformity that marks the initiation of the overfilled stage of the basin. This surface is absent along the western flank of the ECB and most of the LLB, Fig 3.3 and 3.5. The facies distribution from the Uribe, Sagu to the Wells suggests this transgression may have flooded the area adjacent to the present-day location of the wells 1-2 (Fig 3.12a), even so, the northwards migration of the shoreline (Fig 3.12b and 3.13a), in combination with the lithospheric flexure, produced a forced regression and the subsequent SU reworked and eroded these deposits. Thereby, our data indicate the eastern margin of the basin was subject to superimposed subaerial exposure, implying the presence of a positive relieve.

These first-order surfaces coincide with the data presented by Spikings et al. (2015) and Villagómez & Spikings (2013). They demonstrated that the initiation of the uplift and exhumation of the Central Cordillera took place during the late Campanian (±70-±75 Ma. They stated this event was diachronous. The sedimentary record from Sagu and the wells (1-3) reveals the synchronic progradation of the facies. Notwithstanding, we identified some prograding and retrograding patterns throughout the late Campanian to middle Maastrichtian strata. We interpret the shoreline may have flooded the area of the present-day wells during the latest Campanian, but the superimposition of subaerial conditions driven by lithospheric flexure prevented its preservation. Indeed, the correlations reveal that while the east LLB was under subaerial exposure, the depocenter experienced positive accommodation, Figs 3.6 and 3.7.

The trajectories of the shoreline are registered across the depocenters. We recognize that the increase of marine palynomorphs (e.g., Piedras and Aico), or the occurrence of a high population of authigenic glauconite (e.g., Medina and Bogota), or the variations in organic matter content and sediment structures (e.g., San Juan de Rio Seco and Girardot), are contemporaneous and coincide with the evidence from the Sagu and the sections of the wells. The biozones from Jaramillo et al. (2011) were fundamental to establish the correlations of the facies across the whole basin and to determine the contemporary events.

Regarding the location of the forebulge, our results are consistent with the theory by Gómez et al. (2003, 2005) and Parra et al. (2009). They proposed the forebulge was located between the eastern flank of the ECB and the LLB. In that scenario, no sediment record should have been preserved, and the paleocurrents from the eastern ECB should reflect the control exerted from the exhuming forebulge. According to our data, the presence of *Paleocystodinium* in the Sagu unveils that sedimentation took place in that area during the early Maastrichtian, while the late

Maastrichtian to early Paleocene was a period of subaerial exposure. We define this exposure is related to a forced regression driven by the lithospheric flexure related with the forebulge unconformity. Likewise, the new paleocurrent data from Sagu (this study, Figs 3.3, 3.12, 3.13 and 3.14) point to the NW, indicating a structural control from the east. Indeed, the data suggest the Guiana craton acted as the main sediment source in that area.

In addition to our data, the SU reported by Bayona et al. (2003), Caicedo et al. (2002), and Ramon & Rosero (2006) in Fusa, Carmen de Apicala, and Prado Synclines, evidences subaerial exposure during the latest Campanian to the Eocene. Based on the palinspastic restorations, we evaluated its relationship with the existence of the forebulge. The results suggest this area extended about ±80-120 km. Furthermore, the thermochronological data from the Cobardes Anticline - Santander Massif area from Caballero et al. (2013), Sanchez et al. (2012), and Silva et al. (2013b) indicate the western ECB exhumed and uplifted since the Maastrichtian, Fig 3.12b to 3.13b. Therefore, the data suggest the exhumation migrated northwards along the strike. We interpret this as the result of the northward migration of the orogen. For that reason, the paleocurrent data and U-Pb ages in detrital zircons from Caballero et al. (2013) and Moreno et al. (2011) from the Nuevo Mundo Syncline unveil the influence of the western flank of the ECB in the drainage systems and the sediment supply did not start until the Early Paleocene. Although a forebulge may have been present at this latitude, there is not enough information to confirm it. While the deformation migrates northwards, its east-west movement is unclear. Also, the difference in the sedimentary thickness is not enough to determine if the adjacent depocenters are the corresponding foredeep and backbulge. We suggest further evaluate the lateral movement of the deformation restoring and decompacting the thickness of the strata to constrain the basin architecture.

The Paleocene deposits in the Sagu Creek and adjacent wells sections are capped by composite paleosols associated with a new episode of subaerial exposure that occurred in the late Paleocene to middle Eocene. The ages on the wells were constrained using the biozones reported by ECOPETROL (2012b). We recognize this SU correlates westwards and northwards, Fig 3.6, 3.7, 3.11, and 3.17. According to the data, it becomes relatively younger northwards in the LLB (see Fig 3.5), yet it is highly diachronous, and the youngest peak is in the Bogota area, where the sedimentation was steady, and no significant gap is preserved within the sedimentary record. Based on the basin architecture, we suggest it is the consequence of the migration of the depocenter during the overfilled stage. However, this regionally traceable SU is synchronic with the period of tectonic quiescence identified by Mora et al. (2013) and Parra et al. (2009) in the LLB. The authors state that erosional unloading led to a period of tectonic quiescence in the middle Eocene in the LLB. At the same time, the MMVB experienced basin narrowing (Gómez et al., 2005). However, we recognize these events as the result of the termination of the foreland basin. Consequently, this is a first-order SU, and its diachroneity indicates the basin ended during the Latest Paleocene to the Middle Eocene. The deposits from the Late Eocene belong to a new first-order sequence and are not genetically related.

Continuous sedimentation is identified near the Bogota area similar to San Juan de Rio Seco. Nevertheless, the sedimentation rate varies over time. Although the resolution of the data limits the full understanding of this fact, we associate it with the eastward migration of the depocenters. Bayona (2018) proposed that dynamic subsidence may have occurred in that area. Notwithstanding, Catuneanu (2019a) clarifies dynamic subsidence results in positive accommodation along the forebulge, which differs from the new data incorporated from the wells 1-3. The analysis of the outcrops across the western flank of the Eastern Cordillera and their correlation with the presented data is suggested to constrain the basin architecture and evolution. Additionally, thicknesses should be decompact to estimate and establish their temporal variation. Biostratigraphy, thermochronology, and detrital zircon are key information to improve the understanding of the evolution of the forebulge. The stratigraphic surfaces presented are a powerful element to control the facies correlation. We recommend carrying on a detailed calibration of the palinspastic restorations to obtain a more precise measure of the retroarc foreland basin extent and architecture.

Despite the identification of the boundaries of the first-order retroarc foreland basin sequence is a crucial insight to understand the correlation of the facies deposited during its lifespan and hence contribute to recognizing the distribution of the main reservoirs across the study area. For instance, in the Llanos Basin, the most important reservoirs (e.g. Chichimene and Akacias fields) are the rocks episodically deposited from the Campanian to the Paleocene and are separated by subaerial unconformities of different hierarchical orders, Fig 3.17. Although these units were prone to erosion due to the superimposed forced regressions identified along the Sagu and Wells 1-2, the overlaying marine deposits from the new first-order sequence potentially prompted stratigraphic traps.

The first-order sequence stratigraphic sequences presented in this study are the first step to establish constrained stratigraphic correlations. The identification of the sequence boundaries will not only contribute to a better understanding of the facies distribution but also detect areas with higher risk due to the presence of the first-order unconformities. Likewise, these boundaries provide insight to improve the understanding of the behavior of the lithofacies deposited during the regional foreland basin and contribute to the determination of a more detailed sequence stratigraphic framework across the UMVB, MMVB, ECB, and LLB. Therefore, the identification of lower hierarchy sequence stratigraphic surfaces will ensure success in future exploratory works.

3.7.Conclusions

(I) The first-order retroarc foreland sequence identified in the Sagu and the adjacent area of the available wells, is bounded by a composite surface at the base. The lower boundary is composed of an MRS in the center part of the depocenters and it is connected to the exhuming blocks, where the normal regressive deposits are missing, throughout a SU. The subaerial unconformity along the LLB indicates the proximity to the forebulge area. Therefore, that SU is the forebulge unconformity.

(II) The diachroneity of the surface is the result of the allogenic controls. In the case of the study, the northwards advance of the deformation that uplifted and exhumed the Central Cordillera from the late Campanian to the Maastrichtian is reflected in the diachroneity of the surfaces. For instance, the unconformity along the western ECB.

(III) The upper boundary of the retroarc foreland sequence is the first-order SU, its diachroneity is related to the basin architecture and the uneven orogenic unload that occurred in the early to middle Eocene and marked the end of the retroarc foreland basin. The continuous stratigraphic record in Bogota is the result of the eastwards migration of the orogen that triggered the eastwards migration of the depocenters in the overfilled stage.

(IV) In the late Maastrichtian to early Paleocene, subaerial exposure took place in the Sagu and the area of the wells. Indeed, this event is correlatable across the study area. The facies distribution and the basin architecture indicate the change from the underfilled to the overfilled stage. The sedimentation rate and the sediment thickness in Bogota and Umbita demonstrate the depocenter migrated eastwards to the proximity of these locations. The time gap associated with this second-order SU increases towards the east, this feature is a generic characteristic of a subaerial unconformity in a marginal part of a basin.

(V) Based on the palinspastic restorations from previous studies and the facies analysis, we estimate the lateral extend along the dip of the retroarc foreland basin to be ±300-470 km, approximately, during the latest Campanian to earliest Maastrichtian. The western depocenter, composed of the UMVB and MMVB, extended for ±60-100 km. While the eastern depocenter that extended from the ECB to the westernmost LLB was ±160-250 long. The exhuming block of the ECB extended for ±80-120 km. The extension of the forebulge, located in the LLB, is still unclear.

(VI) We associate subaerial exposure during the Maastrichtian in the Fusa Area as the result of the exhumation driven by the flexure of the lithosphere and the inherited basin architecture. This SU extends northwards and southwards of the study area. In the south, the connection can be seen in the Prados and Carmen de Apicala Synclines, where the latest Cretaceous is missing, and Paleogene to Neogene rocks overlie the SU. Likewise, it connects northwards with the subaerial exposure recorded in the Cobardes Anticline since the Middle Maastrichtian. This subaerial unconformity corresponds to a first-order unconformity. Following the basin architecture, we identify the possibility of this area being the forebulge. However, the data do not support this hypothesis. Nevertheless, this feature contributed to the subsequent exhumation of the ECB in the Late Eocene to the Miocene.

(VII) According to the data, the Lower Lidita, and the lowermost part of the Umir formations in the MMVB and UMVB; the Olini Gp and Labor Fm in the ECB; and the lower Guadalupe and Palmichal groups in the LLB were deposited during the last stage of the extensional basin. While the upper part of the Teruel and Hoyon formations in the UMVB and MMVB; Bogota and Upper Socha formations in the ECB and Los Cuervos Fm in the LLB, were deposited during the final stage of the retroarc foreland basin.

(VIII) The principal hydrocarbon reservoirs in the Llanos Basin were subaerially exposed at different times. In particular, the Late Cretaceous reservoirs were exposed during (1) the initiation of the retroarc foreland basin due to the exhumation of the forebulge, (2) the shift from its under- to the overfilled stage, and (3) at the end of the basin lifespan. A forced regression took place in each of these events. Thus, these rocks are prone to form either a stratigraphic trap or just a corridor of sandstones with overlaying marine facies. For that reason, our regional sequence stratigraphic framework is the first step to a better understanding of the distribution of the reservoirs across the basin, which is essential to identify future accumulations and fields. The eastwards tracking of these SU is crucial to determine the prospectivity of the stratigraphic traps.

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Chapter 4: Sequence stratigraphic framework of the Campanian-Eocene foreland basin, Colombia

ABSTRACT

During the Campanian to the Eocene, a retroarc foreland basin extended across the Colombian territory, from the Magdalena Valley to the Llanos Basin. Outcrop and well cores data from the southern Llanos Basin indicate the sedimentary record preserves four second-order sequences, formed during the under- and overfilled stages of the foreland basin. Tectonism controlled their development. The diachroneity of the surfaces and sequences is related to the northward migration of the orogen that influenced the tectonic stages and architecture of the basin. The southern Llanos Basin was at the marginal part of the foreland, where the role of the tectonism resulted in the formation of multiple unconformities. Their formation processes vary regarding the proximity of the shoreline and the tectonic stage. These unconformities reworked the boundaries of the sequences, so their connection towards the depocenter also varies. In the Sagu area, the three lowermost four second-order sequences deposited during the underfilled stage are incomplete and pinch out eastward as subaerial unconformities truncate them. The uppermost sequence was formed during the overfilled stage when fluvial deposition took place across the basin, and the eastward migration of the depocenter renewed the sedimentation along the basin margins. At this time, accommodation was outpaced by sedimentation due to the high sediment supply resulted from the uplifting orogen and forebulge. Albeit, the reduced amalgamation of the channels suggests the creation of accommodation during this stage. The nomenclature and classification of surfaces and systems tracts may diverge from Llanos Basin to the depocenters. Nevertheless, the surfaces and sequences from the southern Llanos Basin are connected across the entire basin regardless of the tectonic stage. Their partial or total absence and the facies changes are the consequence of the basin architecture and tectonism.

Keywords: Campanian, Eocene, sequence stratigraphy, foreland basin, second-order surfaces

4.1. Introduction

The Upper and Middle Magdalena Valley Basins (UMVB and MMVB), along with the Eastern Cordillera Basin (ECB) and the Llanos Basin (LLB), were part of a regional basin since the Jurassic (Colleta et al., 1990; Cooper et al., 1995 and Sarmiento, 2001), and subsequently separated in the Paleogene due to the inversion and exhumation of the Eastern Cordillera (Mora et al., 2006; Silva et al., 2013; and Reyes-Harker et al., 2015). Although the basin started as an extensional basin, the tectonic interaction of the Caribbean and the South American plates transformed it into a retroarc foreland basin during the Campanian (Cediel et al., 2011; Horton et al., 2010). This retroarc basin ended in the late Paleocene to early Eocene when orogenic unloading took place (Parra et al., 2009). The resulting UMVB, MMVB, and LLB accumulated sediments from the last first-order change, whereas restored cross-sections have demonstrated the ECB exhumed and exposed the rocks from the Paleozoic to the Paleogene (e.g., Ramirez-arias et al., 2012; Tesón et al., 2013).

According to Carvajal-Torres et al. (*2021*), the first-order retroarc foreland sequence is bounded by a compound surface in the base and a subaerial unconformity on top. This compound surface is formed by a subaerial unconformity and a maximum regressive surface on top of the latest deposits from the back-arc basin (e.g., Upper Lidita, Monserrate, and Labor formations). Meanwhile, a regional subaerial unconformity caps the latest sediments of the retroarc sequence (e.g., Los Cuervos, Hoyon, San Fernando, and Upper Socha formations). Once the Central Cordillera initiated its exhumation (Bayona et al., 2013 and Villagómez & Spikings, 2013), and the basin started and experienced subsidence. This underfilled stage finished in the Latest Maastrichtian when fluvial conditions dominated, and the shoreline moved northward (Bayona, 2018; Caballero et al., 2020; Carvajal-Torres et al., *2021*).

Moreover, subaerial exposure is identified in the LLB, UMVB, and the western part of the ECB (Ramon & Rosero, 2006; Veloza et al., 2008; and Martínez, 2016;). During the Paleocene, fluvial deposition controlled the study area (Caballero et al., 2010; Cardona et al., 2018 and Gómez et al., 2005), and the exhumation of the western ECB increased the sediment supply (Caballero et al., 2013 and Moreno et al., 2011). However, the sedimentation rates and the thickness of the sedimentary record reported by Bayona et al. (2013) and Lamus et al. (2013) indicate the creation of accommodation. The orogenic unloading from the Early to Middle Eocene determined by Parra t al. (2009), marked the end of the retroarc foreland basin.

