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Chapter 10

From Facies Analysis, Stratigraphic Surfaces, and Depositional Sequences to Stratigraphic Traps in the Eocene – Oligocene Record of the Southern Llanos Basin and Northern Magdalena Basin

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Abstract Available outcrop sections, rock cores, and well logs, as well as previous sedimentary geology and palynology studies, provide the opportunity to study shallow marine and continental rock records within the context of unconformity–bounded depositional sequences. This approach provides insight into the sedimentary evolution of reservoirs and their properties in the Middle Magdalena Basin and the southern Llanos Basin in Colombia.

This work illustrates and analyzes facies and facies successions of the Eocene – Oligocene stratigraphic units in the Nuevo Mundo Syncline in the northern Middle Magdalena Basin and the southern Llanos Basin. The facies analysis results support the identification of subaerial unconformities, transgressive ravinement surfaces, flooding surfaces, depositional environments, and depositional sequences. Stratigraphic correlation allows the identification of spatial and temporal distributions of the facies, the stratigraphic architecture of reservoirs and potential of several types of plays in these basins, in addition to the common stratigraphic histories.

Thirteen facies were combined into ten facies successions, which led to the identification of three depositional sequences in the southern Llanos Basin and two in the Nuevo Mundo Syncline. A strongly developed paleosol and an unconformity at the base of the Eocene units allowed a buried, preserved landscape from the end of the Paleocene to be identified in the southern Llanos Basin, and the same relief features were identified in the Middle Magdalena Basin and Eastern Cordillera. The first depositional sequence comprises the Lower Mirador, Upper Mirador, and lower part of the C8 Member of the Carbonera Formation in the southern Llanos Basin and the La Paz and Esmeraldas Formations in the Nuevo Mundo Syncline. The second depositional sequence is composed of Oligocene basal sandstones and the upper part of the C8 Member of the Carbonera Formation in the southern Llanos Basin and the Oligocene Mugrosa Formation in the Middle Magdalena Basin. The third sequence is composed of both the C7 and C6 Members of the Carbonera Formation in the southern Llanos Basin.

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The porosities and permeabilities allowed the identification of the favorable reservoir units in these basins and the geometries and lithologies below and above the buried landscape explain several types of traps/plays that must be searched for in these basins, including paleogeomorphic traps, such as buried hills, fluvial and incised valleys, and erosional pinchouts, and previously identified stratigraphic traps, such as depositional pitchouts, onlap pinchouts, and facies changes.
Keywords: *origin and depositional history of sedimentary basins, facies analysis, facies successions, sequence stratigraphy correlation, Llanos Basin, Middle Magdalena Basin, reservoir architecture, stratigraphic trap, reservoir properties.*

Resumen Las secciones de afloramiento, núcleos y registros de pozo disponibles, así como estudios previos de sedimentología y palinología, son una oportunidad para estudiar los registros sedimentarios marinos someros y continentales en el contexto de la estratigrafía de secuencias. En la Cuenca del Valle Medio del Magdalena y sur de la Cuenca de los Llanos, este enfoque proporciona información sobre la evolución de los reservorios y sus propiedades.

En este trabajo se ilustran y analizan las facies y sucesiones de facies en las unidades estratigráficas del Eoceno–Oligoceno en el Sinclinal de Nuevo Mundo localizado en la parte norte de la Cuenca del Valle Medio del Magdalena y en el sector sur de la Cuenca de los Llanos. El análisis de facies contribuye en la identificación de discordancias subaéreas, superficies de ravinamiento transgresivo, superficies de inundación, ambientes de depósito y secuencias de depósito. La correlación estratigráfica permite identificar la distribución temporal y espacial de facies, la arquitectura estratigráfica de los reservorios y el potencial de varios tipos de trampas en estas cuencas, además de las historias estratigráficas comunes.

Trece facies fueron combinadas en diez sucesiones de facies, lo que ayudó a identificar tres secuencias de depósito en el sur de la Cuenca de los Llanos y dos en el Sinclinal de Nuevo Mundo. Un paleosuelo fuertemente desarrollado y una discordancia en la base de las unidades del Eoceno permitieron identificar un paisaje enterrado y fosilizado desde el final del Paleoceno en el sur de la Cuenca de los Llanos, este mismo paisaje ya había sido identificado en la Cuenca del Valle Medio del Magdalena y en la cordillera Oriental. La primera secuencia de depósito incluye las formaciones Mirador Inferior y Mirador Superior y la parte baja del Miembro C8 de la Formación Carbonera en el sur de la Cuenca de los Llanos y las formaciones La Paz y Esmeraldas en el Sinclinal de Nuevo Mundo. La segunda secuencia de depósito está compuesta por las areniscas basales del Oligoceno y la parte superior del Miembro C8 de la Formación Carbonera en el sur de la Cuenca de los Llanos y la Formación Mugrosa del Oligoceno en la Cuenca del Valle Medio del Magdalena. La tercera secuencia está compuesta por los miembros C7 y C6 de la Formación Carbonera en el sur de la Cuenca de los Llanos.

Los valores de porosidad y permeabilidad permitieron identificar las mejores unidades reservorio en estas cuencas y las geometrías y litologías debajo y encima del paisaje fosilizado explican varios tipos de trampas que deberían buscarse en estas cuencas, incluyendo trampas paleogeomorfológicas, tales como colinas enterradas, valles fluviales y valles incisos y pinchamientos por erosión, y también trampas estratigráficas identificadas previamente, tales como pinchamientos por depósito, pinchamientos por *onlap* y cambios de facies.
Palabras clave: *origen e historia de depósito de cuencas sedimentarias, análisis de facies, sucesiones de facies, correlación de secuencias estratigráficas, Cuenca de los Llanos, Cuenca del Valle Medio del Magdalena, trampa estratigráfica, propiedades de reservorio.*

1. Introduction

The deposition of the sedimentary rocks in the Middle Magdalena Basin (MMB), Eastern Cordillera (EC), and Llanos Basin in Colombia has been controlled by tectonics, eustasy, and climate (Cooper et al., 1995; Gómez et al., 2005a; Mora et al., 2008, 2010, 2015; Bayona et al., 2008, 2012, 2013; Parra et al., 2010, 2012; Ramirez–Arias et al., 2012). Extensional tectonics and eustasy controlled the deposition of the Mesozoic rocks in rift basins across the entire Magdalena Basin, Eastern Cordillera, and Llanos Basin (LLB) (Etayo–Serna et al., 1969, 1983; Fabre 1985, 1987), whereas compressive tectonics and climate mainly controlled the uplift of the Central and Eastern Cordilleras during the Late Cretaceous – Cenozoic (Gómez et al., 2003, 2005a, 2005b; Mora et al., 2006, 2009, 2010, 2013; Bayona et al., 2008, 2013; Horton et al., 2010a, 2010b; Caballero et al., 2010; Saylor et al., 2011, 2012a; Nie et al., 2010, 2012; Moreno et al., 2011; Villagómez et al., 2011).

Late Cretaceous – Cenozoic flexural subsidence in front of uplifting terrains created the accommodation space for sediment to be deposited as it was generated in the new source areas. The sedimentary response (e.g., facies, facies successions, geometry, stacking pattern, distribution, depositional trends) can be linked to changes in base level controlled by tectonics, climate, sources of sediment, and sedimentary basin geomorphology.

The areas of the Middle Magdalena Basin, axial Eastern Cordillera Basin, and Llanos Basin were once part of a unique foreland basin that was coupled to the Central Cordillera during the early Paleocene (Gómez et al., 2003, 2005a, 2005b; Saylor et al., 2011; Horton, 2010b; Moreno et al., 2011; Nie et al., 2010, 2012). By the Late Paleocene – Oligocene, the foreland basin was increasingly fragmented due to the reactivation of faults in the former Mesozoic rift system (Dengo & Covey, 1993; Colletta et al., 1990; Cooper et al., 1995; Mora et al., 2006), and a bivergent fold–thrust belt developed (Cooper et al., 1995; Sarmiento–Rojas et al., 2006; Bayona et al., 2008, 2013, Tesón et al., 2013).

This process resulted in three main separate sedimentary systems as the fold–thrust belt deformation migrated to the east in the Eastern Cordillera (Mora et al., 2010; Saylor et al., 2011; Bayona et al., 2013): the intermontane Middle Magdalena Basin on the western flank of the Eastern Cordillera, the axial intermontane Eastern Cordillera (Floresta and synorogenic basins within the Eastern Cordillera), and the Llanos Basin near the eastern flank of the Eastern Cordillera. The current foreland basin system consists of a hinterland composed of the Magdalena Basin and the Eastern Cordillera and a foreland basin that corresponds to the Llanos Basin.

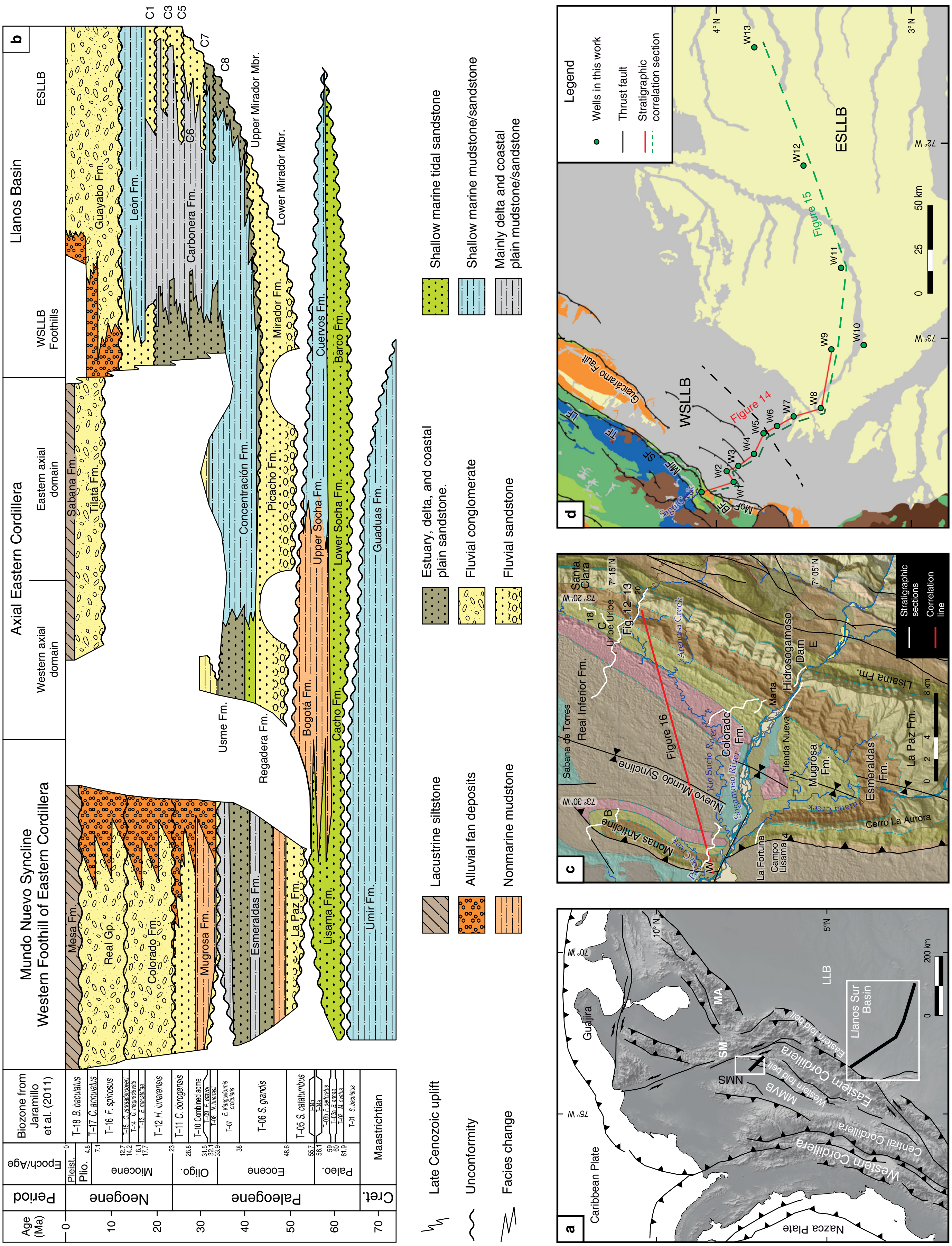
The synorogenic sedimentary deposits in the Magdalena Basin, axial Eastern Cordillera, and Llanos Basin contain the sedimentary record of orogenesis as well as the sedimentary and stratigraphic histories of the Magdalena Valley, Eastern Cordillera, and Llanos Basin. This record has been previously analyzed, but no attempt to correlate the events, depositional trends, and common stratigraphic histories has been attempted. Analysis of the sedimentary record and stratigraphic correlations will enable us to identify the common or distinct stratigraphic histories during the latest Paleocene to Oligocene.