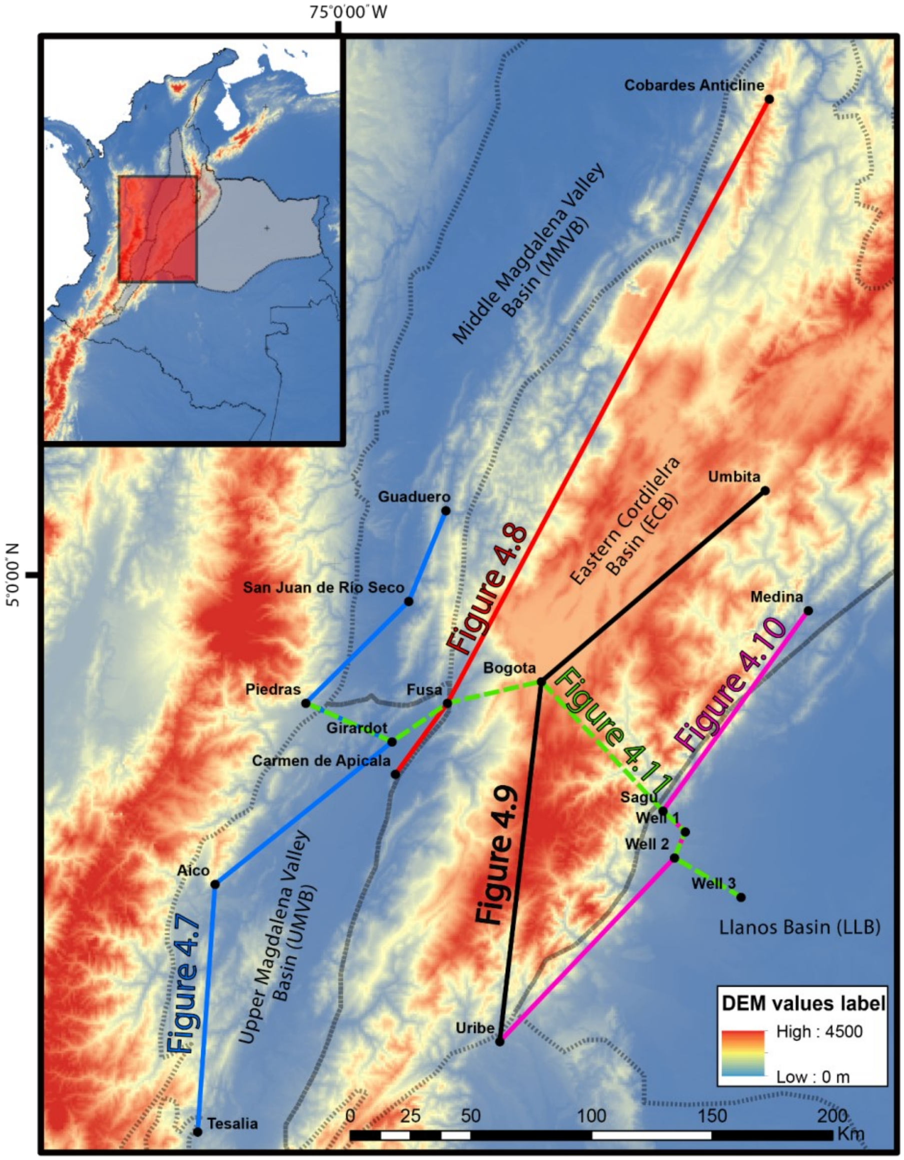


Fig. 4.1. Location map of the study area. The lines are different chronostratigraphic sections and their unique color is intended to facilitate the differentiation of their trace. Location of the study area in the central part of Colombia. UMVB: Upper Magdalena Valley Basin, MMVB: Middle Magdalena Valley Basin, ECB: Eastern Cordillera Basin, LLB: Llanos Basin. The reviewed authors are: Guadero: Bayona et al., (2013), De Porta, (1965), and Lamus et al., (2013); Umbita: Bayona et al., (2013) and Ulloa & Rodríguez, (1975); San Luis de Gaceno: Guerrero & Sarmiento, (1996), Jaramillo, (1999) and Parra et al., (2010); San Juan de Rio Seco: Bayona et al., (2013), Gómez et al., (2003) and Lamus et al., (2013); Bogota: Bayona et al., (2010), Pérez & Salazar, (1978), Sarmiento, (1992), Vergara & Rodriguez, (1997); Sagu: This study and Martínez, (2016); Wells 1-3: This Study; Piedras: Guerrero et al., (2000); Girardot: Acosta et al., (2002) and De Porta, (1966); Fusa: Bayona, (2018) and Bayona et al., (2003); Tesalia: Jiménez et al., (2012) and Veloza et al., (2008); Aico: Carvajal et al., (1993), Garzon et al., (2012) and Yepes, (2001b); Uribe: Buchely, (2015) and Buchely et al., (2015).

Undoubtedly, the allogenic controls (e.g., tectonism) influence the initiation and termination of a retroarc foreland basin (Catuneanu, 2004, 2018, 2019b). The exhumation of the Central Cordillera that resulted in the closure of the extensional basin and the beginning of the retroarc foreland basin, not only produced these first-order changes but also lower hierarchy changes such as the maximum flooding surfaces reported by Garzon et al. 2012, Jaramillo & Dilcher (2000) and Vergara & Rodriguez (1997). Despite multiple studies identified stratigraphic surfaces in the distinct localities of the Colombian Andes, the results do not establish how these local cycles (transgression-regression) are connected across the different depocenters (UMVB, MMVB, ECB, and LLB). We hypothesize that the different depocenters (Upper and Middle Magdalena, Eastern Cordillera, and Llanos) preserve all those lower hierarchy cycles formed during the Campanian to the earliest Oligocene. In this scenario, the stratigraphic surfaces formed in one area have an equivalent correlatable surface in other areas regardless of the distance and the intracontinental paleo-highs such as the western flank of the Eastern Cordillera, the Macarena, or the Cira-Infantas.

The purpose of this study is to identify lower hierarchically changes in the Sagu Creek and Wells 1-3, the southern part of the LLB, and establish their regional equivalences across the UMVB, MMVB, and ECB. Subsequently, construct the sequence stratigraphic framework of the retroarc foreland basin that contributes to the recognition of the interplay between the sedimentation and accommodation because of the allogenic controls. Furthermore, providing an insightful understanding of the connectivity of the depocenters.

4.2. Regional Setting

In the farther southwestern part of Colombia, the Andes is divided into the Western, Central, and Eastern Cordilleras. The Western Cordillera bounded in the east by the Romeral Fault System, accreted during the Late Cretaceous, is mainly composed of mafic igneous rocks (Villagómez & Spikings, 2013). The Central Cordillera, limited at east by the Palestina Fault System, is composed of metamorphic and igneous rocks dated from the Cenozoic and older and has been exhumated since Paleozoic with a higher rate during the Early Cretaceous (Villagómez & Spikings, 2013; Horton et al., 2010; Spikings et al., 2015;). The Eastern Cordillera delineated by a double vergence faults systems, Cambao-La Salina in the west and Guaicaramo in the east, exposes a complex sedimentary record from Paleozoic Basement to Holocene deposits (Colleta et al., 1990; Cortés et al., 2006 and Tesón et al., 2013). The basement is underlying either continental deposits from Triassic or Jurassic to fully marine Cretaceous rocks. The marine Cretaceous rocks are overlaid by Continental facies and Coastal to Marginal sediments, showing changes in depositional environments and active tectonism (Bayona et al., 2013). The Eastern Cordillera diachronically uplifted since the latest Cretaceous to Paleocene along the western flank (Bayona et al., 2010; Mora et al., 2013; Caballero & Mora, 2014; Reyes-Harker et al., 2015; Bayona, 2018). These mountain ranges were a sediment source for the basins at every stage and exerted control on the fluvial channels (Horton et al., 2010; Nie et al., 2012 and Silva et al., 2013).

During the Cretaceous to the Paleogene, the regional tectonic setting was influenced by the subduction of the Caribbean Plate beneath the South American plate (Pindell & Kennan, 2009). This interaction resulted in highly diachronous first-order changes that spread from south to north. Although no major faults were active at that time, the western part of the ECB was under subaerial exposition from the Late Campanian (e.g., the subaerial unconformity along the Carmen de Apicala Syncline reported by Caicedo et al. 2000). Likewise, the eastern part of the LLB was exhumed and subaerially exposed. Bayona et al. (2007) and Caballero et al. (2020) expose how the Cretaceous rocks pinch out towards the west and it is truncated by a Late Cretaceous-Paleocene unconformity. According to Gómez et al. (2005) and Carvajal-Torres et al. (2021b), this is a subaerial unconformity that corresponds to the forebulge unconformity. It is contemporaneous to the subaerial unconformity reported by Julivert (1959) and Bayona et al. (2003) in the Fusagasuga and Lebrija areas, respectively.

4.3. Previous Studies

The discovery of the first oil field in Colombia (La Cira-Infantas) in the 1930s triggered the increase in geoscientific studies along the territory, aiming to have a better understanding of the geological framework of the basins. Van der Hammen (1954) established the first chronological analysis of the Cretaceous rocks using paleontological information. Subsequently, during the ‘90s, several authors (e.g., Colleta et al., 1990 and Dengo & Covey, 1993) promoted the regional geological models of the Eastern Cordillera and adjacent basins (Magdalena and Llanos Basins). Cooper et al. (1995) presented a regional detailed and synthesized geological model of the Colombian Andes. Based on eustatic changes, they established a series of sequences from the Latest Jurassic to the Neogene. Likewise, Föllmi et al. (1992) examined the cyclicity of the phosphatic-rich Late Cretaceous, and Vergara & Rodriguez (1997) identified super sequences within the Late Cretaceous to Paleocene in the ECB and the LLB.

Likewise, the geological model and the chronology of the tectonic events were further constrained in the next decade. Cortés et al. (2006), Mann et al. (2006), Mora et al. (2006), Parra et al. (2009), and Rueda et al. (2007) are among the most relevant studies that calibrated the timing of the uplift of the Eastern Cordillera. These studies include a sedimentological analysis of the LLB in relationship to tectonism. Moreover, Sarmiento (2001) established a complete stratigraphic analysis along the MMVB, ECB, and LLB, and determined an accurate stratigraphic correlation of the facies. In addition, this study evaluated the paleogeographic reconstruction of the geological context, including variables such as facies distribution, sedimentary cover, and crustal thickness. Guerrero (2002) and Hoedemaeker (2004) studied the Cretaceous rock succession and established the presence of maximum flooding (MFS) and maximum regressive surfaces (MRS).

During the last decade, Bayona et al. (2013), Mora et al. (2013), Moreno et al. (2011), Reyes-Harker et al. (2015), Silva et al. (2013), and Villagómez & Spikings (2013) used thermochronology, heavy minerals analysis, and detrital zircon ages to improve and adjust the geological evolution of the Colombian Andes. Their data demonstrate the influence of the exhumation of the Central and Eastern Cordilleras on the paleocurrents, facies distribution, sediment supply, and accommodation rates. Indeed, paleogeographic restorations from Bayona (2018), Caballero et al. (2020), Cediel et al. (2011), and Sarmiento (2011) demonstrated how the facies distribution was controlled by the sedimentation rates.

The studies related to sequence stratigraphy increased in the last decade. Caycedo-Garcia & Catuneanu (2018) and Torrado (2012) built stratigraphic frameworks for the Miocene deposits in particular areas of the LLB. In the UMVB, based on the variations of the population marine palynomorphs, Garzon et al. (2012) identified MFS through the Cretaceous rocks in the Piedras area. Also, Caballero et al. (2015) and Naranjo et al. (2017) defined MFS and MRS for the Maastrichtian to Paleogene rock succession of the LLB. Their model is synthesized in Caballero et al. (2020). Carvajal-Torres et al. (*2021b*) established the first-order stratigraphic boundaries of the foreland basin that existed from the Campanian to the Eocene. A large volume of geoscientific data contributed to the improvement of the perception and knowledge regarding tectonic and sedimentation history.

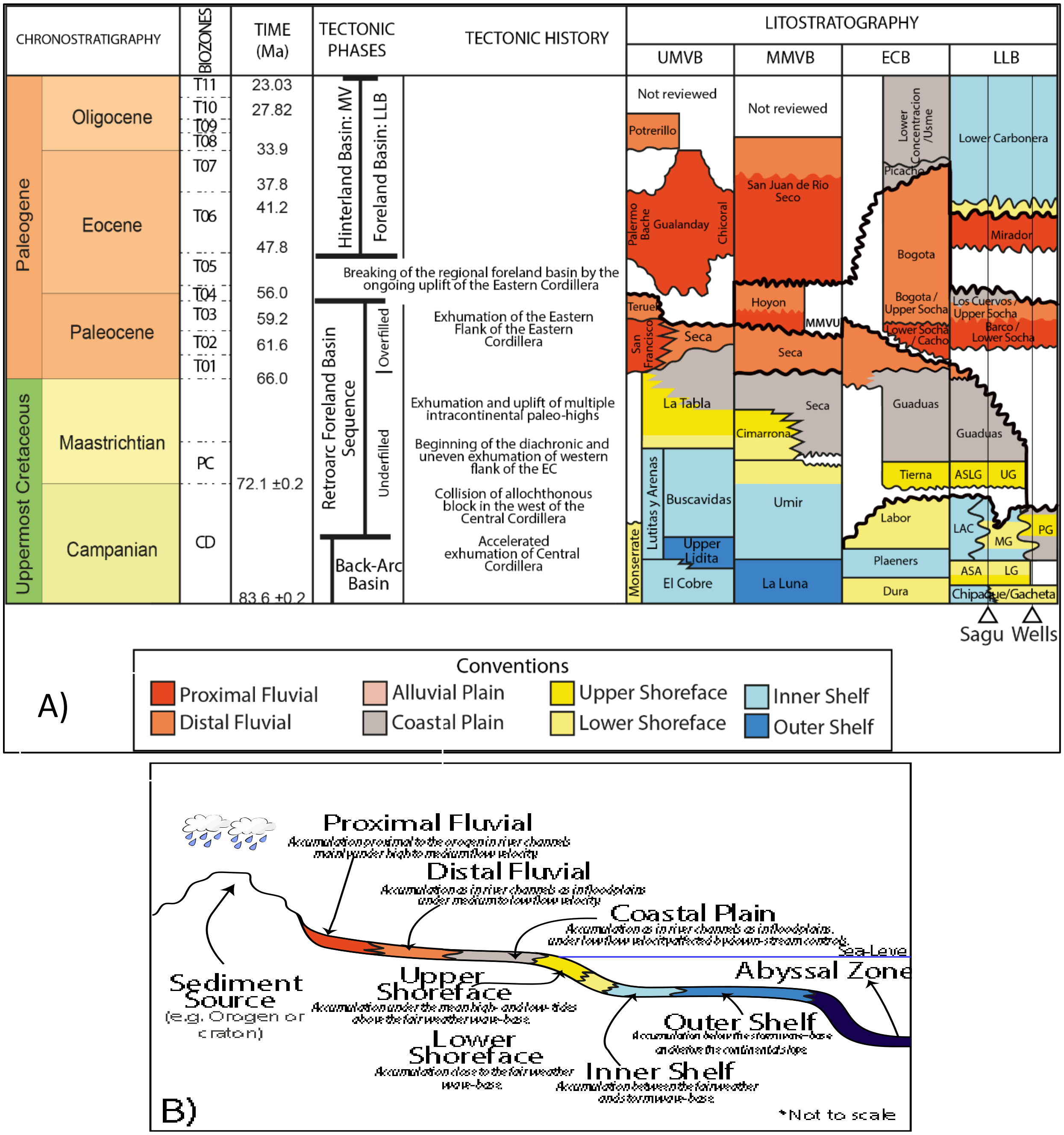


Fig. 4.2. A) Chronostratigraphic chart of the study area indicating the lithostratigraphic and age correlativity of the different rock formations across the Upper Magdalena Valley Basin (UMVB), Middle Magdalena Valley Basin (MMVB), Eastern Cordillera Basin (ECB) and Llanos Basin (ECB). The major tectonic events are summarized to facilitate the understanding of the tectonic history. The white triangles indicate the estimated location of the Sagu and wells. ASA: Arenitas de San Antonio; LAC: Lodolitas de Aguascalientes; ASLG: Arenitas de San Luis de Gaceno; MG: Middle Guadalupe; LG: Lower Guadalupe; UG: Upper Guadalupe; PG: Palmichal Group; MMVU: Middle Magdalena Valley Unconformity; CD: Cerodinium-Dinogymnium; and PC: Paleocystodinium. Biozones following Jaramillo, et al. (2011), ICP - Ecopetrol (2014), and Martínez (2016). **B)** Depositional environment model.

4.4. Methodology

Outcrop data were obtained from the Sagu creek, Fig 4.1, combined with well cores from the southern Llanos Basin. The ages of the strata were defined following previous studies in the area. The Campanian rock units in the Sagu and the wells were identified following the *Cerodinium-Dinogyminium* biozone from Caballero et al. (2020), ICP - Ecopetrol (2014), and Martínez (2016). While the presence of Maastrichtian rocks in the Sagu Creek was established due to the *Paleocystodinium, Proteacidites dehaani, Echitriporites suescae, Gabonisporites vigorouxi,* and *Ulmoideipites krempii* biostratigraphic ages from ICP - Ecopetrol (2014) and Vergara & Rodriguez (1997). Their absence in the wells was delimited according to Caballero et al. (2020). Likewise, the detrital zircon UPb ages presented by Carvajal-Torres et al. (2019) indicate that the strata overlying the Cretaceous in the Sagu and the wells deposited during the middle to late Paleocene due to the population of Seladian and Thanenian detrital zircon ages.