In this study we illustrate, with unpublished images, the facies and facies successions in the southern Llanos Basin (SLLB), which is subdivided into the foothills of the Eastern Cordillera, the western sector of the Llanos Basin (WSLLB), and the eastern sector of the Llanos Basin (ESLLB) (Figure 1). We build upon our previous work by complementing the descriptions and illustrations of the facies and facies successions in the Nuevo Mundo Syncline (NMS) with published studies in the Middle Magdalena Basin and the axial Eastern Cordillera sedimentary basin.

The facies analysis supports the identification and characterization of bounding surfaces and depositional sequences. These units were traced throughout the basins using the sequence stratigraphic surfaces to study the distribution, lateral continuity, and stratigraphic architecture of the reservoirs rocks as well as to compare their potential as stratigraphic plays.

1.1. Previous Work in the Middle Magdalena Basin

The along–strike lower Eocene rock record of the Middle Magdalena Basin is dominated by a sandy fluvial system with proximal facies to the south in the area of the Guaduas Syncline and distal facies to the NE in the region north of the basin near the NMS. In the southern part of the MMB, the early Eocene proximal facies of an alluvial to fluvial system is represented by the Middle–Upper Hoyón Formation. This unit consists of an alluvial matrix–supported conglomerate, reddish siltstones, and sandstone intervals with horizontal bedding, cross–bedding, and E–NE paleocurrent directions (Gómez et al., 2003; Bayona et al., 2013). The distal facies of the system to the north is represented by the La Paz Formation. The La Paz Formation is not continuous across strike in the MMB due to the presence of an intrabasin high, the La Cira–Infantas–Sogamoso Paleohigh (LCISP). The paleohigh is more than 130 km long by 25 km wide, is located in the center of the basin and extends N–NE from southern Puerto Parra to the area of the Sogamoso Field (Suárez, 1997, Gómez et al., 2005a; Caballero, 2010). This unit consists of amalgamated, cross–bedded sandstones and fluvial floodplain mudstones and rippled sandstones (Suárez, 1997; Gomez et al., 2005a). The fluvial valleys of this landscape were fed by competing sources in the Central Cordillera, uplifts inside the Middle Magdalena Basin and areas of the western flank of the Eastern Cordillera (Gomez et al., 2005a; Caballero et al., 2013b; Moreno et al., 2011; Lamus et al., 2013).


b
Mundo Nuevo Syncline
Western Foothill of Eastern Cordillera
Axial Eastern Cordillera
Western axial domain
Eastern axial domain
Llanos Basin
WSLLB Foothills
ESLLB
Age (Ma)
Period
Epoch/Age
Biozone from Jaramillo et al. (2011)
Neogene
Paleogene
Cret.
Pleist.
Plio.
Miocene
Oligo.
Eocene
Paleo.
Maastrichtian
Mesa Fm.
Real Gp.
Colorado Fm.
Mugrosa Fm.
Esmeraldas Fm.
La Paz Fm.
Lisama Fm.
Umir Fm.
Usme Fm.
Regadera Fm.
Bogotá Fm.
Cacho Fm.
Sabana Fm.
Tilatá Fm.
Concentración Fm.
Picacho Fm.
Upper Socha Fm.
Lower Socha Fm.
Guaduas Fm.
Guayabo Fm.
León Fm.
Carbonera Fm.
Mirador Fm.
Cuervos Fm.
Barco Fm.
Upper Mirador Mbr.
Lower Mirador Mbr.
C1
C3
C5
C6
C7
C8
Late Cenozoic uplift
Unconformity
Facies change
Lacustrine siltstone
Alluvial fan deposits
Nonmarine mudstone
Estuary, delta, and coastal plain sandstone.
Fluvial conglomerate
Fluvial sandstone
Shallow marine tidal sandstone
Shallow marine mudstone/sandstone
Mainly delta and coastal plain mudstone/sandstone
a
Caribbean Plate
Nazca Plate
Guajira
SM
MA
NMS
MMVB
LLB
Llanos Sur Basin
Western Cordillera
Central Cordillera
Eastern Cordillera
Western fold belt
Eastern fold belt
200 km
c
Monas Anticline
Nuevo Mundo Syncline
Real Inferior Fm.
Colorado Fm.
Mugrosa Fm.
Esmeraldas Fm.
La Paz Fm.
Lisama Fm.
Figure 16
Fig. 12–13
Sabana de Torres
Santa Clara
Uribe Uribe
La Fortuna
Campo Lisama
Hidrosogamoso Dam
Tienda Nueva
Marta
Cerro La Aurora
Sogamoso River
Rio Sucio River
Aronosa Creek
8 km
Stratigraphic sections
Correlation line
d
Legend
Wells in this work
Thrust fault
Stratigraphic correlation section
WSLLB
ESLLB
Guaicáramo Fault
Figure 14
Figure 15
W1
W2
W3
W4
W5
W6
W7
W8
W9
W10
W11
W12
W13
50 km
4° N
3° N
72° W
73° W

←

Figure 1. (a) Locations of the main three cordilleras; the insets indicate the locations of both study areas. (NMS) Nuevo Mundo Syncline; (SM) Santander Massif; (MA) Mérida Andes; (MMVB) Middle Magdalena Valley Basin; (LLB) Llanos Basin. **(b)** Wheeler diagram showing the time stratigraphic units in the Middle Magdalena and Llanos Basins (after Mora et al., 2010). Data from MMV and NMS: This study and Caballero et al. (2010, 2013a). Data from western and eastern axial EC: Bayona et al. (2013). Data from southern Llanos Basin: This study. (WSLLB) western sector of the Llanos Basin; (ESLLB) eastern sector of the Llanos Basin; (Fm.) Formation. **(c)** Locations of stratigraphic columns (white lines) and stratigraphic correlation and section in the NMS. **(d)** Location of a stratigraphic correlation section and well cores in the Llanos Basin used in this study. (LF) Lengupá Fault; (TF) Tesalia Fault; (SF) Servitá Fault; (MiF) Mirador Fault; (BF) Boa Fault; (MoF) Monserrate Fault.

In the eastern part of the MMB, the La Paz Formation is 1090 m thick in the NMS and pinches out 38 km to the west above the axial LCISP (Suárez, 1997; Gómez et al., 2005a; Caballero, 2010). The Cantagallo sandstones in the western part of the Middle Magdalena Basin (Yariguí–Cantagallo Oil Field) are the fluvial equivalent to the La Paz Formation in the eastern region; it is 580 m thick in the Yariguí–1 well and pinches out above the LCISP approximately 18 km to the east (Suárez, 1997).

The middle – upper Eocene rock record is composed of fluvial sandstones and mudstones of the Armadillo Member of the San Juan de Rio Seco Formation in the Guaduas Syncline, where paleocurrent measurements indicate paleoflow to the north (Gómez et al., 2003), and the fine–grained fluvial meandering Esmeraldas Formation in the northern region of the MMB, which shows variable paleocurrents with SE paleoflow in the lower section, W–NW paleocurrents in the middle section, and SE paleocurrents in the upper section (Suárez, 1997; Gómez et al., 2005a, Caballero, 2010; Caballero et al., 2010). Across strike, the middle – upper Eocene deposits extend across most of the Middle Magdalena Basin. The Esmeraldas Formation has an equivalent unit in the northwestern part of the MMB, the upper part of the Cantagallo sandstones (Suárez, 1997; Gómez et al., 2005a). Los Corros fossil horizon at the top of the Esmeraldas Formation is not continuous and is restricted to the central and northern parts of the Middle Magdalena Basin (Morales, 1958; Gómez et al., 2005a).

A recent palynological study of the Esmeraldas Formation in the Middle Magdalena Basin found that this unit is late – early Eocene to late Eocene in age and is time–equivalent with the upper part of the Picacho Formation and the lower part of the Concentración Formation in the Eastern Cordillera and with the middle–upper part of the Mirador Formation and the lower part of the C8 Member of the Carbonera Formation in the LLB (Rodríguez–Forero et al., 2012). By integrating the data from Pardo–Trujillo (2004) with their results, Rodríguez–Forero et al. (2012) suggested an early Eocene age for the La Paz Formation based on its stratigraphic position (T–05 of Jaramillo et al., 2011).

The Oligocene rock record comprises variegated and mainly reddish brown pedogenized mudstone and claystone with interbedded discontinuous muddy granule coarse sandstones of the alluvial Oligocene Mugrosa Formation in the NMS (Caballero et al., 2013a). In the southern Middle Magdalena Basin, the equivalent Almácigos Member of the San Juan de Rio Seco Formation is composed of nearly the same facies with thick mudstone intervals containing decimeter– to meter–scale cross–bedded sandstones that grade upward into thick layers of variegated mudstones with caliche and paleosols (Gómez et al., 2003). Floodplain cumulative paleosols and channelized sands were deposited in the northern part of the basin (Suárez, 1997).

1.2. Previous Work in the Axial Eastern Cordillera

Correlations between the axial Eastern Cordillera, Llanos Foothills, Llanos Basin, and the Magdalena Basin have been performed in several previous studies. According to these studies, the Maastrichtian – Paleocene activity formed two depocenters in Colombia, one in the Magdalena Valley and the other to the east of the western flank of the Eastern Cordillera, the axial Eastern Cordillera – Llanos Basins (Bayona et al., 2013). Deformation and intraplate magmatism shifted to the eastern flank of the Eastern Cordillera during the late Paleocene – early Eocene and separated the second depocenter in the axial Eastern Cordillera and the Llanos Basin during early Eocene. In the early Eocene, three depocenters (the Magdalena Valley, axial Eastern Cordillera, and Llanos Basins) were separated by low–amplitude uplifts that exposed the Cretaceous sedimentary cover and were filled by sediments from the Central Cordillera to the west, the craton to the east, and local uplifts (Bayona et al., 2010, 2013).

Farther to the north in the axial Eastern Cordillera Basin, the Floresta Basin records depositional environments ranging from shallow marine to low–gradient fluvial and estuarine deposits from the Maastrichtian to the Oligocene. The sediment provenance for this basin was from the Guiana Craton during the Cretaceous – early Paleocene and from the Central Cordillera from the mid–Paleocene until the middle Eocene. During the late Eocene to Oligocene, the source was the fold–thrust belt of the Eastern Cordillera (Saylor et al., 2011, 2012a).

Previous studies suggest that the southernmost part of the axial Eastern Cordillera was connected to the Upper Magdalena Basin, the axial Eastern Cordillera, the foothills of the Eastern

Cordillera, and the southern Llanos Basin from the Paleocene to early Eocene, forming a N–NE–oriented fluvial to coastal plain sedimentary system that was linked to the Maracaibo Sea (Casero et al., 1997, Reyes–Harker et al., 2015). The Middle Magdalena Basin was a N–NE–oriented fluvial to estuarine system that was confined by the Central Cordillera and the low uplifts of the Los Cobardes–Peñon Anticlines and was connected to the Maracaibo Basin to the north. By the Oligocene, the Magdalena Valley Basin, the axial Eastern Cordillera Basin, and the Llanos Basin had separated.

1.3. Previous Work in the Llanos Basin

In the foothills of the Eastern Cordillera, previous studies (Ramon & Fajardo, 2006) interpreted the Lower Mirador Formation as coastal plain facies that were deposited in channels, crevasse splays, swamps, and flood–plain environments and the Upper Mirador Formation as being composed of bay fill, bay–head delta, and channel facies. Jaramillo et al. (2009) found that this unit is diachronous in the Llanos Basin; they dated this unit as early to middle Eocene in outcrops exposed along the Llanos Foothills and as Oligocene in the stable foreland basin to the east. Pulham (1994), Cooper et al. (1995), and Cazier et al. (1995) interpreted the Mirador Formation in the Cusiana Field as incised valley fill after a period of falling base level at the end of the Paleocene.

The Mirador Formation is thicker to the north and thinner to the south; it is approximately 100 m thick in the Medina area (Parra et al., 2009a) and 131–144 m thick in the Cusiana area (Cazier et al., 1995). These thicknesses reported to the north include both the Lower and Upper Mirador Formation. To the south in the area of the Ariari River, the Lower Mirador Formation is 30 m thick, and in the Macarena Formation is only 15 m thick (Sandoval, 2016).