Similarly, that study showed the presence of middle Eocene detrital zircon ages within the *Gx* facies of the Sagu and the wells, indicating that those rocks deposited relatively during the middle-late Eocene. Nonetheless, the age of the Eocene strata was constrained following Caballero et al. (2015, 2020), Jaramillo et al. 2011, and Parra et al. (2009). The stratigraphic sections from each location are presented in Fig 4.3 (Sagu), Fig 4.5 (Well 1), Fig 4.7 (Well 2), and Fig 4.9 (Well 3). We combined well logs and cores provided by the Geological Survey of Colombia (SGC) to build the sections from the wells.

We defined the lithofacies following Farrell et al. (2012), see Table 4.2. Their associations were specified according to the detailed facies analysis from Carvajal-Torres et al. (2021), see Table 4.3. The definition of the depositional environments took place under the simplified depositional model, see Fig 4.2B and Table 4.3. The model is explained in Carvajal-Torres et al. (2021). Furthermore, following their results we placed the 1) late Campanian regressive surface of marine erosion (RSME), 2) the Cretaceous-Paleocene and Paleocene-Eocene boundaries as subaerial unconformities (SU), and 3) the middle to late Eocene transgressive surface of erosion (TSE), Fig 3.3. The late Campanian RSME is absent in the wells, Fig 3.4.

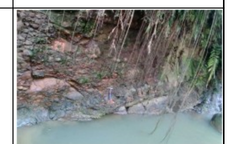
Dominant Lithofacies Code	Lithologic Characteristics	Picture	Dominant Lithofacies Code	Lithologic Characteristics	Picture
S/M b	Heterolithic sandstones and mudstones with horizontal burrows (thalassinoides)		Z lam	Laminated gray siltstone with iron oxides	
(z)S w-lam	Wavy laminated silty fine-grained sandstones		Z lam org	Laminated gray siltstone with plant debris	
Z lam b	Wavy laminated siltstones with horizontal burrows (thalassinoides)		Z rt-mot	Gray siltstone with root traces and iron oxides	
S lam b	Laminated fine to coarse-grained sandstones with vertical burrows (ophiomorphas)		S m	Massive fine to medium-grained sandstone	
S x b	Cross-bedded medium-grained sandstone with vertical burrows (ophiomorphas		S rt	Fine to medium-grained sandstone with root traces	
S biot	Bioturbated medium-grained sandstones		G x	Cross-bedded gravel	
Z/S w lam b	Wavy laminated heterolithic siltstone and sandstone with horizontal burrows (thalassinoides)		Z l	Lenticular bedded gray to reddish siltstone	
S x	Through cross-bedded medium to coarse grained sandstone				

Table 4.1. Lithofacies of the Southern Llanos Basin: from the Sagu and the wells.

Facies Association	Dominant Lithofacies Code	Depositional Context (mechanism of deposition)	Dep Env
FA 1	S/M b	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.	Inner Shelf
	(z)S w-lam	Low energy setting close to the storm wave base, dominated by tides and often affected by storm waves	
	Z lam b	Hempilagic setting below the storm wave base with a very low energy flow dominated by tides.	
	S lam b	Low energy setting proximal to the fair weather wave base, and often affected by storm waves	
FA 2	S x b	Softground and substrate-controlled. Biogenic reworking in medium energy flow, above the fair weather wave base.	Lower Shoreface
	S biot	Soft ground and substrate-controlled. Biogenic reworking in medium to low energy flow, close to the fair weather wave base.	
	S lam b	Same as above	
	Z/S w lam b	Same as above	
FA 3	S x	High energy regime setting affected by the oscillatory flow-landward transportation of the waves.	Upper Shoreface
	S x b	Softground and subtrate-controlled. Biogenic reworking in medium to high energy flow, affected by oscillatory movements of the waves. With K and P enrichment and low sedimentation rates.	
	S lam b	Soft ground and substrate-controlled. Biogenic reworking in medium to high energy flow typical of plane-bed conditions.	
FA 4	Z lam	Aerobic low energy setting with suspension deposition.	Coastal Plain
	Z lam org	Aerobic low energy setting with suspension deposition, with some episodes of increased water level that caused anaerobic temporary conditions.	
	Z rt-mot	Aerobic low energy setting with suspension deposition.	
	S m	Hyperconcentrated flow during abrupt changes in flow speed from low to high energy.	
	S x	Same as above	
	S rt	Same as above	
FA 5	S x	Same as above	Contiental Fluvial
	G x	Migration of bedforms related to high turbulent flow energy channels.	
FA 6	S x	Migration of bedforms related to medium flow energy channels.	Marginal Fluvial
	Z l	Aerobic low energy setting with suspension deposition.	
	S rt	Migration of bedforms related to medium flow energy channels.	

Table 4.2. Facies association and interpreted depositional environment.

We carried out an independent interpretation of depositional environments for the Sagu and the wells, see Table 4.2. Also, we used the information from previous studies to associate the environmental interpretation of each author with our model. Subsequently, multiple chronostratigraphic correlations with the adjacent depocenters were constructed., Fig 4.1, 4.7, 4.8, 4.9, 4.10, and 4.11. Using the principles from Qayyum et al. (2017, 2015) and Wheeler (1959), we first correlated the isochrones according to the strata ages from each author listed in Fig. 4.1. Then, we correlated the regional unconformities such as the K-T and the Paleocene-Eocene boundaries. The missing record varies in each location. Based on, Bayona et al. (2013) exposed in Bogota lacuna is almost null, whereas in Umbita, Medina, and San Juan del Rio Seco it is at least ±2My. We also reviewed the biostratigraphic gaps and numerical methods from Caballero et al. (2015), Caballero et al. (2020), Contreras et al. (2010), De La Parra (2009), Gómez et al. (2003), Jaramillo (1999), Jaramillo et al. (2011), Vergara & Rodriguez (1997), and Yepes (2001a). Although we understand that their results are highly reliable, they are subject to further calibration and so they are more relative than definitive. The subaqueous TSE and RSME unconformities from the Sagu and wells were limited to the Llanos Basin and part of the ECB, (Carvajal-Torres et al. 2021).

Then, we made the correlation of the chronostratigraphic units. We carried out this correlation following the facies associations, depositional environment, and our depositional model to interpret the lateral changes. Afterward, based on the grading observations, authigenic minerals, content of marine and continental palynomorphs, presence of coal, and sedimentary structures we defined stacking patterns. The results are plotted in Figs 4.7, 4.8, 4.9, 4.10, and 4.11. We identified and interpreted multiple prograding and retrograding contacts related to shoreline trajectories for the late Cretaceous underfilled deposits. Nonetheless, the Paleocene-Eocene overfilled deposits required the analysis of the amalgamation of the channels according to Catuneanu (2019). Finally, the definition of stratigraphic surfaces and systems tracts was developed based on Catuneanu (2019a, 2019c) and Catuneanu et al (2011).

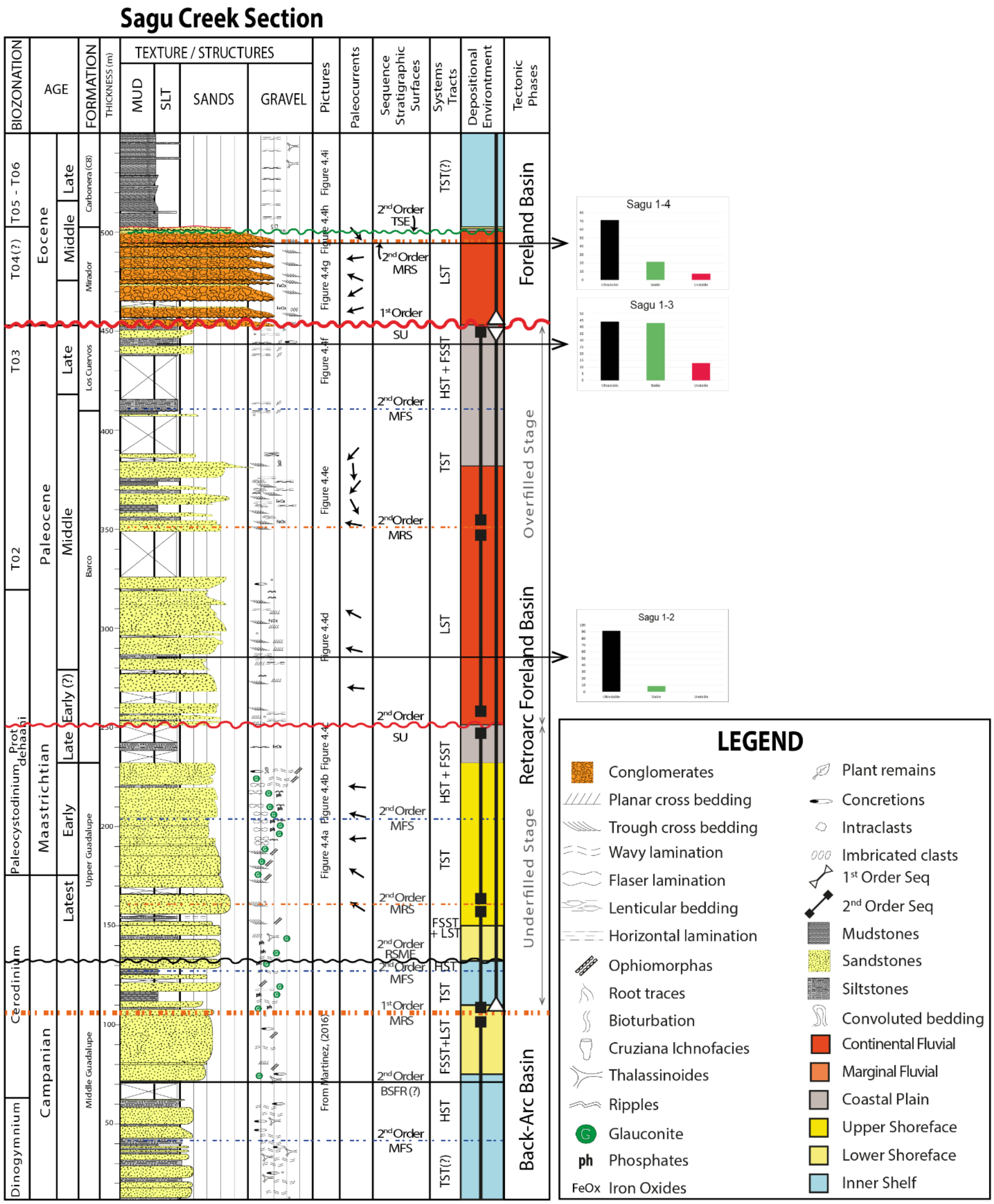


Fig. 4.3. Stratigraphic section of the Sagu creek. TST: Transgressive systems tract, LST: Lowstand systems tract, HST: Highstand systems tract, FSST: Falling stage systems tract; MFS: Maximum flooding surface, MRS: Maximum regressive surface, SU: Subaerial unconformity, BSFR: Basal surface of forced regression, TSE: Transgressive surface of marine erosion; HAST: High-amalgamation systems tract; and LAST: Low-amalgamation systems tract. The thickness of the surfaces differentiates their hierarchy. Samples 1-2, 1-3 and 1-4, show the heavy mineral distribution, black: ultrastable, green: stable, and red: unstable. Biozones from Jaramillo, (2011), ICP-Ecopetrol (2014) and Martinez, (2016).

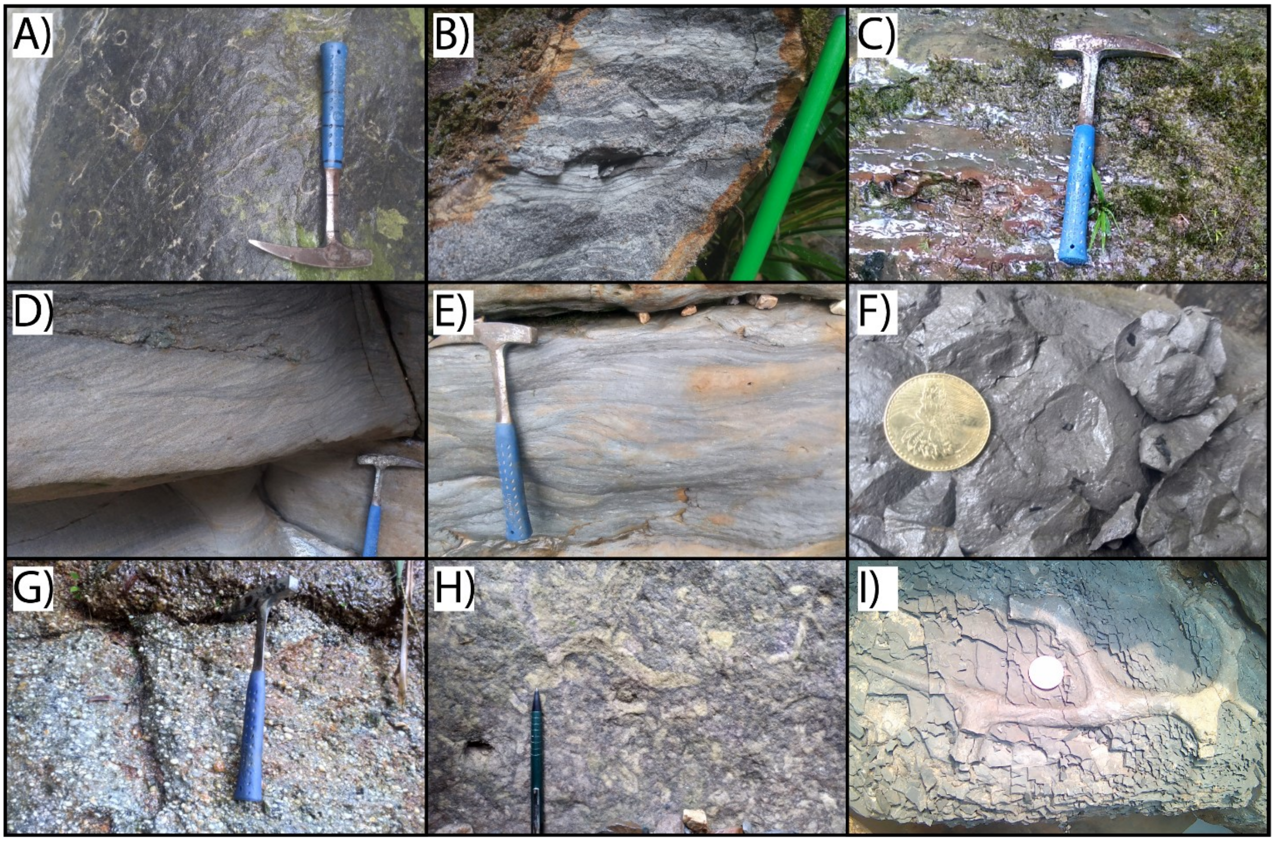


Fig. 4.4. Photographs of the Sagu Creek facies. A) medium to coarse grained sandstones with cross bedding; B) medium to fine grained sandstones with ophiomorphas, glauconite and phosphates; C) reddish gray muddy siltstones; D) pebbly coarse grained sandstone with trough cross bedding; E) medium to coarse grained sandstones with hummocky cross bedding; F) gray silty mudstones with plant remains; G) conglomerates with imbricated clasts and cross bedding; H) fine to medium grained sandstones with cruziana facies; I) gray to dark mudstones with thalassinoides.

		Ultraestables			Estables			Unstables									
AGE	**Sample**	**Zircon**	**Rutile**	**Tourmaline**	**Garnet**	**Muscovite**	**Monazite**	**Chlorite**	**Epidote**	**Olivine**	**Orthopyroxene**	**Titanite**	**Andalusite**	**Zoisite**	**Clinozoisite**	**Total**	**Opaques**
Lower Paleocene	Sagu 1-2	150	25	40		20										235	50
Upper Paleocene	Sagu 1-3	40	20	25	20	63		5			1	3		16		193	230
Eocene	Sagu 1-4	90	15	60	25	25		5			12					232	160

Table 4.3. Heavy minerals distribution values for the samples from the Sagu. Location of the samples in Fig 4.3.