Paleogeographic reconstruction of the Cenozoic strata in Colombia shows that the lower Eocene strata of the Mirador Formation are dominated by sandy fluvial facies and that the middle – upper Eocene is dominated by mudstones and sandstones that accumulated along a NNE–elongated fluvial system with periods of marine ingression (Reyes–Harker et al., 2015; Santos et al., 2008). This late Eocene depositional configuration continued in the Oligocene with the accumulation of mudstones of the C8 Member of the Carbonera Formation to the west and coeval sandstone deposits to the east; these sandstones predominate along the eastern border of the southern Llanos Basin and are called Oligocene basal sandstones or basal sandstones of the Carbonera Formation (Malagón, 1997; Bayona et al., 2006).

The Carbonera Formation was deposited in a basin that extended to the west far beyond the present–day Llanos Basin (Villamil, 1999). The sandy units are interpreted as nearshore, coastal plain and deltaic deposits, whereas the muddy units are transgressive shales (Ramon & Fajardo, 2006). Mondragón et al. (2016) named the basal sandstones of the early Eocene in the central part of the Llanos Basin the C9 Member of the Carbonera Formation; however, these sandstones are part of the C8 Member of the Carbonera Formation, especially in the ESLLB.

Several profiles of the Carbonera Formation were measured in the Medina Basin in the foothills of the Eastern Cordillera. The C8 Member of the Carbonera Formation is approximately 200 m thick and is characterized by thick intervals of dark gray mudstone with cross–laminated sandstones and coal of a marine–influenced deltaic plain. The C7 Member of the Carbonera Formation is composed of a set of thickening and coarsening–upward tide–influenced delta facies successions. In the Medina Basin, the C6 Member of the Carbonera Formation consists of fluvial channel conglomerates and sandstones with interbedded scarce alluvial plain variegated mudstones covered by thick intervals of variegated mudstones on the western flank and thick intervals of dark gray mudstone with cross–laminated sandstones and coal of a marine–influenced deltaic plain on the eastern flank. Both the C7 and C6 Members of the Carbonera Formation vary in thickness from 1150 m on the western flank to 450 m on the eastern flank of the Medina Basin (Parra et al., 2009a, 2010).

2. Materials and Methods

The descriptions of the facies and facies successions are based on several measured stratigraphic sections in outcrops in the Llanos Foothills and well cores throughout the Llanos Basin (Figure 1a, 1d). The data in this study from the Middle Magdalena Basin are mostly based on measured outcrop stratigraphic sections from the eastern and western limbs of the Nuevo Mundo Syncline (Caballero, 2010; Caballero et al., 2010, 2013a, 2013b) (Figure 1c).

We described the facies using the methodology proposed by Farrell et al. (2012), which is a texture–based classification of clastic sedimentary facies that conveys information about the sedimentary processes responsible for their deposition. Postdepositional features that require very short to extensive periods of time after physical deposition of the sediments, such as bioturbation and paleosol development, were also considered as criteria for facies identification. The ichnofossils and bioturbation were described following the guides and criteria of Gerard & Bromley (2008). The paleosol identification and nomenclature were based on Kraus (1999) as well as the useful paleosol classification nomenclature of Catuneanu (2006).

We describe the textures, compositions, sedimentary structures, thicknesses, and contact relationships between the facies and facies successions. Sedimentary structures are among the most valuable data for interpreting the depositional environments of rocks. The structures are especially useful in determining the energy level and direction of flow of the transporting medium and the biological activity, and they are often the only way to define the sedimentary processes by which sediment is deposited (Weimer, 1975).

The biozones identified in the correlated sections were classified at the Biostratigraphy Laboratory at Instituto Colombiano del Petróleo (ICP) following the palynology zonation proposed by Jaramillo et al. (2011). The correlations were used to determine the distribution of facies throughout the basins, and the stratigraphic distribution and abundance of ecological important palynomorphs were also used to support the depositional environment interpretations. In addition, palynology provides information about the depositional environments. For example, it is possible to distinguish nonmarine and marine organic matter. The former is dominated by continental particles and freshwater algae, whereas marine organic matter contains marine algae, such as dinoflagellates and acritarchs.

Gamma ray logs aided in the identification of sharp versus gradational trends and changes in stacking patterns, and they allowed the identification of candidate surfaces for unconformities, maximum flooding surfaces, truncations, and context. Pattern–matching analysis aided in the correlations. All of the information was integrated using the sequence stratigraphy methodology proposed by van Wagoner et al. (1990), van Wagoner & Bertram (1995), Posamentier & Allen (1999), and Catuneanu (2006), which was calibrated with palynology analysis using proprietary information at the ICP.

Facies analysis is fundamental for interpreting stratigraphic surfaces, such as marine erosion surfaces, unconformities, maximum flooding surfaces, fluvial incision, and subaerial exposure. The regional correlations integrated information from well logs, facies from outcrops/cores, biozones, and stratigraphic markers such as paleosols and coal beds. This information and analysis aided in the identification of time lacunas, facies changes, transposition of facies and environments, and changes in the depositional trends and unconformities (Walker, 1984; Walker & James, 1992; van Wagoner & Bertram, 1995; van Wagoner et al., 1990; Shanley & McCabe, 1994; Posamentier & Allen, 1999; Kraus, 1999; Catuneanu, 2006). These analyses resulted in a synthetic sequence stratigraphic framework that was calibrated with biostratigraphy data.

3. Results

3.1. Facies Description

"A facies is a body of rock characterized by a particular combination of lithology, physical, and biological structures that bestow an aspect ("facies") different from the bodies of rock above, below, and laterally adjacent" (Walker & James, 1992).

In the following sections, we describe, illustrate, and interpret the processes that generated each facies or association of facies in the Eocene to Oligocene Mirador Formation and the C8, C7, and C6 Members of the Carbonera Formation in the SLLB and the La Paz, Esmeraldas, and Mugrosa Formations in the NMS (Figures 2 to 6). We then describe, illustrate with stratigraphic columns, and interpret the facies successions in these lithostratigraphic units in terms of the environmental context of their occurrence (Figures 7 to 13). Using correlations, we depict the spatial and temporal distributions of the facies and facies successions and interpret the depositional environments of these units (Figures 14 to 17). Finally, we depict the distribution of the depositional systems in maps (Figures 18 to 20).

3.1.1. Facies and Facies Associations, Descriptions, and Interpretations

3.1.1.1. Facies 1 (F1): sG x, sG h, sG m, sG imb

Facies: Clast–supported pebble conglomerate with sandy matrix. Clasts are pebbles and cobbles with very rounded shapes that are mainly composed of quartz with chert (possible second sedimentary cycle) (Figures 2b, 4a).

Sedimentary structures: Planar to trough cross–bedding, planar beds, imbricated clasts, graded to aggradational sets, no organic structures. x = cross–bedded; h = horizontally bedded; m = massive; imb = imbricated.

Thickness and contacts: Erosive base, sharp to gradational transition from gS x to S x. Sets 1 to 4 m thick in the Mirador Formation in the WSLLB (Figure 2a, 2b) and 0.5 to 24 m thick in the southern part of the La Paz Formation in the NMS. Composed of pebble to cobble conglomerates with clasts 2 to 15 cm in diameter.

Interpretation: Bedload sediment deposited in an upper flow regime (dilute stream flows) by traction (sG x), rolling (sG imb), or fluidized flow (sG m). The sandy matrix infiltrated during the waning of the event (sG m) (Rust, 1977). Massive aspect = hyperconcentrated flows.

3.1.1.2. Facies 2 (F2): S x, gmS x, mS x, mS m, S x rh

Facies: Medium– to coarse–grained sandstone (S x), gravelly sandstone (gS x), and muddy sandstone (mS x) (Figures 2c, 2e, 4b, 5a). Rhythmic cross–bedded sandstone (S x rh) with mud draped over each sandy foreset in the upper part of the Lower Mirador and Esmeraldas Formations (Figure 2d, 2e left photo). Muddy or gravelly muddy sandstones (mS x, gmS m, gmS x) are also present, especially in the Mugrosa Formation (Figure 6c, 6d, 6g). And massive sandstone (S m) as in La Paz Formation (Figure 4c).

Sedimentary structures: Planar to trough cross–bedding, massive bedding. No organic structures observed.

Thickness and contacts: From 40 cm to 1.5 m thick in the lower Eocene Mirador Formation and basal Oligocene sandstones of the C8, C7, and C6 Members of the Carbonera Formation in the ESLLB. Sets are 60 cm to 2 m thick in the La Paz

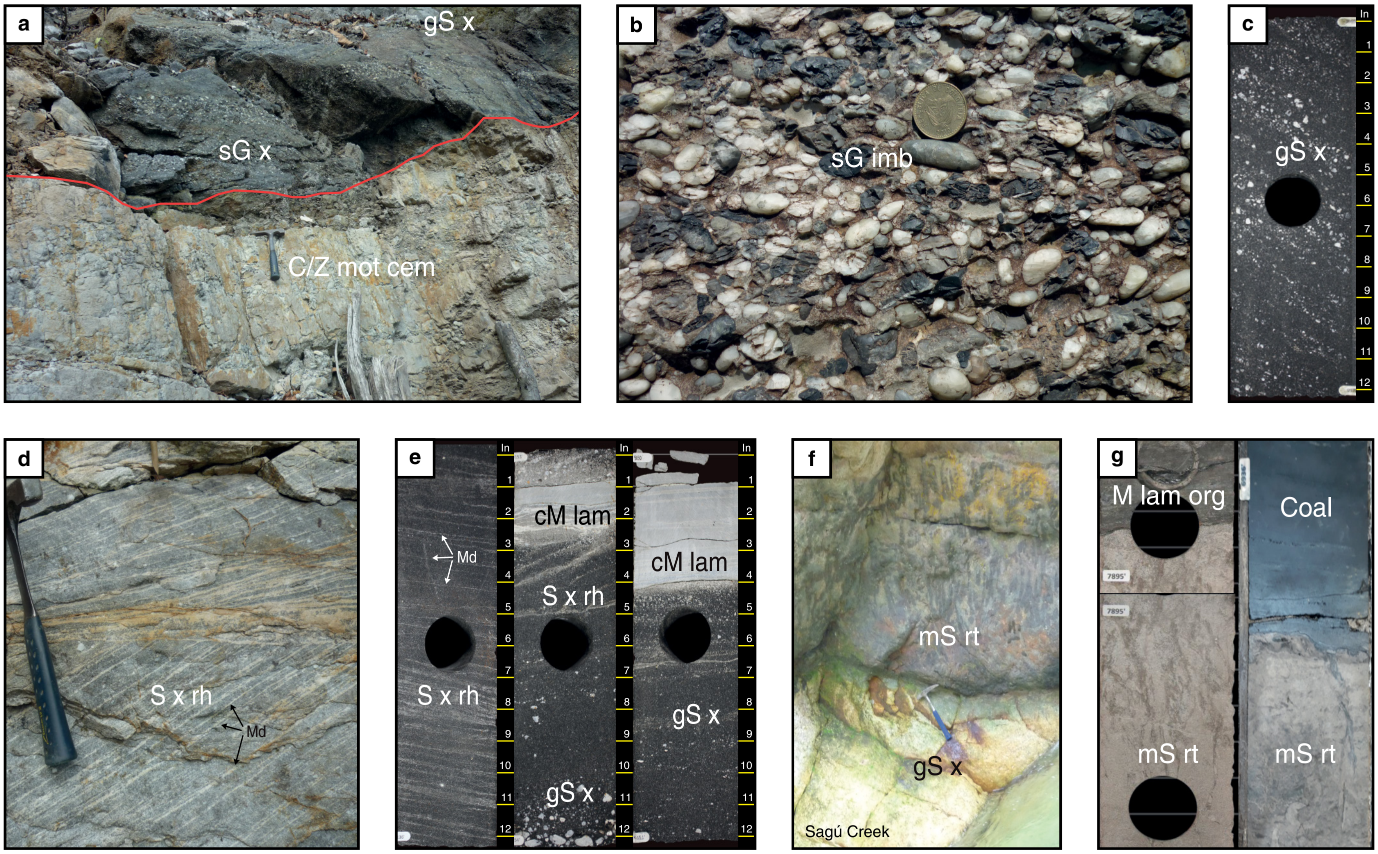


Figure 2. Images of the lower Eocene Lower Mirador Formation facies in the LLB. **(a)** Conglomerate facies (sG x) over well–developed paleosol (C/Z mot cem). This paleosol defines the Paleocene/Eocene unconformity (red line). **(b)** Detail of the conglomeratic facies with imbricated clasts (sG imb). **(c)** Conglomeratic sandstones with planar cross–bedding (gS x). **(d, e)** Cross–bedded rhythmic sandstone (S x rh) with mud drapes (Md) and clayey mudstone laminated (cM lam) between sets of cross–beds. **(f)** Rooted and mottled muddy sandstone (mS rt) above conglomeratic sandstone (gS x). **(g)** Same facies (mS rt) in cores with carbonaceous mudstone (M lam carb) or coal above the rooted sandstone. (a, b, d, and f): Outcrops in the foothills, (c, e): well 1 to well 4, (g): wells 1 and 7.

and Esmeraldas Formations and from 0.5 to 2 m thick in the Mugrosa Formation.