4.5. Campanian to Oligocene Stratigraphy

The late Campanian to earliest Oligocene rock succession from the Sagu Creek and the wells mainly consists of siliciclastic sediments deposited under shallow marine to fluvial conditions (Fig 4.3 and 4.5). Similarly, the reviewed data from the authors listed in Fig 4.1 indicate that siliciclastic deposition also dominated along the UMVB, MMVB, and ECB. We present the results separated by the next intervals:

4.5.1. Upper Campanian:

In the Sagu Creek, the Middle Guadalupe belongs to the *Cerodimnium-Dynogimnium* biozone (Martínez, 2016; Caballero et al., 2020). This coarsening upwards unit is composed of the intercalation of sandstones and mudstones. In the lower part, the sandstones are fine-grained, and the gray-colored mudstones preserve *thalassinoides* and wavy lamination. In the middle part of the unit, a very thick bed of medium-grained sandstones with ophiomorphas is identified. The upper part of the interval is composed of medium-grained sandstones with phosphates, glauconite, and ophiomorphas. In the uppermost part, a very thick bed of coarse-very coarse-grained sandstones with trough cross-bedding is recognized. These beds are intercalated with gray to dark mudstones with some thalassinoides in the upper part, see Fig 4.3 and 4.4. In the wells, the equivalent coarsening upwards interval is controlled by medium to coarse-grained sandstones with some ophiomorphas, Fig 4.5 and 4.6. An association of very coarse-grained sandstones is identified in the uppermost part of the interval.

According to the facies association, the Sagu deposits were deposited in shallow marine environments, varying from inner shelf to lower shoreface. The uppermost part of the interval is related to upper shoreface deposits, Fig 4.3. In the wells, the environments become shallower as they vary from lower to upper shoreface, and the uppermost part is interpreted to be deposited in a coastal plain dominated by fluvial channels, Fig 4.5. The late Campanian interval in those localities is truncated by an unconformity. An irregular contact is recognized between the lower shoreface above and the inner shelf below of the late Campanian in the Sagu Creek, Figs 4.3 and 4.5.

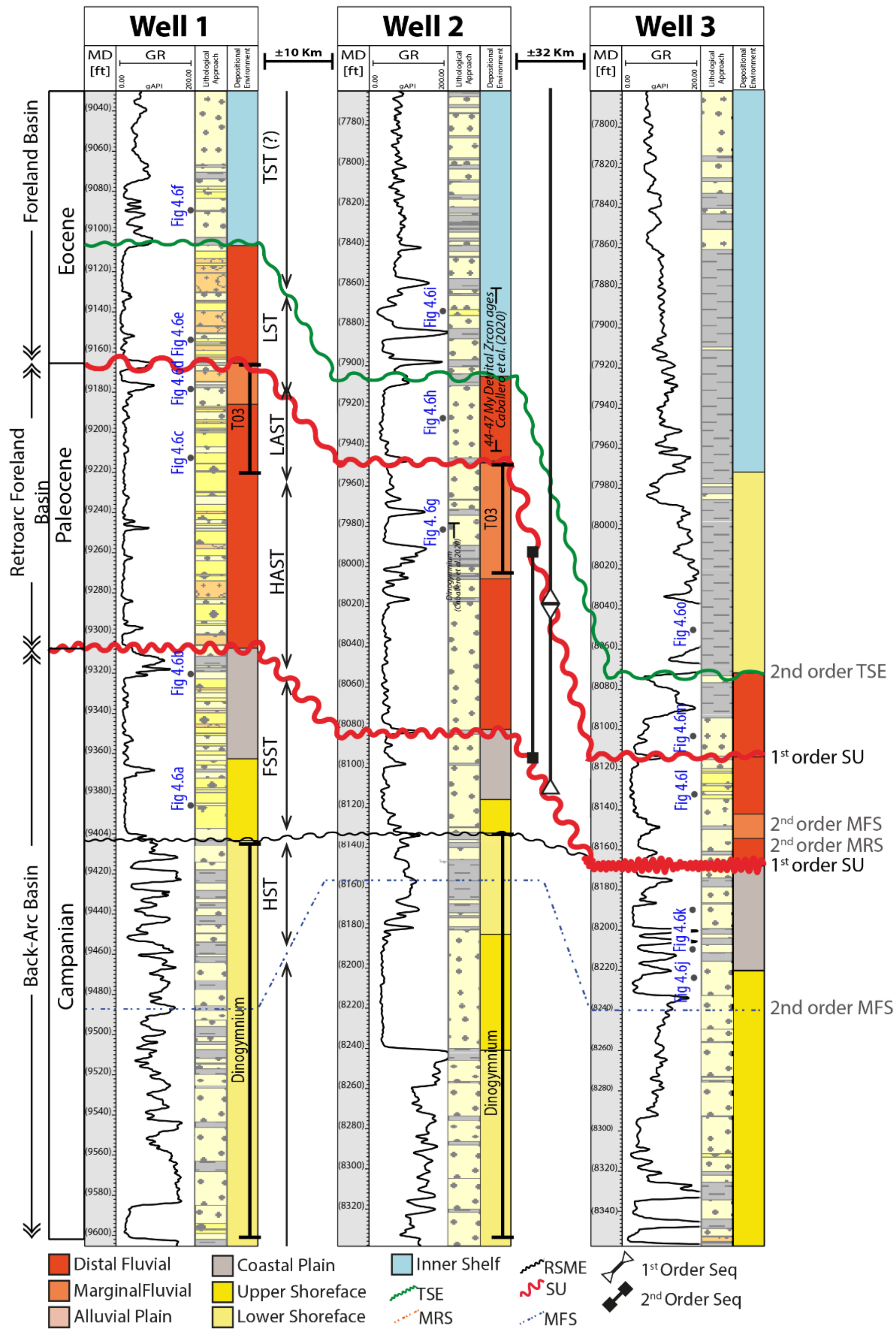


Fig. 4.5. Stratigraphic correlation of the Wells Sections. Abbreviations: MFS: Maximum Flooding Surface, MRS: Maximum Regressive Surface, SU: Subaerial Unconformity, RSME: Regressive Surface of Marine Erosion, TSE: Transgressive Surface of Erosion; HAST: High-amalgamation systems tract; and LAST: Low-amalgamation systems tract. The thickness of the surfaces differentiates their hierarchy. Biozones from Jaramillo, (2011), ICP-Ecopetrol (2014) and Martinez, (2016).

Northward to these locations, the Lodolitas de Aguascalientes in the Medina area indicates inner shelf deposition. Likewise, the UMVB and MMVB coetaneous deposits from the Lutitas y Arenas, Buscavidas, and Umir formations suggest inner shelf conditions during the Late Campanian. Meanwhile, the facies association of the Labor formation along the ECB unveil deposition under lower shoreface conditions, Fig 4.2. Similarly, subaerial exposure is recognized (Fusa and Carmen de Apicala areas), whereas other areas (Bogota) exhibit subaqueous erosion. Facies association nearby indicates the Cobardes Anticline may have accumulated sediments from the inner shelf environment, fig 4.8.

4.5.2. Early Maastrichtian

This is characterized by the presence of *Paleocystodnium* within the sedimentary record of the Sagu Creek (ICP - Ecopetrol, 2014). The ±100 m rock succession is mainly composed of medium-grained sandstones with a slight difference from base to top. In the lower part, medium to coarse-grained sandstones shows through cross-bedding, ophiomorphas, and glauconite, whereas the middle part preserves medium-grained sandstones with flaser bedding, phosphates, and glauconite, Figs 4.3 and 4.4B. The upper part of this interval presents an abrupt change from coarse-grained sandstones with wavy lamination and ophiomorphas to gray to black-colored siltstones and mudstones with horizontal bedding and iron oxides, Fig 4.4C. They are truncated by a subaerial unconformity, which extends eastwards to the area of the wells. No Maastrichtian deposits were recognized along the wells.

The facies association suggests deposition in an upper shoreface marine environment, and the uppermost siltstones and mudstones indicate coastal plain deposition. These facies are correlatable with the upper shoreface and coastal plain deposits from the Arenitas de San Luis de Gaceno and lower Guaduas formations in the Medina area, Fig 4.2. Synchronically, the Tierna and lower Guaduas formations unveil shallowing upwards deposition in the ECB, equally passing from upper shoreface to coastal plain deposits, Fig 4.2. This shallowing upwards trend is also found in the UMVB and MMVB, where the previous inner shelf deposition switched to lower shoreface environments of the lower Cimarrona and La Tabla formations. The Fusa and Carmen de Apicala areas were under subaerial exposure along with Uribe and Tesalia. According to the facies preserved in the proximity of the Cobardes Anticline, a change to coastal plain deposition occurred during the Latest Campanian to Lowermost Maastrichtian, Fig 4.8.

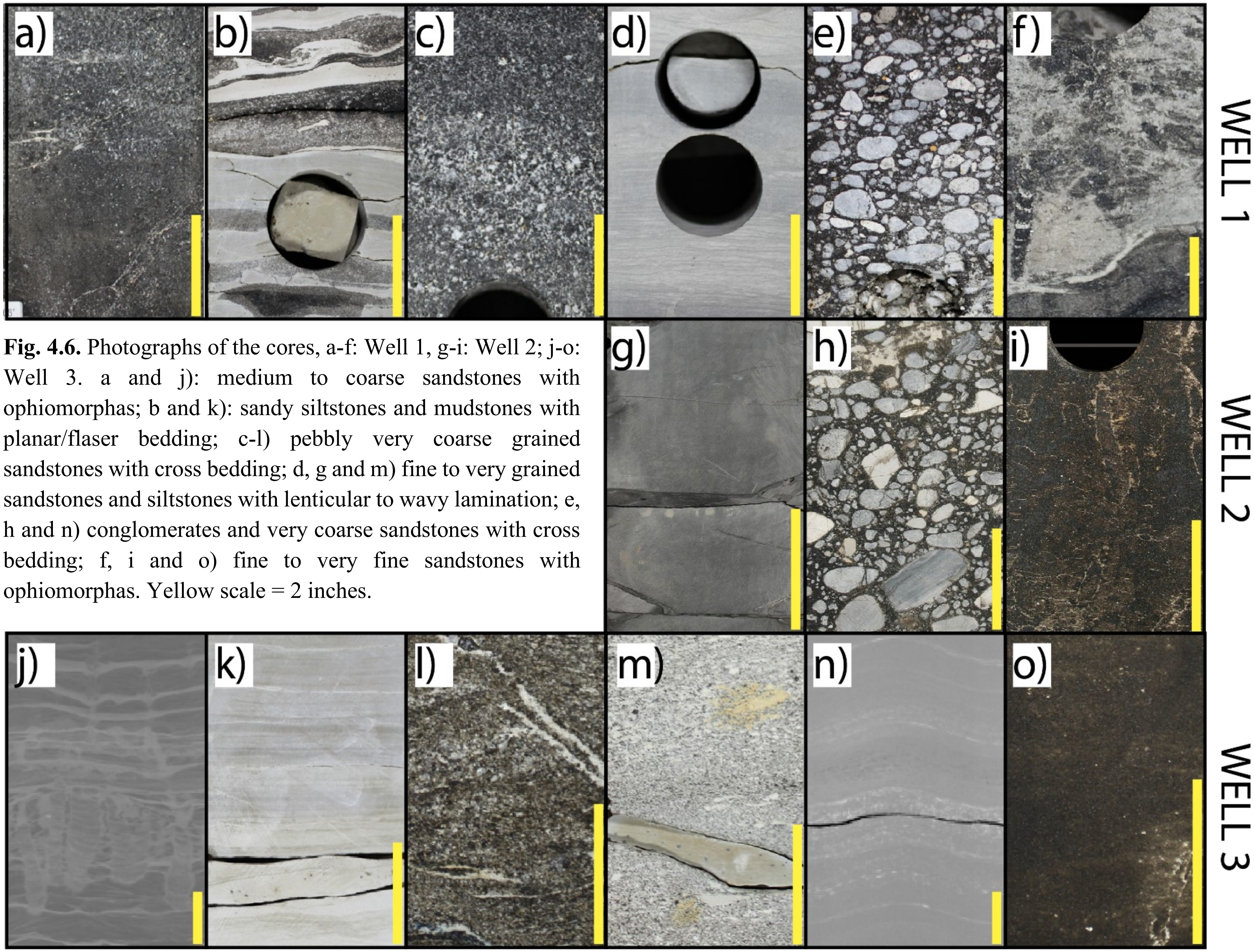


Fig. 4.6. Photographs of the cores, a-f: Well 1, g-i: Well 2; j-o: Well 3. a and j): medium to coarse sandstones with ophiomorphas; b and k): sandy siltstones and mudstones with planar/flaser bedding; c-l) pebbly very coarse grained sandstones with cross bedding; d, g and m) fine to very grained sandstones and siltstones with lenticular to wavy lamination; e, h and n) conglomerates and very coarse sandstones with cross bedding; f, i and o) fine to very fine sandstones with ophiomorphas. Yellow scale = 2 inches.

Despite the shallowing upwards trend across the study area, several features unveil a short period of increased accommodation that resulted in a minor transgression. The presence of phosphatic- and glauconitic-rich deposits in the Sagu creek, are coetaneous with the same characteristics in the Medina and Bogota areas, Figs 4.11 and 4.13. In the UMVB and MMVB, an increase in the portion of marine palynomorphs is reported by previous studies (e.g., Garzon et al., 2012 and Tchegliakova, 1996), Figs 4.7, 4.11, and 4.13.

4.5.3. Late Maastrichtian

During this period, subaerial exposure occurred in the Sagu and wells areas as indicated by the unconformity reported by Vergara & Rodriguez (1997), Martínez (2016), Caballero et al. (2020), Fig 4.10. This unconformity truncates the rock units within the *Proteacidites dehaani* biozone, Fig 4.3. The Guaduas formation in the Bogota, Umbita, and Medina areas demonstrates coastal plain deposition. Similarly, the lower shoreface facies of the La Tabla and Cimarrona formations across the UMVB and MMVB reveal a shallowing pattern to upper shoreface and coastal plain deposits in the latest Maastrichtian. Although facies are shallowing upwards, these formations preserve evidence (e.g., coal beds in Guaduas and increased portion of palynomorphs in La Tabla formations) of a minor transgression during this period, Figs 4.7, 4.9, and 4.10. The Maastrichtian facies are capped by an unconformity among the UMVB, MMVB, and ECB. In these areas, the lacunae associated is negligible, but in the Sagu and LLB, the missing record is ±10 Ma and ±16 My, respectively, (Carvajal-Torres et al., 2021a). Thermochronological data indicates the Cobardes Anticline started its uplifting during the middle to late Maastrichtian. At this time, no deposition is recognized from the Carmen de Apicala to the Cobardes Anticline, Fig 4.8.

4.5.4. Early Paleocene

The U-Pb detrital zircon ages and biozones from Caballero et al. (2020) indicate the Sagu Creek and the wells are were still under subaerial exposure during the earliest Paleocene. Likewise, the data from the Medina area demonstrate the subaerial exposure reached that area, as indicated by the few meters of the coastal facies from the Guaduas formation below the unconformity, Figs 4.10, 4.11, and 4.13. However, fluvial deposition expanded from the UMVB/MMVB to the ECB. The marginal fluvial facies of the Seca and Guaduas formations imply the disconnection from the shoreline during this period. Indeed, the renewed sedimentation in Tesalia demonstrates the development of a complex fluvial system as these areas preserved the continental fluvial facies of the San Francisco formation. Moreover, in the Fusa area coastal deposits are identified, yet, the Carmen de Apicala, Cobardes Anticline, and Uribe areas were under subaerial exposure, Fig 4.8.

4.5.5. Middle to Late Paleocene

The coarse- to medium-grained sandstones with through and planar cross-bedding of the Barco formation indicate the subaerial conditions ended. Subsequently, the facies change to gray-colored siltstones and mudstones with horizontal bedding, and some plant debris (Los Cuervos formation). A transition of gray to red-colored siltstones with lenticular bedding interbedded with medium-grained sandstone with cross-bedding, see Figs 4.3 and 4.4, marks the transition from the lower Barco to the upper Los Cuervos. Those rock formations belong to the T02, T03, and T04 biozones from Jaramillo et al. (2011). The facies association suggests a change from base to top from proximal to marginal deposition in the Sagu, Fig 4.3. A similar pattern is recognized in the Medina area, Fig 10, where fluvial facies of the Lower Socha change into coastal plain deposits of the Upper Socha with brackish palynomorphs (e.g., *Mauritidites franciscoi* reported by Guerrero & Sarmiento, (1996), suggesting some influence from a distal shoreline by the late Paleocene. In the Wells area, the sedimentation was also renewed with coarse to pebbly grained sandstones with cross-bedding from the T03 biozone, Fig 4.6, implying fluvial continental deposition, Fig 4.5.

According to Samples 1-2 and 1-3 (Fig 4.3 and Table 4.3), the distribution of the heavy minerals varied during this period. The ultrastable zircons, rutile, and tourmaline are the main components of Sample 1-2, whereas Sample 1-3 reveals the presence of unstable minerals such as chlorite, orthopyroxene, titanite, and zoisite. In addition, Sample 1-3 contains a considerable amount of garnet. The paleocurrents measured along the Sagu Creek imply that the sediment source was in the east by the middle Paleocene.

In the ECB, the sediments from the Bogota and Umbita areas preserve mainly fluvial facies. Nonetheless, a change is also identified as the Cacho and Lower Socha formations. These formations reveal a change from proximal fluvial deposition into a marginal fluvial deposition of the Bogota and Upper Socha formations. A crucial diagnostic characteristic is a variation in the amalgamation of the channels, which decreases upwards. The Hoyon formation of the MMVB preserves an equal transition, Fig 4.2. Except for Bogota, where the Late Paleocene deposits are truncated by a subaerial unconformity, and paleosols are identified across the study area (Bayona et al., 2010, 2013). According to previous studies, The Cobardes Anticline continued its exhumation and exerted control on the paleocurrents (e.g., Caballero, 2010; Moreno et al., 2011).

4.5.6. Early to Middle Eocene

Based on the biozonation and U-Pb detrital zircon ages from Caballero et al. (2020), at least the earliest Eocene was a period of non-deposition and subaerial exposure in the Sagu Creek and the area of the wells, Figs 4.3 and 4.5. Nonetheless, the conglomerates of the Mirador formation overlaying the subaerial unconformity in the Sagu and wells indicate the deposition was renewed during the early-middle Eocene, Figs 4.4 and 4.6. This formation is also reported in the Medina area with the same conglomeratic facies, implying new continental fluvial deposition occurred in these areas. Sample 1-4 unveils a reduction in the distribution of unstable and stable minerals compared to the 1-3, and the paleocurrents from the Sagu Creek expose a westward direction.

Among the UMVB and MMVB, an early Eocene unconformity is truncating the Teruel and Hoyon, Fig 4.7. Moreover, the overlaying Palermo/Bache, Lower Gualanday, Chicoral, and Lower San Juan de Rio Seco formations reveal proximal fluvial deposition was renewed in these areas during the middle Eocene. In the ECB, the preserved section in the Fusa, Bogota, and Umbita areas indicates a similar diachronous period of subaerial exposure and erosion. In Fusa, it started in the latest Paleocene to the earliest Eocene, whereas in Umbita, it began in the early to middle Eocene, and in Bogota, there is no missing record.

4.5.7. Late Eocene to Earliest Oligocene

An abrupt lithological change is identified in the Sagu area. The conglomerates from the Mirador formation are overlaid by one thick bed of medium-grained sandstone highly bioturbated by cruziana ichnofacies from the T05 biozone. Then, a succession of more than 100 m, of gray to black mudstones and siltstones with thalassinoides and horizontal bedding is identified, the C8 member of the Carbonera formation, Figs 4.3 and 4.4. In the wells, medium sandstones with some ophiomorphas are recognized, Fig 4.6, but the lithological succession is mainly composed of interbedded sandstones with mudstones, Fig 4.5. Following the facies associations, this period depicts a change from proximal fluvial to fully marine deposition, lower shoreface to inner shelf facies. Correspondingly, the rock succession of the Medina area preserves fully marine (lower shoreface to inner shelf) facies on top of the Mirador formation.

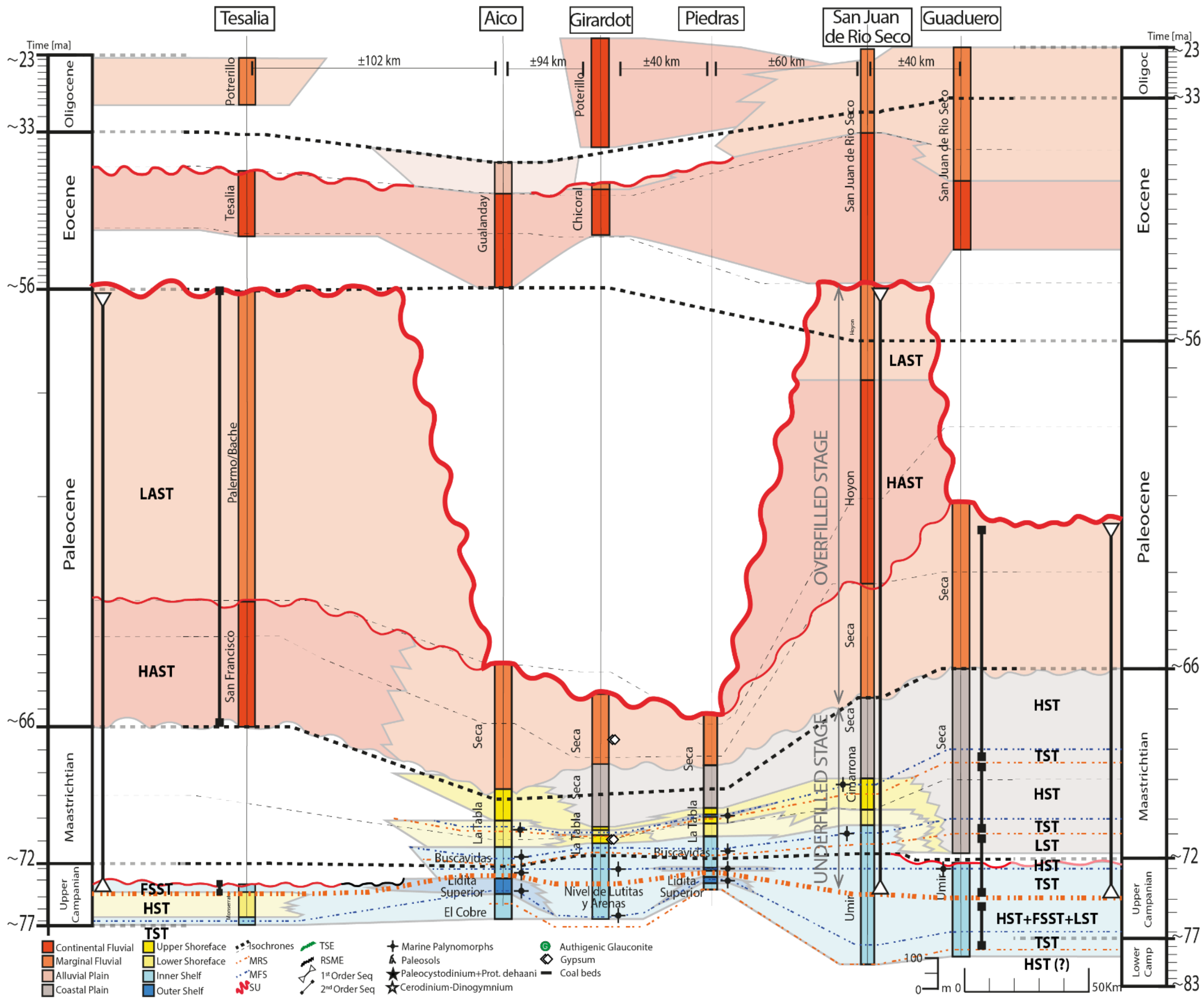


Fig. 4.7. Chronostratigraphic correlation across the foredeep of the retroarc foreland basin (UMVB and MMVB). See how the facies prograde northward and how the systems tracts vary from the under- to the overfilled stage. The reviewed authors are: Guadero: Bayona et al., (2013), De Porta, (1965), and Lamus et al., (2013); San Juan de Rio Seco: Bayona et al., (2013), Gómez et al., (2003) and Lamus et al., (2013); Piedras: Guerrero et al., (2000); Girardot: Acosta et al., (2002) and De Porta, (1966); Tesalia: Jiménez et al., (2012) and Veloza et al., (2008); Aico: Carvajal et al., (1993), Garzon et al., (2012) and Yepes, (2001b). TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion

These marine facies are not present along the ECB. Notwithstanding, the Concentracion and Usme formations in the Umbita and Bogota area suggest coastal plain deposition, implying the shoreline was located between the ECB and the LLB. In the Uribe section, the sedimentation was renewed with the coastal deposits of the San Fernando formation. In contrast, the sedimentary record from the UMVB and MMVB remained under fluvial deposition. The upper part of the San Juan de Rio Seco and Potrerillo formations unveil either proximal to a marginal fluvial deposition with no influence of the shoreline.

4.6. Sequence Stratigraphy

A detailed sequence stratigraphic analysis was carried out following the principles and methodologies from Catuneanu (2017, 2019b) and Catuneanu et al. (2011). The studied interval extends from the Campanian to the Early Oligocene and comprises the first-order foreland basin sequence. According to Carvajal-Torres et al. (*2021b*), a first-order MRS combined with a SU composed the lower stratigraphic boundary of this sequence, it is dated from the Late to Latest Campanian. Meanwhile, a regional SU from the Late Paleocene to Middle Eocene is its upper boundary. The ages of these surfaces coincide with the first stages of the exhumation of the paleo-Central Cordillera and with an episode of orogenic unloading (Parra, Mora, Sobel, et al., 2009; Villagómez, 2010; Villagómez & Spikings, 2013). Therefore, the strata bounded by these surfaces deposited in the regional foreland basin setting, in which the paleo-Central Cordillera acted as orogen and most of the Llanos Basin belonged to the forebulge area (e.g., Cooper et al., 1995; Gómez et al., 2005; Horton et al., 2010; Bayona et al., 2020). Several paleogeographic maps were reviewed to constrain and understand the geological context. Carvajal-Torres et al. (2021b) expose a series of palinspatically restored paleogeographic maps built using the data from previous studies (e.g., Sarmiento, 2001; Cediel et al., 2011; Reyes-Harker et al., 2015; Cardona et al., 2018; Bayona et al., 2018, 2020; Caballero et al., 2020).

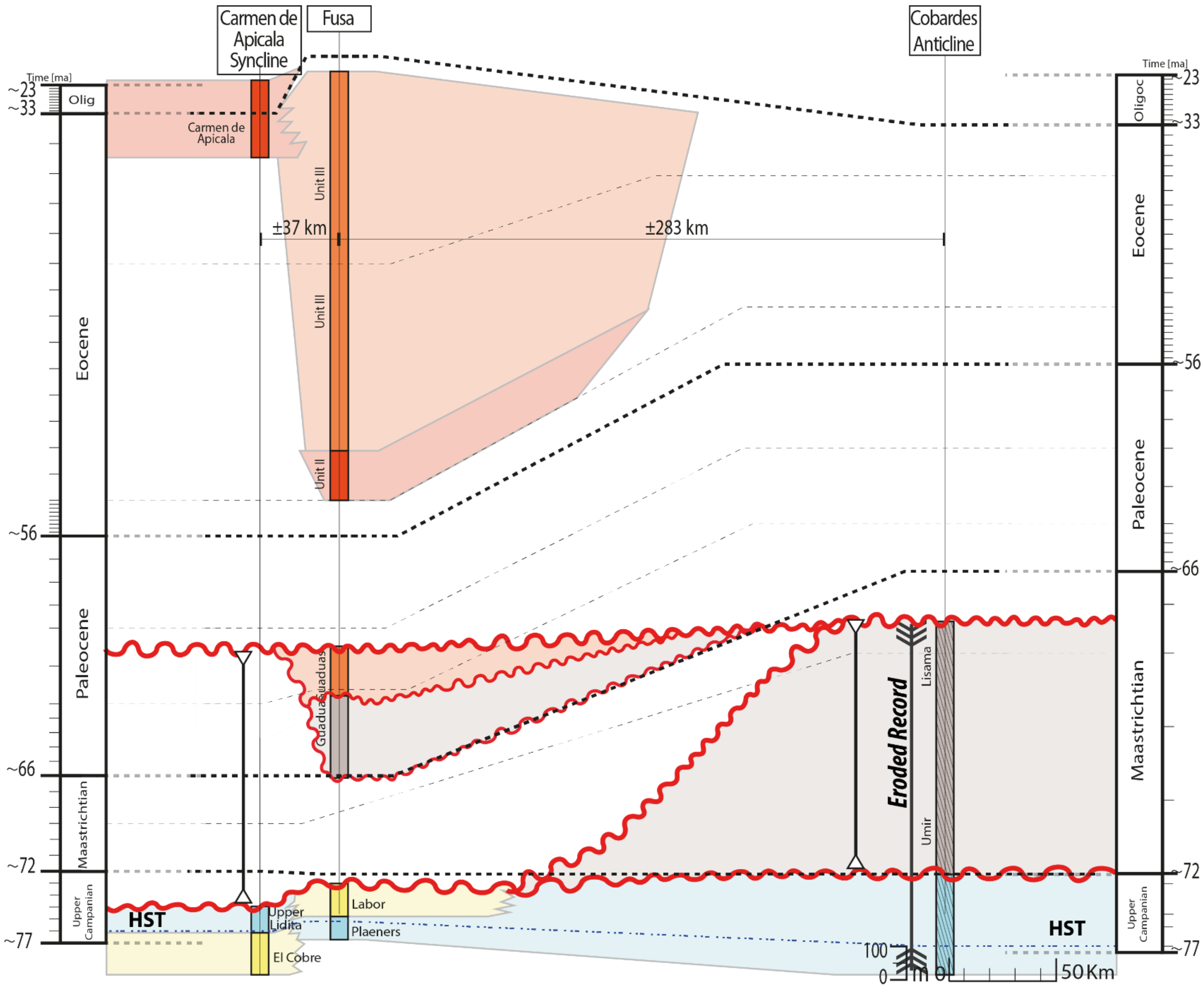


Fig. 4.8. Chronostratigraphic correlation across western part of the ECB. The sedimentary record from Cobardes Anticline was reconstructed. The forebulge unconformity expanded northwards in pulses associated to the northward migration of the orogen. For that reason, it becomes younger. The reviewed authors are: Fusa: Bayona (2018) and Bayona et al. (2003); Carmen de Apicala Caicedo et al. (2002); and Cobardes Anticline: Caballero et al. (2013), Montaño et al. (2016); Silva et al. (2013) and Sarmiento (2001). TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion.

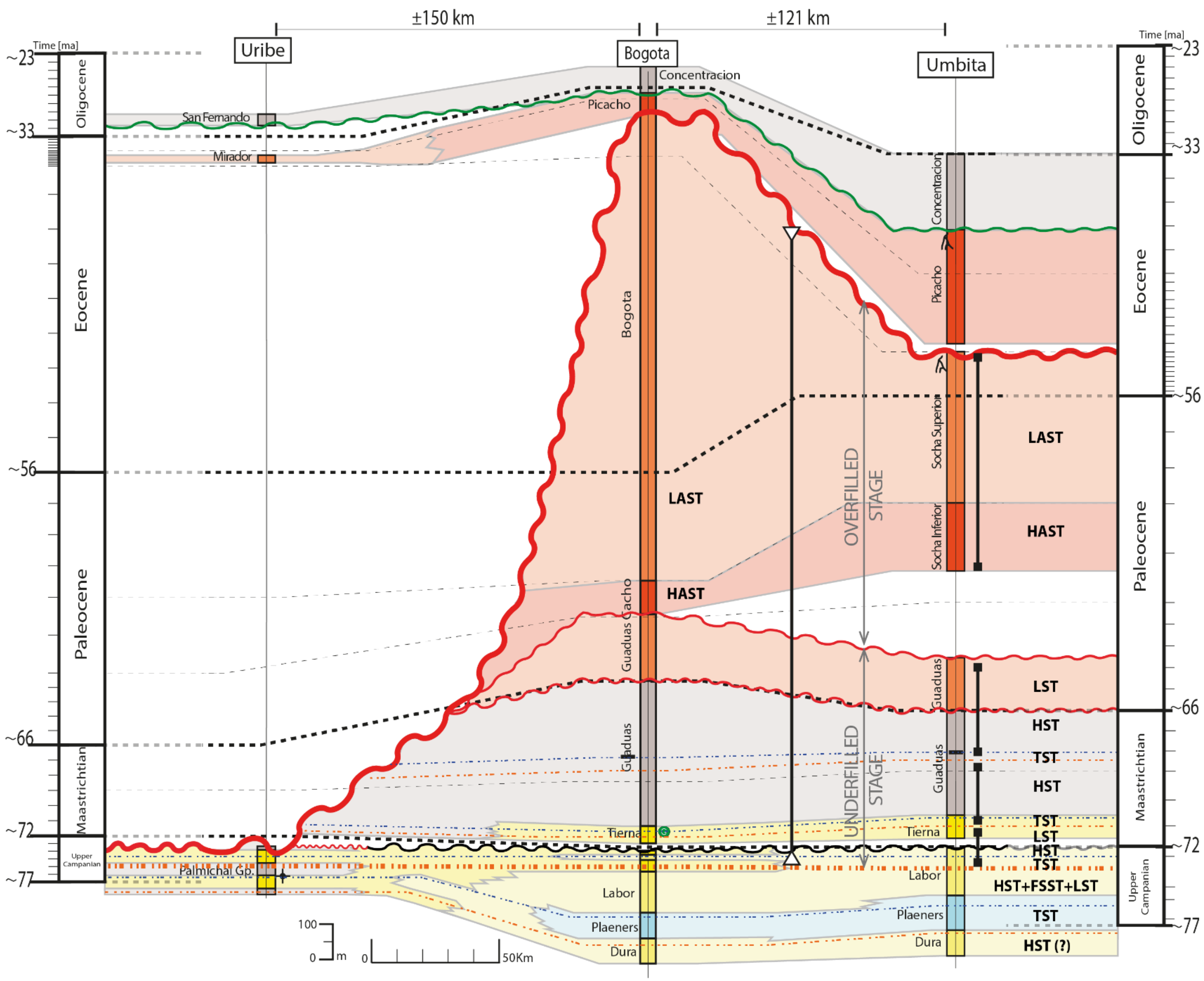


Fig. 4.9. stratigraphic correlation across the axial part of the ECB. This figure illustrates the behavior of the unconformities, which become younger northward as the facies prograde. See how the systems tract nomenclature varies from the under- to the overfilled stage, and how the thickness in Bogota increases in the Paleocene to Eocene. The authors reviewed are Uribe: Buchely, (2015) and Buchely et al., (2015); Bogota: Bayona et al., (2010), Pérez & Salazar, (1978), Sarmiento, (1992), Vergara & Rodriguez, (1997), and Umbita: Bayona et al., (2013) and Ulloa & Rodríguez, (1975). TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion.