Interpretation: High–energy deposits transported in dilute stream flows by traction and rolling particles in a subaquatic migrating dune field with abundant bedload (Collinson et al., 2006). Interpretation depends on the associated facies and the stratigraphic context. Rhythmic structures and surfaces mean rapid and cyclic changes from high to low energy and are probably of tidal origin (Nio & Yang, 1991).

3.1.1.3. Facies 3 (F3): S h, mS h, gmS h

Facies: Fine– to coarse–grained sandstone, horizontally bedded (S h), planar–bedded muddy sandstone (mS h), or planar–bedded gravelly muddy sandstone (gmS h). This facies is present in the Mugrosa Formation in the NMS (Figure 6i, 6j). In the ESLLB, this facies is present in the Oligocene basal sandstones and C7 Member of the Carbonera Formation (Figures 10a, 11a3, 11b4).

Sedimentary structures: Planar bedding.

Thickness and contacts: Up to 2 m thick in the Mugrosa Formation. In the La Paz Formation, it is medium– to coarse–grained and is 0.5 to 1.5 m thick; in the southern Llanos Basin, it is 0.5 to 1 m thick.

Interpretation: Planar or flat bedding is indicative of an upper flow regime in which the energy of the current is strong and destroys the bedforms to form planar beds. It is a confined (high–sediment concentration in stream flows) or unconfined laminar or sheet flow (hyperconcentrated flows and upper flow regime). Its depositional environment can be distinguished by other attributes (Blair & McPherson, 2009; Lunt et al., 2004).

3.1.1.4. Facies 4 (F4): mS rt, mS rt mot

Facies: Fine– to coarse–grained rooted muddy sandstone (mS rt), rooted and mottled reddish to yellowish muddy sandstone (mS rt mot). In the southern LLB, it is composed of white mud-

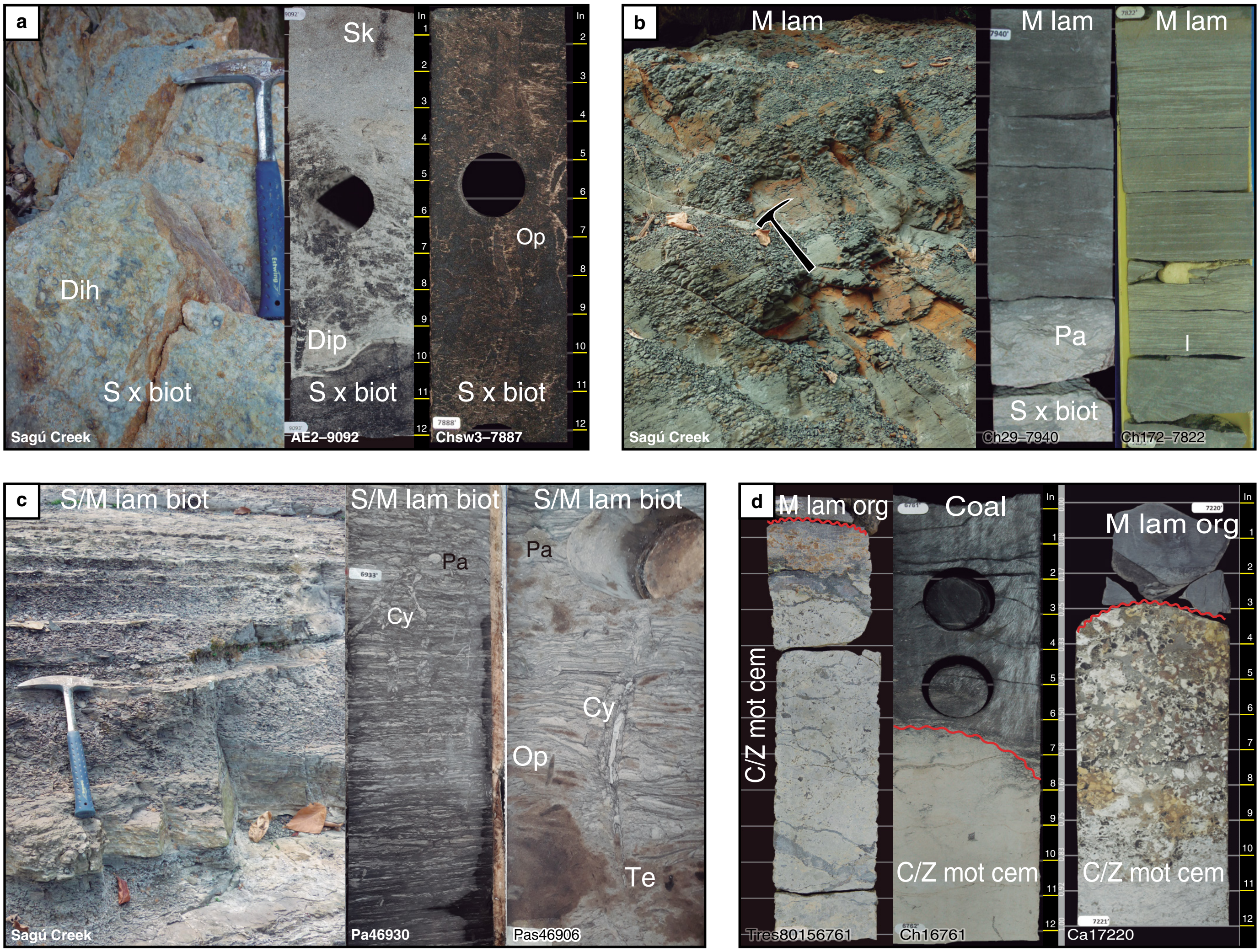


Figure 3. Images of the outcrop (left) and core (right) of the middle – upper Eocene facies of the Upper Mirador Formation and the C8 Member of the Carbonera Formation in the southern LLB. **(a)** Bioturbated fine– to medium–grained cross–bedded sandstones (S x biot). **(b)** Gray to olive gray laminated mudstone (M lam) with thin lenses of silt or very fine sandstone. **(c)** Laminated and bioturbated fine heterolithic sandstone/mudstone (S/M lam biot). **(d)** Paleocene mottled and cemented, well–developed paleosol (C/Z mot cem) below dark gray carbonaceous, coaly mudstone (M lam org) and coal. The red line marks the Paleocene/middle Eocene unconformity. Outcrop images in (a), (b), and (c) are from the Sagú area in the foothills. Cores (a) and (b) are from wells 6, 7, and 8. (Sk) *Skolithos*; (Dih and Dip) *Diplocraterium*; (Op) *Ophiomorpha*; (Pa) *Paleophycus*; (Cy) *Cylindrichnus*; (Te) *Teichichnus*; (l) lenses.

dy sandstone (kaolinite) covered by a thin layer of coal or carbonaceous mud 5 to 15 cm thick (Figure 2g). In the NMS, it is generally associated with variegated mudstone and is present in the lower section of the La Paz Formation (Figure 4f), the lower part of the Esmeraldas Formation (Figure 5c, 5d), and the Mugrosa Formation (Figure 6f).

Sedimentary structures: No physical structures preserved (or structures destroyed by postdepositional processes). Vertical bioturbation structures, root traces.

Thickness and contacts: 1 to 4 m thick in the lower Eocene rocks of the Mirador Formation in the WSLLB (Figure 2g, left core) but less than 1 m thick in the ESLLB (Figure 2g, right core).

Interpretation: After deposition, the sandstones were subaerially exposed and colonized by vegetation for a period of time; weathering and bioturbation masked and destroyed the primary sedimentary structures and mixed the sand with mud. Eventually, the vegetation was preserved as a thin layer of coal or carbonaceous mudstones conforming the paleo–organic soil horizon over the rooted sandstone.

3.1.1.5. Facies 5 (F5): S r, S r biot

Facies: Very fine– to fine–grained, well–sorted sandstones with current or wave ripple laminations (S r), sometimes bioturbated (S r biot). Present in the NMS at the top of the lower section of

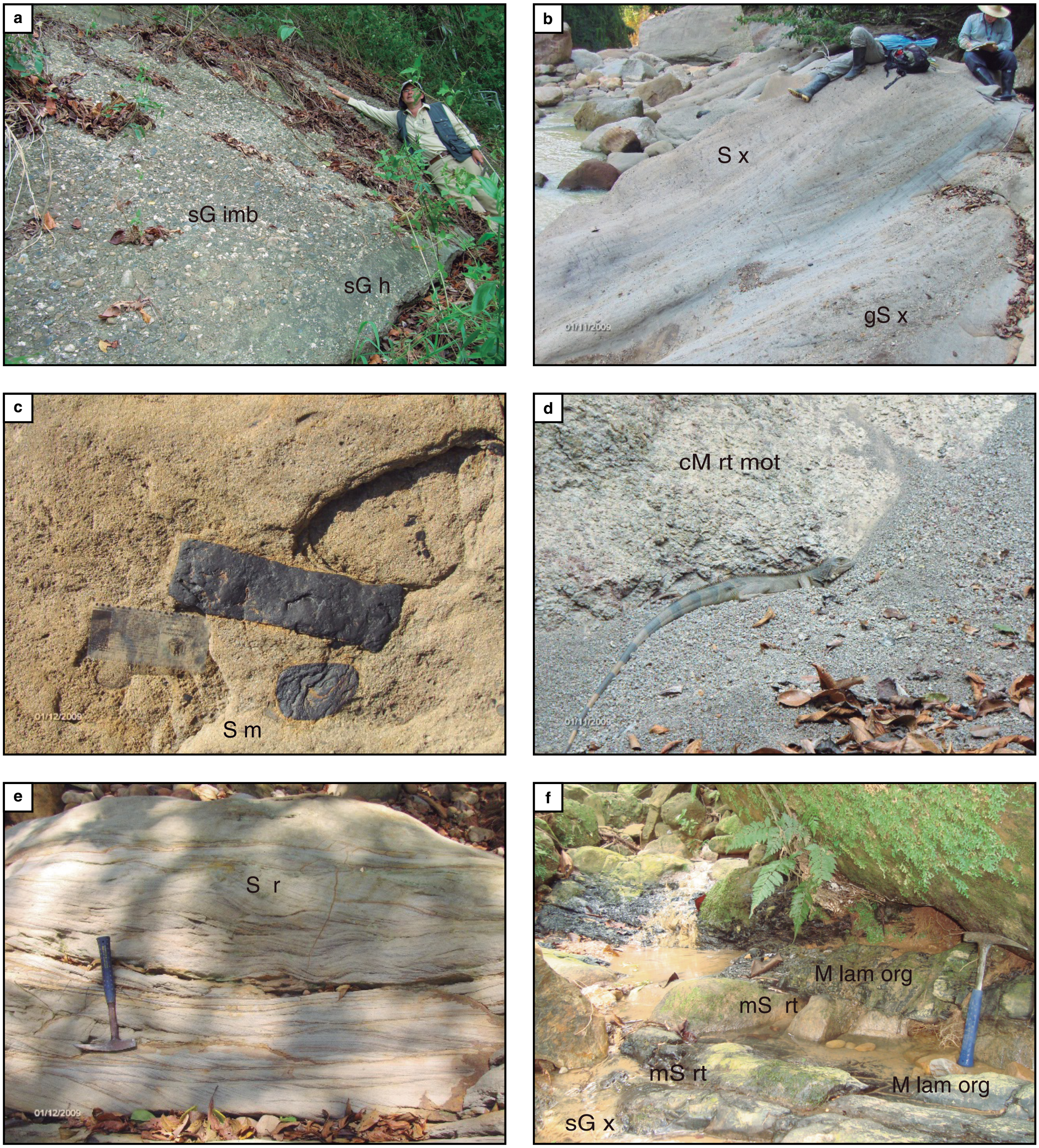


Figure 4. Illustration of the facies identified in the lower Eocene La Paz Formation on the eastern limb of the Nuevo Mundo Syncline (NMS). **(a)** Basal conglomerates (sG imb, sG h). **(b)** Very thick amalgamated trough cross–bedded sandstones (S x, gS x). **(c)** Massive sandstones (S m) containing decimeter–scale intraclasts of coal hydraulically equivalent to sand. **(d)** Variegated mudstones (cM rt mot) (the iguana is 50 cm long) of the Upper La Paz Formation. **(e)** Current and sinusoidal rippled sandstone (S r). **(f)** A rooted sandstone (mS rt) overlain by a thin layer of carbonaceous mudstone (M lam org) at the top of a conglomerate/sandstone (sG x) cycle in the southern basal section of the La Paz Formation.

the La Paz Formation (Figure 4e, unidirectional ripples) and in the Esmeraldas Formation (Figure 5e, bidirectional ripples). In the Oligocene basal sands of the C8 Member of the Carbonera Formation in the ESLLB, this facies contains irregular wavy discontinuous laminations (Figures 10b, 11a2, 11a3).