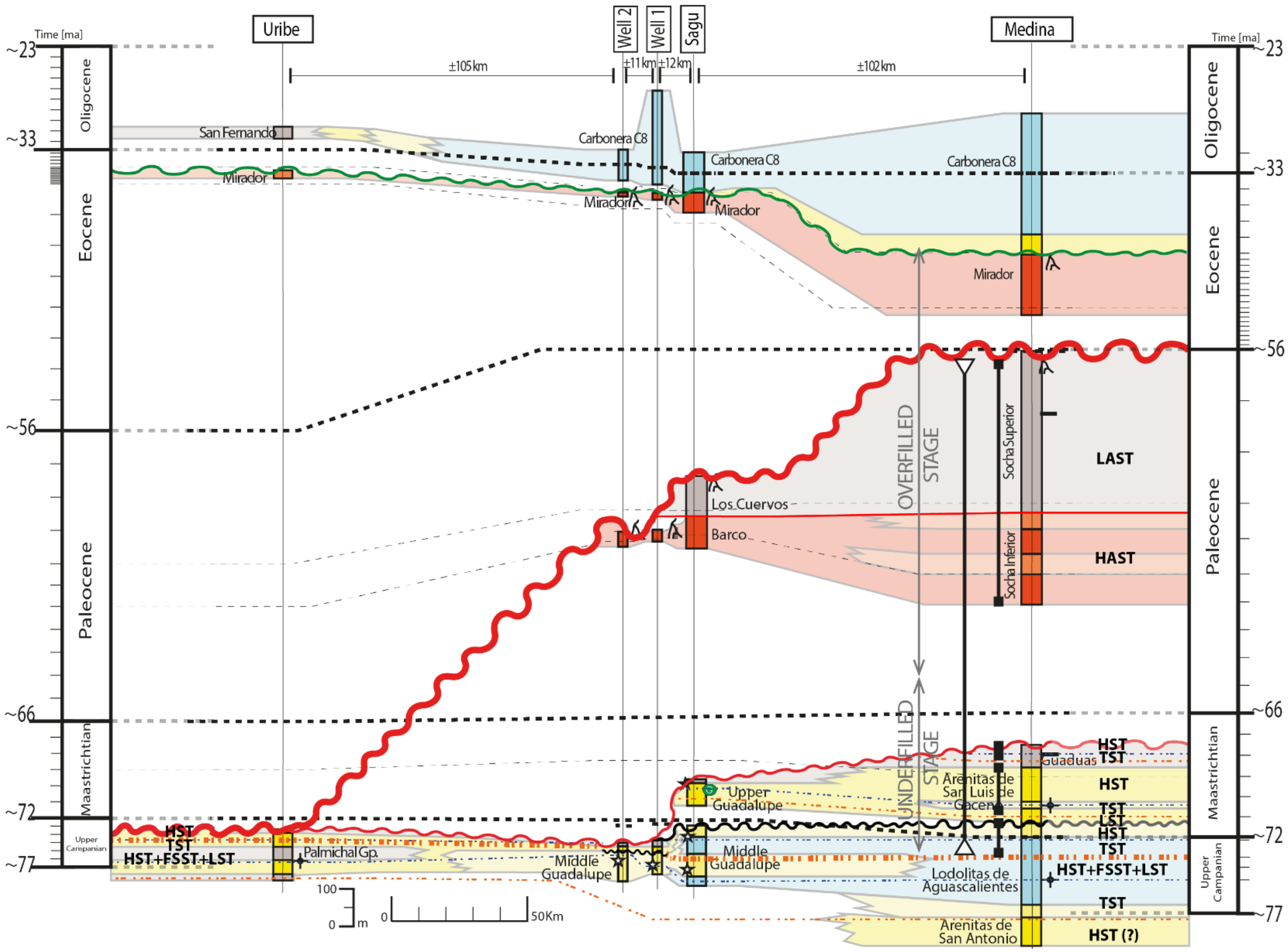


Fig. 4.10. Chronostratigraphic correlation across the Llanos Foothills and westernmost part of the Llanos Basin. This figure illustrates the behavior of the unconformities, which become younger northward as the facies prograde. This reveals the several unconformities formed in this marginal part, and the missing record from the transition from the under- to the overfilled stage. The authors reviewed are Uribe: Buchely, (2015) and Buchely et al., (2015); Well 1 and 2: This study; Sagu: This study and Martinez (2016); Medina: Guerrero & Sarmiento, (1996), Jaramillo, (1999) and Parra et al., (2010). TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion.

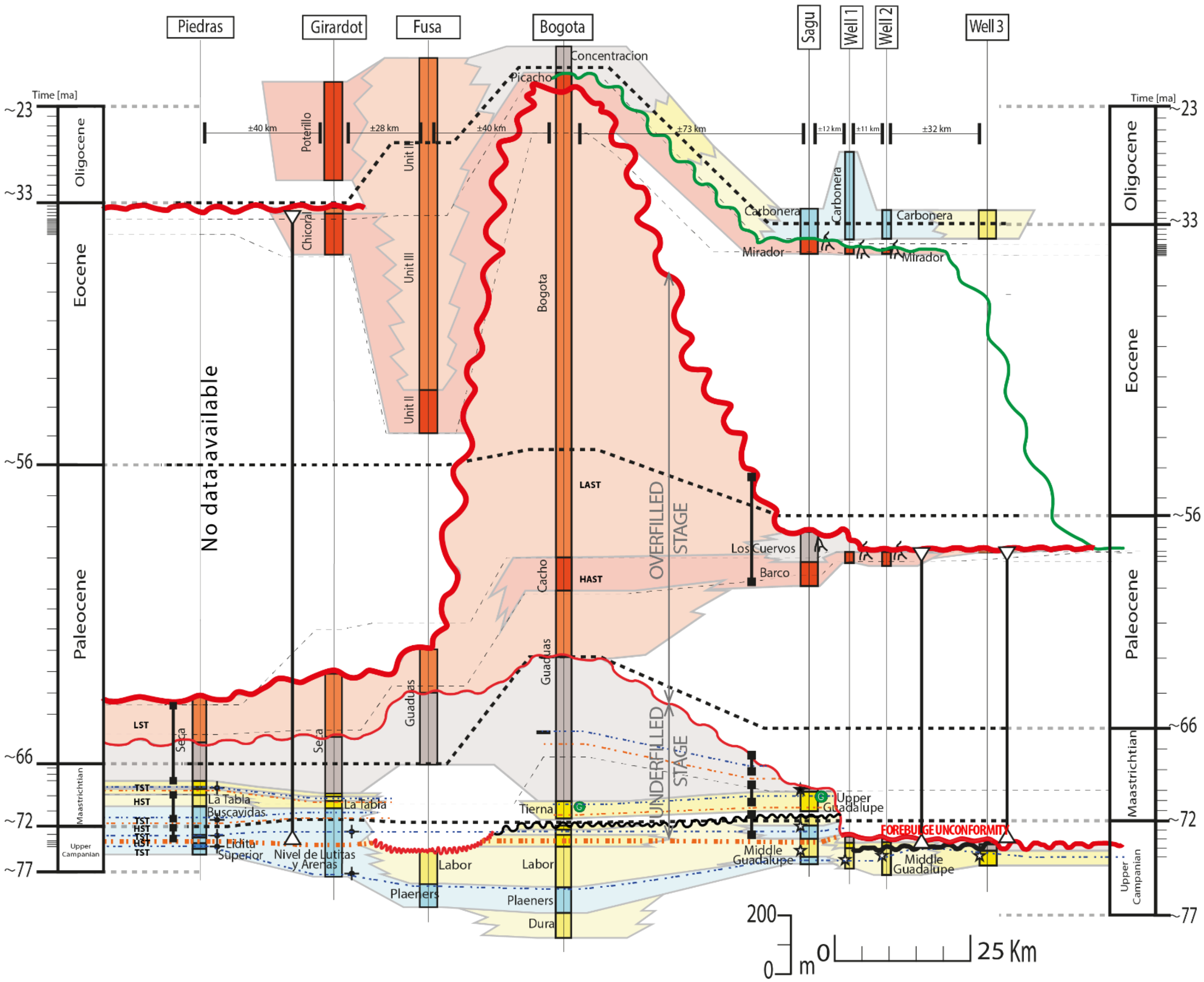


Fig. 4.11. Chronostratigraphic correlation across dip of the foredeep. See the location of the forebulge unconformity, and the truncation of the sequences eastwards due to subaerial exposure. The overfilled deposits thicken in the Bogota area, where the depocenter migrated at the end of the basin lifespan. TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion.

Moreover, the Upper and Middle Magdalena Valley, Eastern Cordillera, and westernmost Llanos Basin were part of the foredeep (Carvajal-Torres et al., 2021). Several paleogeographic restorations have demonstrated that tectonism resulted in the uplift of local intracontinental paleohighs across the foredeep, such as the Carmen de Apicala Syncline, Cobardes Anticline, Cira-Infantas, and Macarena (e.g., Sarmiento, 2001; Moreno et al., 2011; Silva et al., 2013; Bayona, 2018). Although that may have created positive relief that not only resulted in local source areas but also exerted control in the fluvial network (Caballero, 2010), we propose that the foredeep depocenter acted as a whole. In this scenario, the regional tectonism produced second-order cycles that should be traceable across the adjacent areas.

However, we understand it is challenging as the systems tracts and surface names can be different across the study area. Nevertheless, Catuneanu (2017, 2018, 2019) indicates that the name of the systems tracts and surfaces varies regarding the position and influence of the shoreline. In cases when the studied rocks were deposited under downstream controls the name of the systems tracts will be related to the shoreline trajectories (e.g., highstand, lowstand, transgressive, and falling stage systems tracts). On the other hand, the systems tracts deposited under upstream controls (continental setting) should be called in relation to the amalgamation of the channels. In this case, low-amalgamation, and high-amalgamation systems tracts. Likewise, the mentioned studies state that in foreland basins the tectonism is the major controlling factor across the basin. Thus, even when the deposition occurs hundreds of kilometers away, the sediment in either up- or downstream controls preserve evidence of changes in the regional tectonic setting. Regarding the stratigraphic surfaces, Catuneanu (2006, 2017, 2019) explains that even during the same event different surfaces can be formed. For instance, the subaerial unconformity that forms in the fluvial-coastal environment and is ideally connected towards the depocenters throughout the correlative conformity. Nonetheless, there are some cases in which it is connected to a maximum regressive surface. This union of distinct surfaces is called compound surface for example the first-order compound surface defined by Carvajal-Torres et al. (2021).

Thus, following these principles, we identified four second-order sequences produced from the latest Campanian to the earliest Oligocene. The nomenclature varies concerning the basin architecture. For instance, in the underfilled stage, two T-R second-order sequences are preserved in the deeper parts of the foredeep depocenter, Fig 4.11. Towards the basin margins, they change to second-order depositional sequences due to the variation in the boundaries, Fig 4.11. Particularly in the Sagu, where a second-order MRS in the Upper Guadalupe becomes a second-order SU towards the Wells area, Figs 4.11 and 4.12. A Maastrichtian to Paleocene second-order depositional sequence marks the ending of underfilled conditions. While the overfilled stage comprises one second-order fluvial sequence, indicating the termination of the foreland basin, Figs 4.7 to 4.12. Figures 4.7 to 4.11 illustrate the chronostratigraphic correlations along the different parts of the foreland basin. They demonstrate that regardless of the location, the surfaces and systems tracts can be recognized and correlated. Additionally, the correlation across the western flank of the Eastern Cordillera Basin, Fig 4.8, attempts to illustrate the diachroneity of its exhumation. The sedimentary record of the Cobardes Anticline area was estimated using information from Caballero et al. (2010), Sanchez et al. (2012), Silva et al, (2013), Montaño et al. (2016), and Siravo et al. (2018).

4.6.1. Second-order sequence (late Campanian-earliest Maastrichtian)

This sequence is bounded in the base by the first-order compound surface, and at the top by an MRS from the latest Campanian. In the Sagu section, from the bottom to top in the meter 160, a very thick bed of coarse-grained sandstones with through cross-bedding marks the contact between prograding facies below and retrograding facies on top, Figs 4.3, a key diagnostic characteristic of an MRS (Helland-Hansen & Martinsen, 1996). In addition, a maximum flooding surface (MFS) related to the increased portion of mudstones and siltstones in combination with the presence of thalassinoides, ophiomorphas, and phosphate/glauconite-rich deposits, Fig 4.3., unveils a deepening in the environment. Moreover, we include the regressive surface of marine erosion (RSME) determined by Carvajal-Torres et al., (2021a).

Hence, a transgressive systems tract (TST), a highstand systems tract (HST), and an undifferentiated falling stage (FSST) and lowstand systems tract (LST) are identified in the Sagu, Fig 4.3. It implies a second-order full cycle. In the area of the wells, there is no record of this sequence as the Campanian is truncated by an unconformity, the first-order subaerial unconformity from Carvajal-Torres et al. (2021b). The shoreline may have flooded this area, but the following second-order subaerial unconformity reworked and removed the deposits.

Regionally, different pieces of evidence allowed the recognition of these surfaces. In the foredeep (UMMVB and MMVB), a peak of increase in the sandy portion and reduction in the marine palynomorphs is recognized in the earliest Maastrichtian deposits (lower part of Buscavidas and upper part of Lutitas y Arenas and Umir formations), Fig 4.7. Due to the low resolution of the data, a correlative conformity (CC) or a basal surface of forced regression (BSFR), related to the SU and RSME from the Sagu, was not established. However, a SU was recognized in Guaduero, where coastal plain facies overlaid inner shelf deposits. In the Eastern Cordillera Basin (ECB), the Tierna formation of the Upper Guadalupe group preserves a similar pattern to the Sagu, Fig 4.9. In the Bogota and Umbita sections, the same systems tracts were identified.

4.6.2. Second-order sequence (early to middle Maastrichtian)

We established the middle Maastrichtian age of the rock units following the biostratigraphy from Vergara & Rodriguez (1997) and the biozones from Contreras et al. (2010) and De la Parra (2010). The contact between the underlain retrograding and overlain prograding patterns between the 190 – 210 m indicates the presence of a second-order MFS in the early Maastrichtian deposits, see Fig 4.3. In this area, the upper boundary of this sequence is the second-order SU that truncates the overlain coastal plain facies. The Guaduas formation preserves a second-order MRS in other localities around the ECB. For instance, in the Bogota section, ±250 from the base of the Guaduas formation, a peak increase in coarser grain size indicates the presence of a second-order MRS, Fig 4.9. Likewise, the presence of glauconite and phosphates in the underlying Tierna formation at the same locality suggests the existence of a second-order MFS, Fig 4.9, which is correlatable with the glauconite and phosphate-rich sandstones from the Sagu.