Sedimentary structures: Wave ripple laminations, sometimes bioturbated by ichnogenera such as *Ophiomorpha* and *Teichichnus*.

Thickness and contacts: Beds 20 to 50 cm thick.

Interpretation: Migration of ripples in a lower flow regime, which were partly or locally colonized and bioturbated. The environmental interpretation depends on the context: it can be fluvial, estuarine, tidal flat, shallow marine, or lacustrine and may also be present at the tops of turbiditic flows (Reineck & Singh, 1973). Bioturbation indicates a lower shoreface to inner shelf (Clifton, 2006). This kind of bioturbation is only found in the Upper Mirador Formation and the C8 Member of the Carbonera Formation in the LLB.

3.1.1.6. Facies 6 (F6): S x biot

Facies: Fine– to medium–grained well–sorted sandstone with planar cross–bedding burrowed by *Ophiomorpha*, *Teichichnus*, *Skolithos*, and *Diplocraterion* (Figure 3a). Present in the Upper Mirador Formation in the WSLLB (Figure 3a).

Sedimentary structures: Planar cross–bedding and bioturbation by marine ichnofacies; found in sandy marginal marine or lacustrine systems.

Thickness and contacts: Beds 10 cm to 1 m thick; stacked bedsets 3 to 4 m thick.

Interpretation: This facies results from the migration of straight crested dunes in a lower flow regime that were colonized and bioturbated by organisms. The environment is interpreted as a shallow marine, likely upper shoreface subenvironment (Reineck & Singh, 1973; Clifton, 2006; Collinson et al., 2006), although this type of association can also be found in sandy marginal estuarine systems.

3.1.1.7. Facies 7 (F7): S/M w, l, f

Facies: Fine to very fine, well–sorted sand interlayered with medium gray mud with wavy (S/M w), lenticular (S/M l), and flaser bedding (S/M f). These facies are present in the upper part of the Esmeraldas Formation (Figure 5b, 5f) and in the lower Oligocene deposits in the ESLLB (Figure 10i).

Sedimentary structures: Wavy, lenticular, and flaser bedding.

Thickness and contacts: Heterolithic layers 1 to 3 m thick.

Interpretation: Two alternating and repeating stages of deposition: a lower flow regime (sand) followed by a stage of still water (mud). These conditions occur in tidal flats or below the wave base in the lower shoreface (Reineck & Singh, 1973; Nio & Yang, 1991); the sedimentary structures indicate the former.

3.1.1.8. Facies 8 (F8): M lam

Facies: Dark gray laminated mudstone (M lam), locally thin isolated lenses of silt or very fine sandstone, locally bioturbated with *Teichichnus*, *Planolites*, *Thalassinoides*, and *Phycodes*? (Figure 3b). This facies contains lower – middle Eocene palynological assemblages (biozones T–05—T–06). De La Parra et al. (2014) also recorded the presence of marine palynomorphs (dinoflagellates and foram linings) as well as mangrove pollen (*Lanagiopollis crassa*). The Oligocene interval (zone T–08) contains high abundances of freshwater–brackish algae (*Botryococcus*–spp.).

Sedimentary structures: Horizontal laminations in wells and outcrops and subtle wavy to lenticular laminations.

Thickness and contacts: From a few centimeters to several meters thick. Very thick in the Upper Mirador Formation and the C8 Member of the Carbonera Formation in the LLB (Figure 3b).

Interpretation: This facies is interpreted as a subaqueous vertical settling deposit below the fair–weather wave base. When it contains thin silt laminae, the very fine sand or silt was deposited during interruptions between more energetic waves. This facies could be a marine shelf mudstone (Reineck & Singh, 1973; Clifton, 2006).

3.1.1.9. Facies 9 (F9): S/M lam biot

Facies: Fine– to very fine–grained, well–sorted sandstones and medium–gray colored mudstones interbedded with thin to thick laminae. Common evidence of bioturbation by *Ophiomorpha*, *Teichichnus*, *Diplocraterion*, *Cylindrichnus*, and *Thalassinoides*. Present in the middle – upper Eocene to lower Oligocene C8 Member of the Carbonera Formation in the LLB (Figure 3c) and in the LLB.

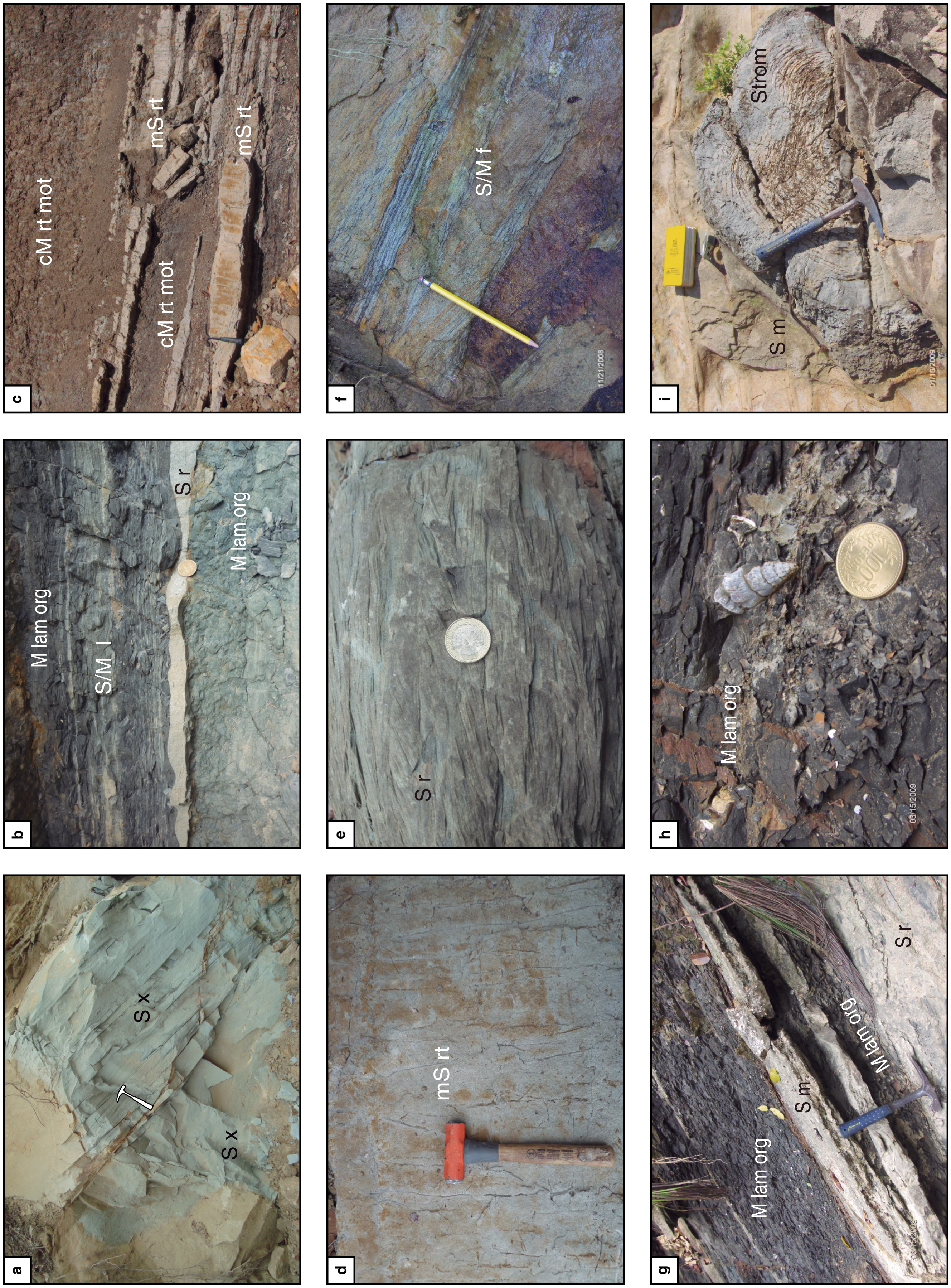
Sedimentary structures: Wavy and lenticular laminations to wavy ripple laminations in sands, bioturbated by *Teichichnus*, *Paleophycus*, *Diplocraterion*, and *Cylindrichnus*.

Thickness and contacts: Centimeters to meters thick.

Interpretation: Vertical settling of mud and low–energy storms that shed sand in a subaqueous environment near the fair–weather wave base due to seasonal variations. This facies could indicate a lower shoreface environment (Reineck & Singh, 1973), although heterolithic laminations may also be found in coastal plains (seasonal variations) and tidal flats (daily variations).

3.1.1.10. Facies 10 (F10): M org, M lam org

Facies: Dark gray to black carbonaceous mudstone with local pyrite nodules. Massive (M org) to horizontally laminated (M


a
S x
S x
b
M lam org
S/M l
S r
M lam org
c
cM rt mot
cM rt mot
mS rt
mS rt
d
mS rt
e
S r
f
S/M f
11/21/2008
g
M lam org
S m
M lam org
S r
h
M lam org
03/15/2009
i
Strom
S m
01/16/2009

←

Figure 5. Middle – upper Eocene facies of the Esmeraldas Formation on the eastern flank of the NMS. **(a)** Thick bedset of planar cross–bedded, medium– to coarse–grained sandstone (S x) (hammer is 45 cm long). **(b, f)** Interlaminations of dark gray mudstone (M lam org) with ripple–laminated, fine– to very fine–grained sandstone (S/M l, f) producing ripple (S r), lenticular, or flaser laminations. **(c)** Variegated mudstone (cM rt mot) with rooted sandstone (mS rt). **(d)** Detail of rooted sandstone (mS rt). **(e)** Ripple–laminated, fine– to very fine–grained sandstone (S r), some of which is bidirectional. **(g, h)** Gray carbonaceous mudstones with shells of gastropods (M lam org) intercalated with massive fossiliferous sandstone (S m) in the Upper Esmeraldas Formation (Los Corros horizon) which are over sandstones with ripple laminations (S r). **(i)** Concentric laminated stromatolite (Strom) structure over sandstones (S m) in the Esmeraldas Formation.

lam org), horizontal burrows, plant debris can be present (Figure 9c, 9d). This facies is found in the middle Eocene rocks of the southern Llanos Basin (Figure 2g left and Figure 3d right). In the NMS, this facies was observed in the lower to middle part of the La Paz Formation (Figure 4f) and in the upper part of the Los Corros fossil marker in the Esmeraldas Formation (Figure 5g, 5h).

Sedimentary structures: Massive to horizontal laminations, horizontal burrows, and plant remains; thin coal interbeds.

Thickness and contacts: Up to 6 m thick in the middle Eocene of the ESLLB; a few cm to meters thick in the La Paz and Esmeraldas Formations in the NMS.

Interpretation: Deposited by vertical accretion in ponded water with a large contribution of vegetal carbonaceous material. It is a marginal paralic deposit that formed in coastal plain swamps and marshes or lacustrine environments (Cecil, 1990) as well as on the coastal plain or a floodplain, where poorly drained conditions could lead to reducing conditions that preserved the organic matter (Shanley & McCabe, 1994).

3.1.1.11. Facies 11 (F11): cM rt mot, cM lam

Facies: White or light gray, violet to reddish brown clayey massive mudstone (cM m), laminated mudstone (cM lam), rooted and mottled (cM rt mot). It is present in the Toro Shale Member of the La Paz Formation (Figure 4d) on the western limb of the NMS. It is a well–developed variegated clayey mudstone that is strongly pedogenized. This facies is also present in the lower section of the Esmeraldas Formation (Figure 5c) and in the entire Oligocene Mugrosa Formation (Figure 6e, 6f). Also in the ESLLB clayey mottled mudstone (cM mot).

Sedimentary structures: Highly bioturbated by roots and other vertical burrows. Highly pedogenized with variegated colors.

Thickness and contacts: Up to 10 m thick on the eastern limb of the NMS in the middle section of the La Paz Formation. It is the most abundant facies in the Mugrosa Formation, with intervals more than 30 m thick.

Interpretation: This facies corresponds to a floodplain deposit exposed subaerially and affected by pedogenic processes.

3.1.1.12. Facies 12 (F12): C/Z mot cem

Facies: White to greenish cream pedogenized silty claystone. This paleosol was observed in outcrops in the WSLLB (Figure 2a) and in cores in the ESLLB (Figure 3d). This facies is a more cemented duricrust than facies cM mot and cM lam. Z = silt, C = clay.

Sedimentary structures: Strongly mottled with ferricretes or silcretes, root traces, ferruginous nodules, and duricrusts.

Thickness and contacts: 1 to 6 m thick observed in cores of the LLB and outcrops in the NMS. This facies is located below the base of the Eocene unconformity, and it may correspond to the paleosol profile in the Paleocene strata.

Interpretation: Weathering of this material over a long period of time and development of a paleosol (higher than mS rt, mS rt mot, and cM rt mot).

3.1.1.13. Facies 13: (F13): Coal

Facies: Coal appears shiny or dull in cores as seams (Figure 3d). It is located at the top of the channel facies, and it decreases in thickness due to erosion of the overlying coarse–grained facies and/or ravinement surfaces between nonmarine and marine facies (Figures 8 and 9). It is thicker at the base or within the organic laminated mudstones (Figure 9, FS3 at base).

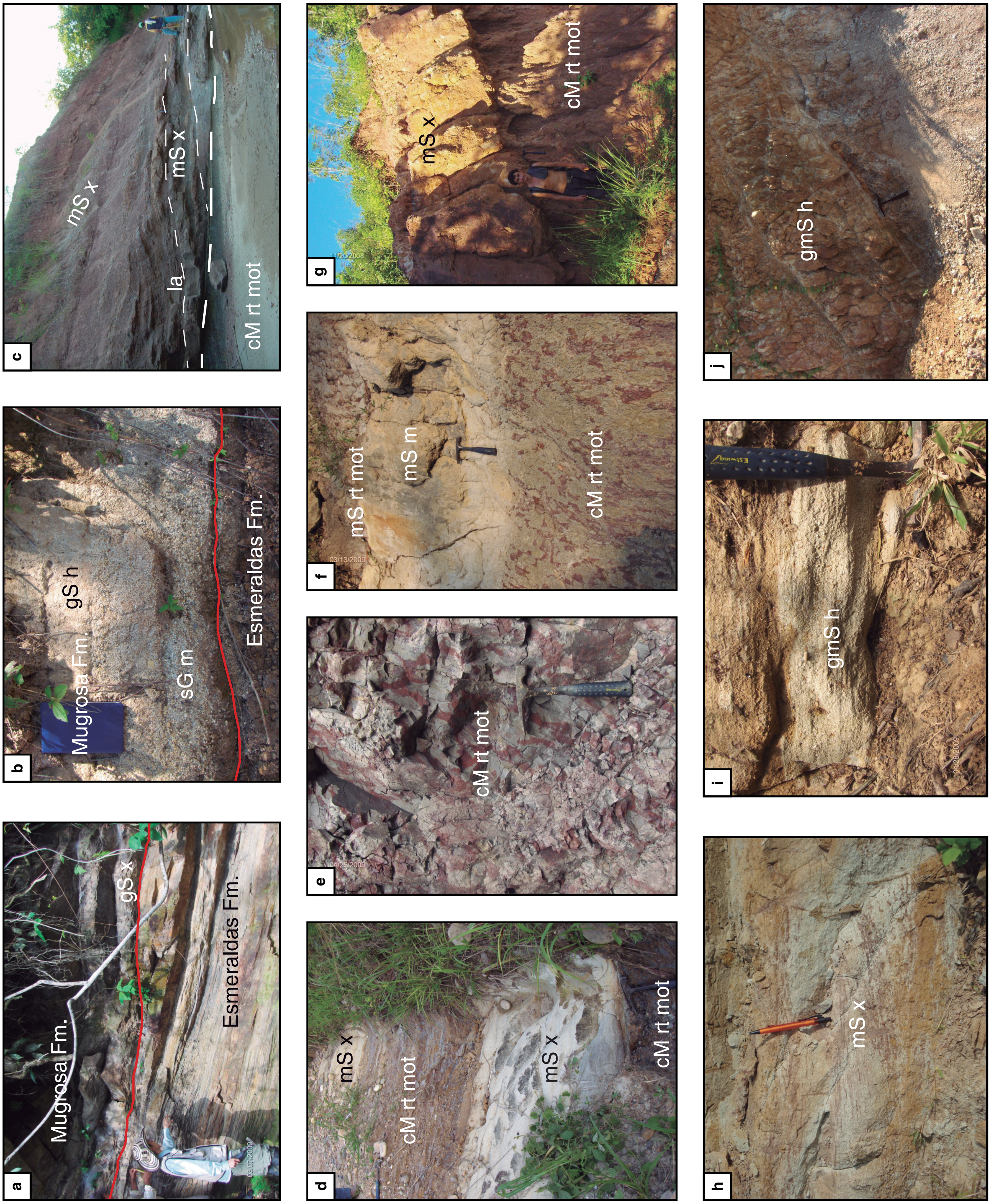
Sedimentary structures: Contains local pyrite nodules; it is located over rooted muddy sandstone or between laminated organic mudstone.

Thickness and contacts: 10 to 80 cm thick coal seams.

Interpretation: Coal forms in swamps or mires in plains. The accumulation of peat (primary material of coal) indicates drowning of a coastal or alluvial plain due to base level rise and a corresponding high water table. These swamps develop vegetation ecosystems that supply large quantities of organic matter. These organic materials deplete the dissolved oxygen in the water, promoting reducing conditions that preserve the organic matter to produce coal during burial.

3.2. Facies Successions (FS) in the Southern Llanos and Nuevo Mundo Syncline

A facies succession is defined as a vertical stack of facies characterized by a progressive change in one or more parameters of the facies, such as thickness, grain size, abundance of sand versus mud, or sedimentary structures (Walker & James, 1992). In the stratigraphic sections presented in this study, the facies successions are the building blocks of the stratigraphic units and are normally repeated several times vertically (i.e., in time). After interpreting the sedimentary processes that deposited each


a
Mugrosa Fm.
gS x
Esmeraldas Fm.
b
gS h
Mugrosa Fm.
sG m
Esmeraldas Fm.
c
mS x
mS x
la
cM rt mot
d
mS x
cM rt mot
mS x
cM rt mot
e
cM rt mot
f
mS rt mot
mS m
cM rt mot
g
mS x
cM rt mot
h
mS x
i
gmS h
j
gmS h

←

Figure 6. Facies in the Oligocene Mugrosa Formation on the eastern limb of the NMS. **(a, b)** Gravelly cross–bedded sandstones (gS x) in 6a; massive sandy conglomerate (sG m) to plane–bedded gravelly sandstone (gS h) in 6b, both overlie lacustrine–estuarine facies of the Esmeraldas Formation (red line is the Eocene/Oligocene unconformity). **(c)** Point bar deposit showing lateral accretion (la) and erosive base over variegated mudstone (cM rt mot); the muddy cross–bedded sandstone (mS x) forms the point bar. **(d, g)** Variegated mudstone (cM rt mot) containing cross–bedded muddy sandstone (mS x) with an erosive contact at the base of the sandstone. **(e)** Rooted mottled mudstone (cM rt mot). **(f)** Massive muddy sandstone (mS m) and rooted and mottled reddish muddy sandstone (mS rt mot) in gradational contact with the underlying variegated mudstone (cM rt mot). **(h)** Muddy trough cross–bedded sandstone (mS x). **(i, j)** Planar–bedded gravelly–muddy sandstone (gmS h) encased in variegated mudstone. (Fm.) Formation.

FS and correlating them with the nearest wells or outcrops, is possible to determine the sedimentary system. The vertical trend of sets of facies successions generally provides important clues about the changes in the depositional system.

The depositional trends are called progradational, retrogradational, or aggradational. Progradational means nonmarine, continental, or proximal facies that shift toward primarily marine, lacustrine, or distal facies; retrogradational means marine, lacustrine, or distal facies that shift toward primarily nonmarine, continental, or proximal facies; and aggradational means that there is no change in depositional trend (Coe, 2003; Catuneanu, 2006). A sedimentary trend can also be erosion and incision or bypass and development of paleosol.

3.2.1. Facies Succession 1 (FS1): Fluvial Braided Deposits

This succession is composed of facies F1 and F2 and consists of an amalgamated fining–upward pebble conglomerate to sandstone that begins with a cross–bedded, imbricated or planar–bedded pebble sandy conglomerate (sG x, sG imb, sG h) followed by a sharp or gradational contact with planar–bedded granule to coarse–grained sandstone or cross–bedded medium– to coarse–grained sandstone (gS h, gS x, S x). Its lower contact is a subaerial unconformity above a strongly developed paleosol (Figures 7, 8).

This facies succession is interpreted as the basic fluvial braided channel bar system with scarce to absent interbedded mudstones. These successions have a fining–upward trend with single story to multistory stacks of coarse sandstones in the Lower Mirador and La Paz Formations. In cores from wells in the foothills and the WSLLB, from base to top, the last cycle of FS1 is overlain by fine– to coarse–grained, yellowish white rooted muddy sandstone (mS rt). The FS1 fluvial facies are inferred to be lower Eocene in the WSLLB, and at Sagú Creek (Figure 7), the overlying shales are early to middle Eocene (De La Parra et al., 2014). In the Nuevo Mundo Syncline, these facies in the La Paz Formation are early Eocene in age (Rodríguez–Forero et al., 2012).

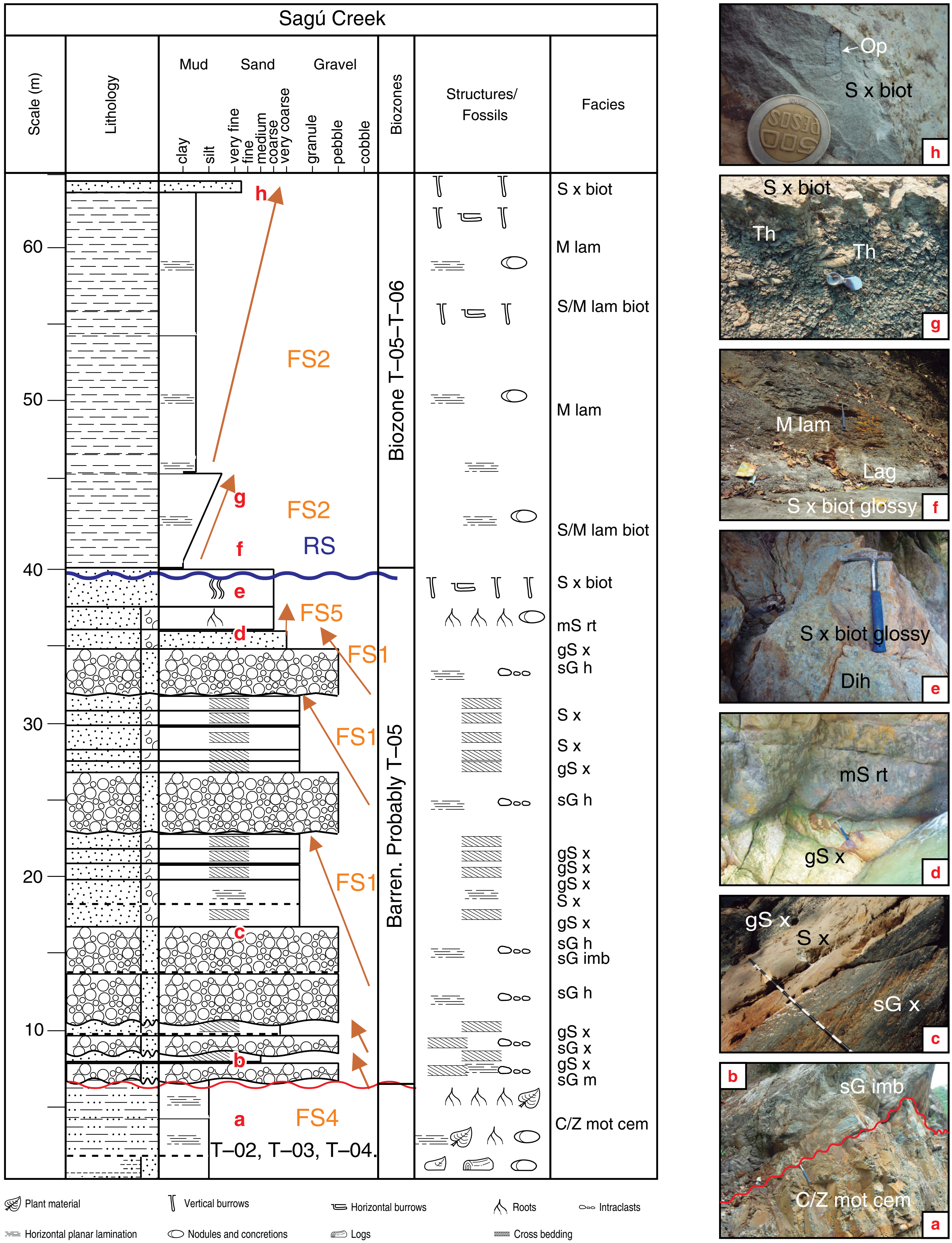
FS1 indicates a low accommodation, high–energy environment with high–gradient rivers that winnow the mud out of the sand and deposit only sand. In the Nuevo Mundo Syncline, however, the La Paz Formation contains some intervals of floodplain mudstones in the middle part of the unit. These floodplain mudstones could be interpreted as high–order fluvial cycles with increased accommodation space (Suárez, 1997) (Figure 12).