In the Magdalena Valley (Upper and Middle), the deposits from the La Tabla, Cimarrona, and Seca formations reveal facial changes and other evidence such as the presence of gypsum (Girardot) or reduced and even absence of marine palynomorphs (e.g., Aico and Piedras), Fig 4.7. However, the upper part of Buscavidas and Umir formations preserve an increase in the content of marine palynomorphs. Then, a second-order MFS and MRS are established along the foredeep. They can be traced from the Magdalena Valley to the Llanos Basin though in the marginal parts (such as Sagu and Wells), the upper boundary changes to a second-order SU. In contrast to the previous sequence, only an HST and a TST are identified.

4.6.3. Second-order sequence (late Maastrichtian to middle Paleocene

This sequence marks the change from the under- to the overfilled stage as the influence of the shoreline trajectories started to end (Catuneanu, 2017). At this time, the sediment supply increased, and the sedimentation outpaced the accommodation. Indeed, most of the deposits from this period are fluvial. Regarding the Sagu and the Wells sections, the low accommodation rate resulted in subaerial exposure from the middle Maastrichtian to the early Paleocene. As a result, this sequence is absent in the Sagu area, Fig 4.3 and 4.10. In the Medina area, late Maastrichtian coastal plain deposits are preserved, which preserve an increase in coal fragments, Fig 4.10. The is correlatable to coal-bearing beds found along the Eastern Cordillera. In Bogota, an interval of 110 m with several profitable coal seams is reported by Sarmiento (1992) for the Guaduas formation, Fig 4.9 and 4.11. Likewise, in the Umbita area, previous studies indicate the presence of coal beds within the Guaduas formation. All these coal beds are coetaneous and represent another second-order MFS formed during the late Maastrichtian.

Along the Magdalena Valley, an increase in marine palynomorphs preserved in the La Tabla Cimarrona formation is identified, Fig 4.7 and 4.11. In the Piedras section, the upper part of the La Tabla formation registers a ±10 m retrograding bed succession in which Guerrero et al. (2000) indicated an increase in *Heterohelix striata, Pseudoguembelina costulata, Heterohelix navarroensis,* and other marine planktic foraminifers. This evidence is correlatable with the second-order MFS from the Bogota and Umbita areas, and the sedimentary record between the lower boundary and this MFS belongs to a new second-order transgressive systems tract (TST). The overlying HST is truncated by the late Maastrichtian to early Paleocene second-order SU, which becomes older towards the Llanos Basin. As the overlain fluvial deposits belong to the overfilled stage, this SU is the upper boundary of the sequence, Figs 4.7, 4.9, and 4.11.

4.6.4. Second-order sequence (late Paleocene to middle Eocene)

The sedimentation was renewed during the early to Middle Paleocene with the continental fluvial Barco formation. This unit preserves a change in the paleocurrents in the upper part, Fig 4.3. Also, the facies show a change from proximal fluvial to a marginal to coastal plain facies from the Los Cuervos formation above. Thus, the contact is determined as a second-order systems tracts boundary. In the Medina area, a correlatable second-order boundary is evidenced within the top of the Lower Socha formation, where a transition to the marginal to coastal plain deposits of the

Upper Socha is preserved, Fig 4.10. The sedimentary record of this sequence is partially absent in the wells. It is bounded by the first-order subaerial unconformity (SU) on top and the Maastrichtian-lower Paleocene second-order SU at the base, Figs 4.10 and 4.11. This sequence represents the end of the late Campanian to early Eocene foreland basin. In the Sagu, this upper boundary is the top of the Los Cuervos formation, Fig 4.3. The 10-meter bed succession of gray siltstones with plant debris in the Sagu suggests a change in the depositional environment. It correlates with the MFS established by Jaramillo & Dilcher (2000) in the coastal plain deposits of the Arcillas del Limbo (Upper Socha) in the Medina area, Fig 4.10. Nonetheless, as mentioned before, the basin did not experience the down-stream controls as all this occurred during the overfilled stage and the position of the shoreline was hundreds of kilometers away (Mann et al., 2006; Reyes-Harker et al., 2015; Bayona, 2018 and Caballero et al., 2020). Then, no conventional nomenclature can be applied, and these formations correspond to the high- (HAST) and low-amalgamation systems tract (LAST), Figs 4.7-4.11. The presence of brackish palynomorphs in the Medina area is related to an increase in accommodation that may have allowed a short connection with the distal shoreline, yet eustasy did not exert control on the systems tracts.

This SU formed during the end of the retroarc foreland basin when an orogenic unload occurred by the late Paleocene to early Eocene (Parra et al. 2009) and triggered a reduction in the accommodation rate that resulted in a non-deposition period that contributed to the development of paleosols on top of the Paleocene strata, Fig 4.3 and 4.4. Despite the biozonation from previous studies (e.g., ICP - Ecopetrol, 2014; Caballero et al., 2020) indicates a complete succession from the late Paleocene to the Oligocene, there is no age control for the conglomeratic facies of the Mirador Fm. They are interpreted to belong to the biozone T05 from Pardo-Trujillo & Roche (2009) and Jaramillo (2011b), which is equivalent to the Ypresian (±9 My). Nonetheless, in case that there was no unconformity between the Paleocene (Los Cuervos Fm) and Eocene (Mirador Fm), there is no explanation for 1) the paleosols on top of the Los Cuervos Fm, and 2) the extremely low fluvial sedimentation rate of the Mirador Fm ($\pm 5.5^{-5}$ cm/year). The latter being implausible with respect to the rates reported by Ferring (1986).

Consequently, the overlaying facies of the Gualanday, San Juan de Rio Seco, Picacho, and Mirador formations belong to a new sedimentation period related to the new tectonic framework that created the present-day geological setting. Therefore, they are not genetically related and must not be regionally correlated as belonging to different basins, Fig 4.12. Sample 1-3 in the Sagu indicates the middle to late Paleocene was a period in which the sediment sources were renewed. The increased amount of unstable minerals such as Chlorite and Zoisite demonstrates the proximity of the sediment sources. Following the paleocurrent data collected in the Sagu and from other studies (e.g., Bayona et al. 2019), the sediment source may have been located eastward, and the channels scoured the older deposits.

4.7. Discussion

The diachroneity is a crucial variable to be considered during a basin analysis because the regional changes occurred at different rates in every place. In the Sagu section, the identified stratigraphic surfaces demonstrate a temporal variation with their equivalents across the study area. For instance, the lower boundary first-order MRS is older in the Sagu but even older along the area of the wells. While the early Maastrichtian second-order MFS in the Sagu indicates a younger age compared to the UMVB and MMVB. Moreover, as the orogen migrated northward, the Sagu and wells area experienced subaerial exposure, resulting in the formation of a late Maastrichtian to early Paleocene second-order SU connected to the second-order MRS to the western areas (Magdalena Valley and Eastern Cordillera). Therefore, some sequences are partial or completely absent. Indeed, it is related to the allogenic controls during the formation of the surfaces. The most relevant is the tectonism because it controlled the basin architecture, the accommodation, and the sedimentation.

Consequently, the recognition of the regional setting is critical to establish the basin architecture. The data from the Wells reveal how the sequences are absent in the marginal parts of the basin. Figure 4.11 illustrates the connection of the first-order SU and the MRS, and Figure 4.13 reveals how the regional tectonic setting influenced the basin margins. Additionally, this data evidence the influence of hierarchically minor events, Fig 4.12. Their correlation to the Sagu section proves that the flooding events that took place during the latest Campanian to the Maastrichtian did not reach these marginal areas (see wells 1 to 3 in Fig 4.11). Likewise, the middle Maastrichtian second-order MFS identified in Bogota or Piedras is absent in the Sagu area. We interpret it is associated with the northward movement of the shoreline and the basin architecture, as the marginal parts of the basins are always prone to subaerial or subaqueous erosion.

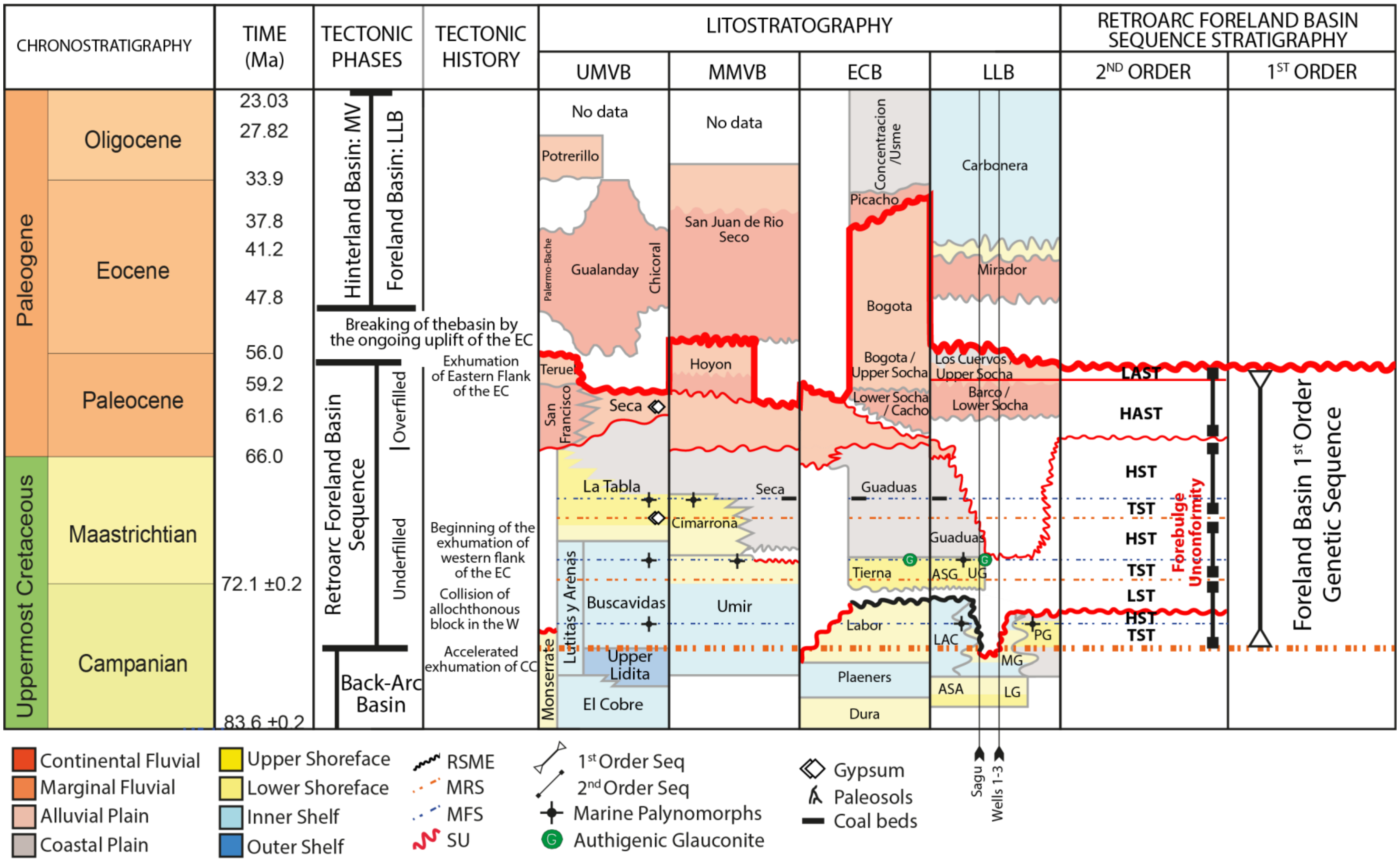


Fig. 4.12. Sequence stratigraphic framework of the retroarc foreland basin of Colombia. See the location of the forebulge unconformity and the fact the main unconformities are developed across the margin area. The relative location of the Sagu and the Wells illustrate the behavior of the unconformities in the southern LLB, and how the subaerial unconformities reworked the other surfaces. In fact, in the wells area, the first-order maximum regressive surface is reworked. TST: Transgressive systems tract; LST: Lowstand systems tract; HST: Highstand systems tract; FSST: Falling stage systems tract; HAST: High-amalgamation systems tract; LAST: Lowstand systems tract; MRS: Maximum regressive surface; MFS: Maximum flooding surface; SU: Subaerial unconformity; TSE: Transgressive surface of marine erosion; and RSME: Regressive surface of marine erosion.

During the underfilled stage, the foredeep (UMVB, MMVB, ECB, and the westernmost part of the LLB) experienced periods where the accommodation temporally outpaced the sedimentation rate, resulting in these second-order transgressions. The reason for their absence in the Medina and Uribe areas is identical to the Sagu and the wells, explained by the northward movement of the orogen. Therefore, the time gap of the SU decreases northwards. Nevertheless, there is another explanation for their absence in Fusa and Carmen de Apicala areas. According to the basin architecture, these areas were part of an exhuming block. This missing record from the latest Campanian to the earliest Paleocene is understood as tectonic deformation that occurred within the foredeep (Carvajal-Torres et al. 2021b).

Based on multiple data from several authors (e.g., Caballero & Mora, 2014, Montaño et al., 2016; Silva et al., 2013a), we reconstructed an approximated stratigraphic section for the Cobardes Anticline area. The results reveal a traceable SU from south to north, where it becomes relatively younger, Figs 4.8 and 4.13. The diachroneity of this SU is the result of the northward movement of the orogen. During the late Campanian, when the retroarc foreland basin started in the south, the Carmen de Apicala and Fusa areas were exhumed, while the Cobardes Anticline received coastal deposition. The values of vitrinite reflectance and thermochronometers from Silva et al. (2013a) from La Luna and Tablazo formations indicate about 1000 m of eroded record since its exhumation in the middle Maastrichtian.

Our data from the Sagu served to identify the switch from the underfilled to overfilled stages. Also, we identified the thickness of the overfilled deposits is thicker than the underfilled stage. This similar pattern was traced in every section, indicating an increase in the sediment supply since the late Maastrichtian. Moreover, the sample Sagu 1-2 from the Barco formation indicates the dominant presence of ultrastable minerals, Fig 4.3, suggesting either the remote position of the sediment source or the presence of reworked material. Our paleocurrent data proves it was in the farther east. It was a combination of the sediments derived from the Guiana craton and the sedimentary cover. The sample Sagu 1-3 from the Los Cuervos formation unveils the sediment source may have been renewed due to the presence of unstable minerals is clear, Fig 4.3. Probably, the lithostratigraphic flexure related to the forebulge changed the topography, resulting in newly eastward exposed areas. Although the paleocurrents at the top of

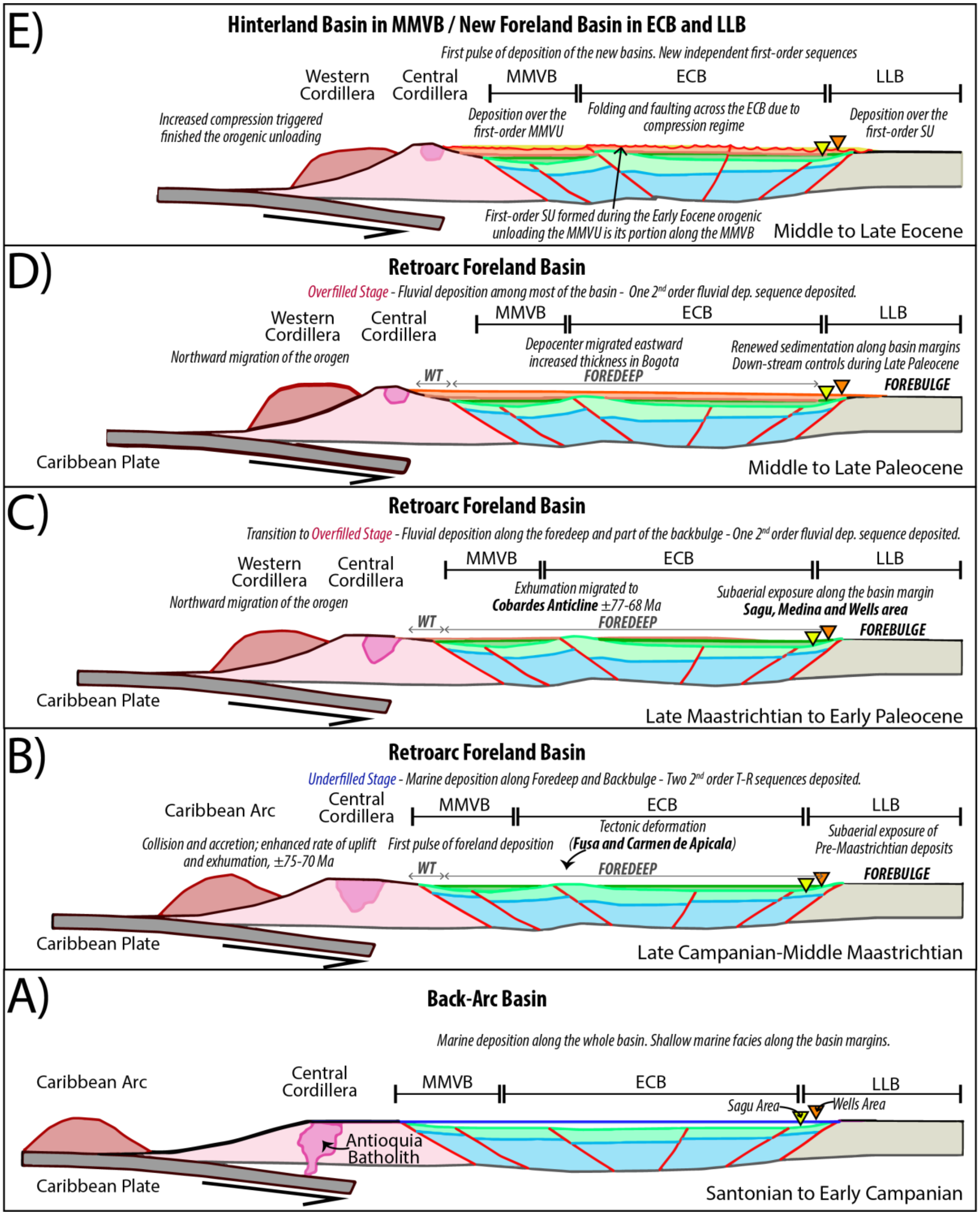


Fig. 4.13. Summarized geological evolution of the retroarc foreland basin illustrating the different tectonic stages: A) the termination of the back-arc basin, B) the initiation of the foreland basin and estimated location of the forebulge, C) Transition from the under- to overfilled stage, D) basin architecture during the overfilled stage and termination of the foreland basin, and E) initiation of the new tectonic setting, where the foreland basin is subsequently separated into the hinterland MMVB and the Llanos foreland basin. After Horton et al. (2010), Bayona et al. (2013) and Villagomez & Spikings (2013). WT: Wedge-top, FD: Foredeep.

the Barco suggests a change, more data is needed to determine the precise location of the sediment source at this time. Detrital zircon analysis will be a reliable idea for future studies.