3.2.2. Facies Succession 2 (FS2): Shallow Marine Low–Energy Shoreface

This succession is composed of facies F6, F8, F5, and F9. In general, FS2 coarsens upward from a laminated mudstone facies (M lam) that gradually increases in sand to become a laminated to bioturbated sandstone/mudstone (S/M lam biot), which is overlain by fine to very fine–grained, well–sorted sandstone with wavy ripples that is sometimes bioturbated (S r biot). These facies are capped by a bioturbated cross–bedded medium–grained sandstone (S x biot) (Figures 7, 8). The contacts between the facies in the succession are transitional to sharp. In some cases, the contacts consist of laminated mudstone over which there is an increase of sandy interbeds with a wavy lower contact, and the change in grain size from mud to fine sandstone is not gradual but sharp. The change sometimes appears to be from coarse–grained to fine–grained, such as in Figure 9 at the contact with the ravinement surface between 10 and 12 m depth. In the WSLLB, FS2 ranges in thickness from 1 m to 20 m (Figures 7, 8), whereas in the ESLLB, the thicknesses range from less than 1 m to 12 m.

The succession sometimes shows a simple intercalation of laminated mudstone bioturbated by *Planolites* or *Thalassinoides* (M lam) in sharp contact with bioturbated wave ripple–laminated fine–grained sandstone (S r biot). These interbeds are repeated several times upward, such as in well 7 (Figure 9), and they were probably generated during high–frequency cycles of regression/transgression along a low–energy shoreline (Clifton, 2006).

FS2 contains marine palynomorphs such as dinoflagellates and foraminifer linings as well as mangrove pollen (*Lanagiopollis crassa*). According to biostratigraphic studies, the facies in this succession are early – middle Eocene at Sagú Creek (De La Parra et al., 2014), whereas in well 7, the same facies are late Eocene to Oligocene, indicating that FS2 becomes younger to the east of the Llanos Basin.


Sagú Creek
Scale (m)
Lithology
Mud
Sand
Gravel
clay
silt
very fine
fine
medium
coarse
very coarse
granule
pebble
cobble
Biozones
Structures/ Fossils
Facies
60
50
40
30
20
10
h
g
f
e
d
c
b
a
FS2
FS2
RS
FS5
FS1
FS1
FS1
FS4
T–02, T–03, T–04.
Biozone T–05–T–06
Barren. Probably T–05
S x biot
M lam
S/M lam biot
M lam
S/M lam biot
S x biot
mS rt
gS x
sG h
S x
S x
gS x
sG h
gS x
gS x
gS x
S x
gS x
sG h
sG imb
sG h
gS x
sG x
gS x
sG m
C/Z mot cem
Plant material
Vertical burrows
Horizontal burrows
Roots
Intraclasts
Horizontal planar lamination
Nodules and concretions
Logs
Cross bedding
Op
S x biot
h
S x biot
Th
Th
g
M lam
Lag
S x biot glossy
f
S x biot glossy
Dih
e
mS rt
gS x
d
gS x
S x
sG x
c
b
sG imb
C/Z mot cem
a

←

Figure 7. Lower – middle Eocene marginal and marine facies successions of the Mirador and C8 units at Sagú Creek in the foothills. From the base to the top, five cycles of fluvial braided channels and sand bars (FS1) of the Mirador Formation disconformably overlie the Cuervos Formation paleosol (FS4) (the red line indicates the disconformity). The last (FS1) is capped by a coastal plain compound paleosol horizon (FS5). The transgressive erosion surface (RS) eroded a sand bed, in which *Diplocraterion hibachi* (Dih) marks the beginning of the marine transgression. After the ravinement surface, we interpreted two cycles of shallow marine, low–energy shoreline to offshore deposits (FS2) that correspond to the C8 unit. See images of the facies in front of the column. The facies indicated by letters a to h are shown in the right column. (Lag) gravel lag; (Th) *Thalassinoides*; (Op) *Ophiomorpha*.

The vertical trend of FS2 is interpreted as deposition in a shallow marine low–energy foreshore to shoreface system (Clifton, 2006). This facies succession has not been documented in the Eocene – Oligocene rocks of the NMS or in the Middle Magdalena Basin.

3.2.3. Facies Succession 3 (FS3): Backshore Swamp–Lacustrine Fill Deposit

This succession is composed of facies F10, F4, and coal. FS3 is a coarsening–upward succession and begins with dark gray to black carbonaceous mudstone with pyrite that is bioturbated by *Planolites* and sometimes *Thalassinoides* (M org, M lam org), which are in gradational contact with overlying fine–grained sandstone (mS rt), which in turn is overlain by a thin layer of coal that is 5 to 15 cm thick (Figure 9c–f).

In the ESLLB, FS3 overlies a strong greenish white strongly developed paleosol (C/Z mot cem) that represents an unconformity (Figure 3d). In the ESLLB, FS3 is the continental equivalent of the shallow marine FS2 succession in the WSLLB.

FS3 is also present in Oligocene basal sands (Figure 10g) and the C7 and C6 Members of the Carbonera Formation. (Figure 11a5, 11b1, 11c7). In the Lower Oligocene strata in the Llanos Basin, this facies contains high abundances of *Botryococcus* spp. as well as few marine palynomorphs (foraminifer lining tests), suggesting lacustrine to brackish environments.

In the NMS, this succession is scarcely present in the lower–middle section of the La Paz Formation (Figure 4f), the middle section of the Esmeraldas Formation (Figure 12b1), and at the top of this unit in the Los Corros fossil horizon. The palynological record of the Los Corros fossil horizon in the MMB (Figure 12b4) shows a relative abundance of freshwater algae (*Pediastrum* spp., *Botryococcus* spp.), suggesting a lacustrine environment (Rodríguez–Forero et al., 2012).

The carbonaceous mudstone was deposited by vertical accretion in ponded water with a large contribution of vegetal carbonaceous material. This mudstone is a marginal paralic deposit that formed in coastal plain swamps and marshes or along the margins of lacustrine environments (Cecil, 1990). The poorly drained conditions in coastal and fluvial plains can lead to reducing conditions that preserve organic matter (Shanley & McCabe, 1994).

3.2.4. Facies Succession 4 (FS4): Strongly Developed Paleosol

This succession is composed of facies F12. FS4 is composed of white to greenish cream silty claystone that is strongly pedogenized (C/Z mot cem) and kaolinitic in composition. This succession is a very mature and well–developed paleosol composed of ferricrete or silcrete. Root traces, nodules, and crusts are common (Figures 2a, 3d, 9a, 9b). This paleosol is 1 to 6 m thick in some wells in the Llanos Basin, but its thickness is variable across the basin. This paleosol is located at the top of the Paleocene, Cretaceous, or Paleozoic units in cores from the southern Llanos Basin. In the Middle Magdalena Basin, below the La Paz Formation, the equivalent paleosol is varicolored, including whitish gray and violet, sometimes with white vertical pedogenic features and nodules of calcium carbonate.

We interpret this unit to be the result of subaerial exposure of the preexisting substrate and weathering over a long period of time. This type of paleosol forms during periods of landscape degradation and/or episodes of landscape stability that may last more than one million years (Kraus, 1999). This kind of paleosol can form during a period of base level fall; thus, it is called an interfluve paleosol and marks a sequence boundary (Krauss, 1999). The genesis of this kind of paleosol is related to allogenic controls, such as base level changes, global or regional climate changes, and/or regional tectonics.

3.2.5. Facies Succession 5 (FS5): Coastal Plain–Backshore Compound Paleosol

This succession is composed of facies F4, F10, and/or F13. This facies succession includes rooted, muddy, fine– to coarse–grained sandstone (mS rt) covered by a layer of carbonaceous mudstone (M lam org) and/or coal layers. This facies succession is 0.5 m to 4.30 m thick in the lower Eocene rocks of the Mirador Formation in the WSLLB (Figure 8b, 8c), but it is less than 1.5 m thick in the ESLLB (Figure 9e, 9f). The carbonaceous mudstone is bioturbated with *Planolites* and *Glossifungites* below the sandstones of the next depositional cycle in the ESLLB.

Tandon & Gibling (1994) identified this type of profile with studding cyclothems and called them seat earths, which

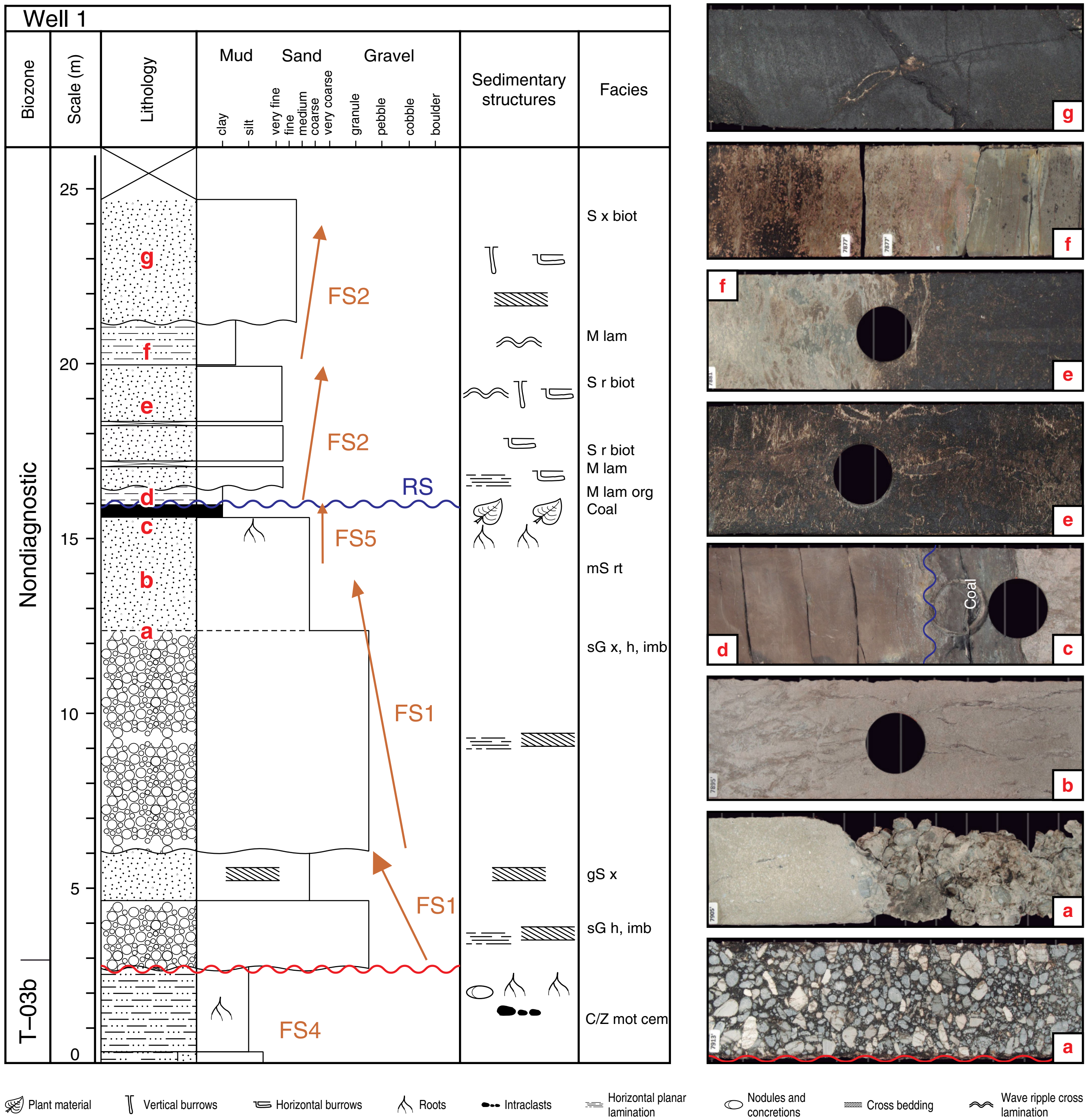


Figure 8. Lower – middle Eocene fluvial marginal and marine facies successions of the Mirador Formation in the WSLLB (well 1). Stacked braided channel and bar sands of the facies succession (FS1) disconformably overlie a strongly developed paleosol (FS4) of the Cuervos Formation. FS1 is capped by a coastal plain compound paleosol horizon (FS5) that is capped by coal. Here, the ravinement surface (RS) erodes the coal bed. After the ravinement surface are two cycles of a shallow marine, low–energy shoreface facies succession (FS2). There is a significant change in thickness of the fluvial facies successions with respect to Sagú Creek (Figure 7). The facies indicated by letters a to g are shown in the right column.

correspond to soils underlying coal seams, but most of them are weakly developed, vertically stacked profiles in aggradational systems (Kraus, 1999). This situation appears to be the case in the southern Llanos Basin and NMS, in which the paleosols developed as sedimentation proceeded. The sedimentation was sporadic and rapid, erosion was insignificant, and pedogenic processes had short periods of time to act on the substrate.