The systems tracts identified in the Sagu are correlatable across the adjacent areas indicating a single extensive depocenter under the influence of the downstream controls during the underfilled stage. Indeed, two full second-order cycles from transgression (TST) to highstand (HST), lowstand (LST), and forced regression (FSST) are preserved within the sedimentary record. We identified the second-order FSST due to the presence of the second-order RSME and SU, Fig 4.3 and 4.12. Nonetheless, the resolution of the data limited the determination of their corresponding connection towards the depocenters. Further studies can focus on the identification of the second-order correlative conformities across the deepest part of the foredeep (Middle Magdalena Valley and Eastern Cordillera). We suggest following the methodology from Catuneanu (2017, 2019b) and Catuneanu et al. (2011). In addition, the transition to the overfilled stage is depicted by another second-order cycle, Fig 4.12, but this is partially missing in the Sagu, and absent around the wells 1-3. The second-order subaerial unconformity formed in this period can be easily traced across the basin, and its time gap decreases toward the west and north, Figs 4.7, 4.9, 4.10, 4.11, and 4.12.

The systems tracts associated with the overfilled stage are more difficult to correlate, as the sedimentation was mainly fluvial. This stage is characterized by the migration of the depocenter towards the ECB. Figures 4.11 and 4.13 illustrate this change. According to Nemčok et al. (2005), that is a characteristic feature of a foreland basin. In fact, during the overfilled stage, the sedimentation is renewed in the distal part of the basin, Fig 4.13. The sedimentary record from Sagu and wells 1 to 3 is a perfect example of this fact, Fig 4.11 and 4.13. Furthermore, we identified the presence of high amalgamation and low amalgamation systems tracts (HAST and LAST) along the UMVB, MMVB, and ECB that are related to the changes in the accommodation and sedimentation rates during the Paleocene. Despite the sedimentation rate was higher and prevented the influence of downstream controls, the Paleocene strata from Bogota indicate accommodation was constantly created at this time. The sedimentary record from Medina suggests a brief connection to a distal shoreline, in which some palynomorphs migrated up to this area. Nevertheless, the deposits from Barco/Lower Socha and Cuervos/Upper Socha belong to HAST and LAST. Regardless of the position, the late Paleocene to early-middle Eocene systems tracts is truncated by a first-order SU. Along the MMVB, this SU corresponds to the MMVU established by Gómez et al. (2005).

Despite the complexity of the geological setting, the data from the Sagu and wells not only reveal lithostratigraphic correlatability with the strata from the adjacent depocenters in the west (Eastern Cordillera, Middle, and Upper Magdalena Valley) but also exhibit second-order cycles related to each other regardless the distance, Fig 4.12. Undoubtedly, these cycles are partially or entirely missing in certain areas such as in wells 1-3. Notwithstanding, this is understood as the result of the lithospheric flexure driven by tectonism. Indeed, the deformation of the forebulge and the intracontinental deformation triggered the exhumation of multiple paleohighs. Although the surfaces indicate diachroneity, it is the product of the northward migration of the orogen, and so, the correlative stratigraphic surfaces and systems tracts are young in the same direction. We recommend treating the late Campanian to early Eocene depocenters of the Colombian Andes instead of separated and independent basins as indicated by the identified surfaces. Even when their separation may have started in the Paleocene by the uneven exhumation of the western flank of the Eastern Cordillera, the facies indicate correlatability and preserve evidence of simultaneous changes in the tectonic setting. In particular, the change from HAST to LAST preserved within the San Francisco, Hoyon, Lower-Upper Socha, Cacho-Bogota, and Barco-Cuervos formations across the study area, Fig 4.12.

Finally, the retroarc foreland deposits are bounded by first-order SU in most of the LLB. The sedimentary record identified in wells 1-3 belongs to the overfilled stage, and they comprise a HAST that pinches out eastward, Fig 4.11 and 4.13, and it is overlaid either by fluvial or marine deposits of the subsequent basin. Hence, the upper shoreface or fluvial deposits of the retroarc foreland basin sealed by the inner shelf deposits of the Carbonera C8 is a potential trap present in the southern LLB. Nonetheless, as they are in contact with the underlying shoreface deposits of the previous back-arc basin, the stratigraphic trap requires a high-detailed facies analysis. If these facies are in contact, they act as a sandy pathway that may have prevented the oil entrapment. For that reason, we encourage to correlate and extend this sequence stratigraphic framework across the LLB, to improve the understanding of the forebulge unconformity and determine prospective areas for this play. The latter being proven as these rocks are black colored in the outcrops and wells due to the presence of oil, Fig 4.4 and 4.6.

4.8. Conclusions

(I) The late Campanian to early Eocene strata from the Sagu and the wells reveals proper correlatability with the same strata across the Upper/Middle Magdalena Valley and Eastern Cordillera. Therefore, it indicates that regardless of the tectonic deformation these areas were part of a single depocenter, which was the foredeep of the regional foreland basin. As tectonism was the major allogenic control, it influenced the formation of multiple cycles that can be traceable from west to east.

(II) These second-order cycles occurred during the underfilled and overfilled stages of the first-order retroarc foreland sequence. The different second-order stratigraphic surfaces can be traced along the former foredeep and backbulge. However, the tectonism and basin architecture controlled the balance between sedimentation and accommodation during their formation. Therefore, their absence and diachroneity are related to the tectonic stage and location. For instance, most of the southern LLB only received sediments during the overfilled stage as it was affected by the forebulge deformation.

(III) During the underfilled stage, the interplay between the accommodation and sedimentation rate resulted in the formation of two full second-order cycles composed of TST, HST, FSST, and LST. Their differentiation relies on the resolution of the data and the location within the basin. Along the foredeep, the recognition of the correlative conformity was impossible due to the low resolution of the data. However, second-order RSME and SU identified in the marginal areas as Sagu and the Wells area, contributed to the definition of the existence of FSST. Indeed, they are correlatable to Bogota and Umbita areas.

(IV) The transition to the overfilled stage occurred during a highstand normal regression that took place since the Maastrichtian as revealed by the Sagu and wells strata. The Seca and Guaduas formations preserve information related to this tectonic phase, in which the accommodation was outpaced by the sedimentation. The enhanced sedimentation was the result of the uplifting and exhumed orogen, forebulge, and intracontinental highs, that triggered the sediment supply across the foredeep. The facies indicate that the high sediment supply led to a forced regression and resulted in the formation of the second-order SU. In the Sagu, it partially removed the sedimentary record, but in the southern LLB, the magnitude of this SU is higher. For instance, there are no Maastrichtian deposits in the Wells area. As they were under subaerial exposure from the Maastrichtian to the early-middle Paleocene due to a forced regression. Their absence is controlled by the scouring action of the channels. Therefore, some remnant portions may exist in certain portions across the LLB.

(V) In the early-middle Paleocene, the overfilled stage renewed the sedimentation across the study area, reaching the south LLB. During this period, the sedimentation dominated despite the accommodation created. A complex fluvial (marginal to proximal) developed across the study area. In the south LLB, the presented data suggest the sediment source was remotely located to the east-southeast. Furthermore, the very thick sediment record of the Bogota section indicates the eastward migration of the depocenter and reveals an increase in the accommodation during this period. For that reason, the amalgamation of the channels among the fluvial deposits decreased and a differentiation between the HAST and LAST was established. In some parts of the LLB, this new accommodation led to a connection to the shoreline. However, the tectonism was the major allogenic factor controlling the basin and so the eustatic level did not exert control on the sequences. We found a correlation between the LAST and HAST to the facies identified in the Sagu and Medina areas.

(VI) The orogenic unloading previously established by other studies resulted in a forced regression that occurred during the end of the retroarc foreland basin. The first-order SU in the Sagu and the Wells evidences this hypothesis. The surface is correlated across the study area, Fig 12. In the MMVB, this surface corresponds to the MMVU. The time gap of this SU decreases towards the proximity of Bogota, because the depocenter may have been migrated to this area, leading to subaerial exposure in the margins, Fig 13. It is a diagnostic characteristic of a terminating overfilled foreland basin. Also, the sedimentary record preserved in Uribe indicates the deposits from the first-order retroarc basin are mostly absent towards the south, as subaerial exposure took place since the Maastrichtian, and so it is unlikely to find these deposits.

(VII) The unconformity in the Carmen de Apicala and Fusa sections unveil these areas were exhuming during the Latest Campanian and part of the Paleogene. Further, during the Maastrichtian to Paleocene, as the orogen migrated northward, the tectonic deformation also migrated northwards to the Cobardes Anticline. The reconstructed section aimed to understand the behavior of the facies. According to them, coastal deposition took place in this area during part of the Maastrichtian and was interrupted then the tectonism triggered its exhumation (around Middle to Late Maastrichtian).

(VIII) The SU unconformities, either first- or second-order, limit the eastward extension of the back-arc retroarc foreland sequence across the LLB. However, their pinch-out is controlled by the scouring of the existing channels during the two periods of subaerial exposure, the Maastrichtian to early Paleocene and the late Paleocene to early Eocene. The fact that they are overlaid by the late Paleocene to early Oligocene marine facies indicates the existence of stratigraphic traps. We consider two plays, (1) pinched-out foreland fluvial overfilled deposits sealed by the Oligocene inner shelf deposits, or (2) the latest Campanian or earliest Maastrichtian highstand prism surrounded and sealed by the Oligocene inner shelf facies. Their analysis requires the expansion and correlation of this stratigraphic framework among the LLB.

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Chapter 5: Conclusions

During the late Campanian, the tectonism triggered the exhumation of the paleo-Central Cordillera and resulted in the reduction of the accommodation along the basin. The data from the Sagu unveil that the mudstone portion decrease while the sandy grains increased is coarser-upwards. In addition, the thalassinoides and wavy lamination disappeared, and through cross-bedding with some ophiomorphas appear. Therefore, showing a change from inner shelf to upper shoreface facies. However, as the tectonism continued, new accommodation was produced and produced retrogradation of the facies during the latest Campanian to earliest Maastrichtian, as suggested by the transition from upper shoreface to inner shelf deposits. Then, indicating a maximum regressive surface (MRS) formed during the transition from back-arc to retroarc foreland basin.

This first-order MRS was identified across several locations from the Eastern Cordillera, Upper, and Middle Magdalena Valley Basins. The revised studies reported the continental microfossils increased within shallowing upwards facies underlain early to middle Maastrichtian retrograding facies. Nonetheless, a different effect was recognized in the Llanos Basin. The stratigraphic sections from wells 1-3 suggest subaerial exposure from the late Campanian to the early-middle Paleocene. Following the basin architecture and the stratigraphic thickness of the Late Cretaceous to early Paleocene strata, we endorse the hypothesis that the forebulge was located along the Llanos Basin. Hence, this subaerial unconformity (SU) is defined as the forebulge unconformity, which along with the first-order MRS, constitutes the first-order compound surface.

The facies that overlain this surface documented multiple cycles related to the shoreline trajectories (transgressions and regressions). In the Sagu Creek, the increase of glauconite, phosphates on top of the early Maastrichtian fining-upwards succession suggest a period in which the accommodation outpaced the sedimentation producing a second-order transgression. This event is traceable across the Eastern Cordillera as similar evidence is preserved in the early Maastrichtian Tierna Fm. In the Upper and Middle Magdalena, previous studies stated an increase in the marine palynomorphs.

The late Maastrichtian to early-Paleocene is missing in the Sagu Creek, and the overlain fluvial facies indicate subaerial exposure during the transition from underfilled to overfilled conditions. Nevertheless, the analyzed sedimentary reports along the Eastern Cordillera and Magdalena Valley (Upper and Middle) state evidence of another second-order transgression. We identified that the multiple thick coal beds in the Guaduas Fm across the Eastern Cordillera formed during this transgressive event. Based on this data, we conclude the late Campanian to early Paleocene was a period of orogenic loading that generated accommodation across the foredeep and exhumation of the forebulge. The latter being linked with the subaerial exposure that expanded from the east to the Sagu Creek. Additionally, our study advocates that this orogenic loading caused the tectonic deformation along the western flank of the Eastern Cordillera.

Moreover, the early-middle Paleocene proximal fluvial facies of the Barco Fm from the Sagu and wells indicate that sedimentation resumed in the area. Likewise, the estimated basin architecture demonstrates that most of the sediment was deposited in the Bogota area, implying the depocenter migrated to the east. Considering that this is characteristic of an overfilled foreland basin, we conclude the fluvial deposition advanced towards the forebulge, explaining the resumed sedimentation along most of the Llanos Basin.

Following the top of the Paleocene strata from the Sagu and the wells, we determined a new period of subaerial exposure took place from the late Paleocene to early Eocene. The paleosols on top of the biozone T03 depict another subaerial unconformity. The associated missing record of this surface is ±5My in the Sagu area, whereas it is up to ±16My in the Llanos Basin. Accordingly, indicating that this surface expanded from the east during a period of orogenic unloading that marked the termination of the regional foreland basin. Following the correlation across the adjacent areas, we define this as a first-order SU. In the Magdalena Valley, it corresponds to the Middle Magdalena Valley Unconformity, and its hiatus is ±10My.

Although the hiatus of the late Paleocene-early Eocene first-order SU varies across the Eastern Cordillera Basin, its missing record is negligible at Bogota. This continued sedimentation is understood as the result of the eastward migration of the depocenter. The basin architecture unveils that it was located along the axial part of the Eastern Cordillera from the Paleocene to the Eocene. We infer that this fact promoted uninterrupted sedimentation in Bogota. Previous studies suggest the influence of dynamic subsidence. However, we consider this hypothesis still needs more analysis.

Finally, our sequence stratigraphic framework demonstrates the Llanos Basin, Eastern Cordillera, Middle, and Upper Magdalena Valley Basins were part of a singular depocenter from the late Campanian to early-middle Eocene, which corresponded to the foredeep area. Regardless of the internal foredeep tectonic deformation, the tectonic activity resulted in minor hierarchical cycles controlled by the tectonism. Nonetheless, after the late Paleocene to early Eocene orogenic unloading, there is no regional correlation of the facies as the foredeep was divided into two independent basins, the Magdalena, and the Llanos Basins. That is evidenced by the disconnection of the late Eocene to the earliest Oligocene marine facies of the Sagu and wells from the Magdalena Valley Basin due to the exhumed Eastern Cordillera.

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Appendices

The following pages show the stratigraphic sections from the Sagu and the wells.