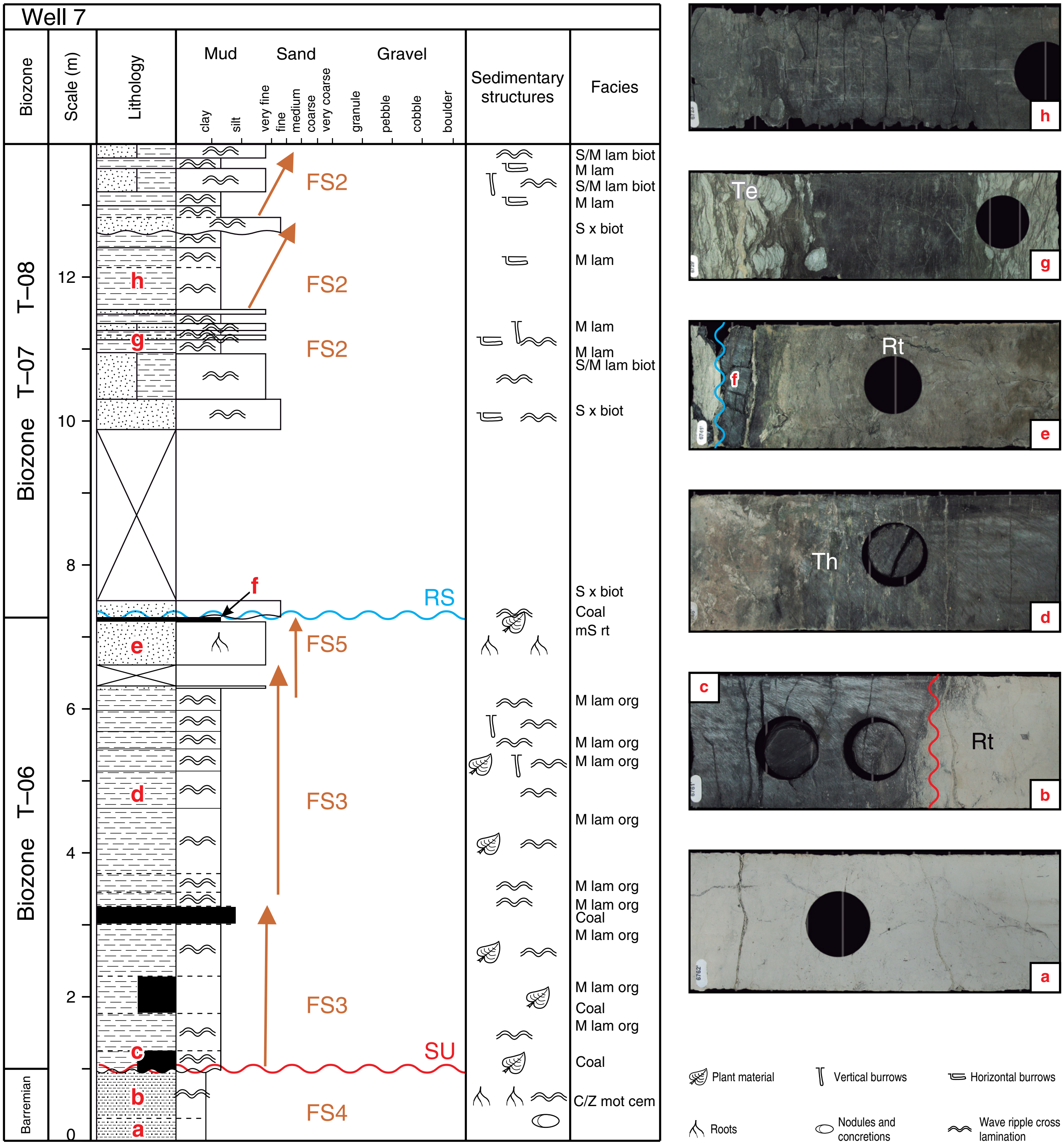
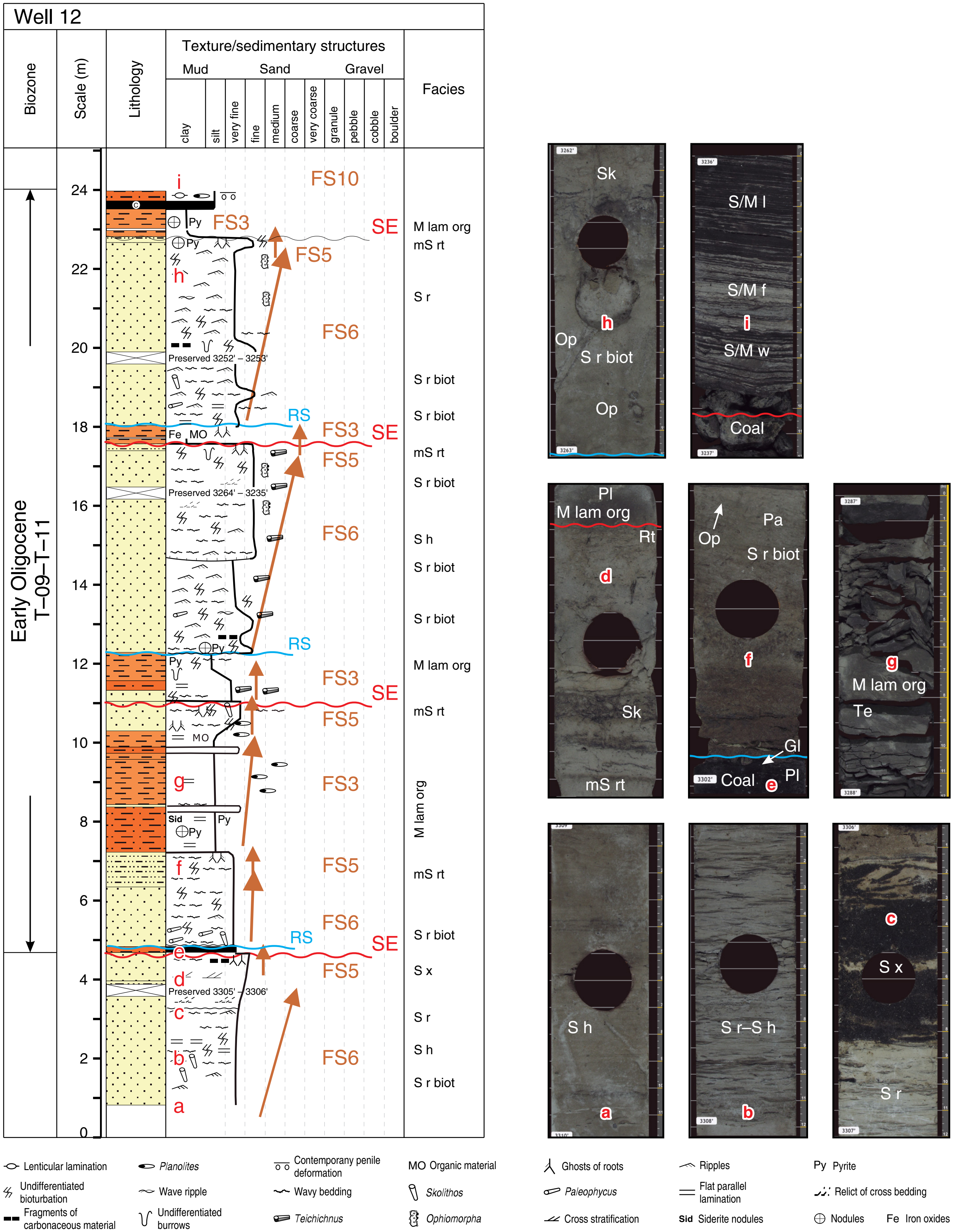


Figure 9. Middle – upper Eocene continental and marginal marine facies in well 7 in the ESLLB. From the base to the top: strongly developed paleosol (FS4) on rocks of the Cuervos Formation (the red line shows the unconformity). Above the unconformity, we interpreted two cycles of backshore swamp–lacustrine deposits (FS3) capped by a coastal plain compound paleosol (FS5). The ravinement surface (blue line) erodes a thin coal layer and marks the beginning of several marine facies successions (FS2). The facies indicated by letters a to h are shown in the right column. (Te) *Teichichnus*; (Th) *Thalassinoides*; (Rt) root traces.

In the studied areas, this facies corresponds to a paleosol profile that developed over a sandstone substrate (abandoned channel deposits or emerged or abandoned sand bars (FS1) in a fluvial system). Eventually, the vegetation that developed the


Well 12
Biozone
Scale (m)
Lithology
Texture/sedimentary structures
Mud
Sand
Gravel
clay
silt
very fine
fine
medium
coarse
very coarse
granule
pebble
cobble
boulder
Facies
Early Oligocene
T–09–T–11
24
22
20
18
16
14
12
10
8
6
4
2
0
FS10
FS3
FS5
FS6
FS3
FS5
FS6
FS3
FS5
FS3
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FS6
FS5
FS6
SE
SE
SE
SE
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RS
Preserved 3252' – 3253'
Preserved 3264' – 3235'
Preserved 3305' – 3306'
Py
Fe
MO
Sid
M lam org
mS rt
S r
S r biot
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mS rt
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S x
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i
Sk
Op
S r biot
Op
S/M l
S/M f
S/M w
Coal
Pl
M lam org
Rt
mS rt
Pa
S r biot
Gl
Coal
Pl
M lam org
Te
S h
S r–S h
S x
S r
Lenticular lamination
Planolites
Contemporany penile deformation
MO Organic material
Ghosts of roots
Ripples
Py Pyrite
Undifferentiated bioturbation
Wave ripple
Wavy bedding
Skolithos
Paleophycus
Flat parallel lamination
Relict of cross bedding
Fragments of carbonaceous material
Undifferentiated burrows
Teichichnus
Ophiomorpha
Cross stratification
Sid Siderite nodules
Nodules
Fe Iron oxides

←

Figure 10. Lower Oligocene basal sandstones of the Carbonera Formation from well 12 in the ESLLB; these strata are coeval with the shales of the C8 Member in the WSLLB. Four facies successions that consist of shoreline successions (FS6) are overlain by a backshore compound paleosol (FS5) separated by subaerial exposure surfaces (SE). The backshore swamp–lacustrine deposit (FS3) oscillates around the compound paleosol (FS5) between the first and second (FS6–FS5) successions. At the top of the core, we interpreted mudstone/sandstone (FS10) as estuarine intertidal flat deposits above an exposure surface. The facies indicated by letters a to i are shown in the right column. (Sk) *Skolithos*; (Op) *Ophiomorpha*; (Pl) *Planolites*; (Rt) root traces; (Pa) *Paleophycus*; (Gl) *Glossifungites*; (Te) *Teichichnus*.

paleosol was preserved as a thin layer of coal or became part of the carbonaceous mudstone once poorly drained conditions occurred because of the rise in the water table.

This paleosol developed on the fluvial braided facies (FS1) (Figure 8b, 8c), but in some wells, the carbonaceous mud or coal is absent because it was eroded by the transgressive erosion surface, such as at Sagú Creek (Figure 7d). In well 7 in the ESLLB, this paleosol profile covers the middle Eocene backshore swamp or lacustrine deposit (FS3) (Figure 9e, 9f). In the easternmost wells of the ESLLB, FS5 is at the top of the prograding shoreline sandstones of the Oligocene basal sandstone member of the Carbonera Formation (Figures 10d, 11a4, 11b6). Finally, this facies succession covers fluvial channel sandstones of the C7 Member of the Carbonera Formation (Figure 11c4, 11c5).

3.2.6. Facies Succession 6 (FS6): Prograding Open Shoreline Succession

This succession is composed of facies F5, F3, and F2. The typical succession is composed of very fine– to fine–grained sandstones with wavy ripples (S r, S r biot) and very fine– to fine–grained sandstones with horizontal laminations (S h, S h biot), which are sometimes bioturbated by *Skolithos*, *Ophiomorpha*, and *Teichichnus*. These fine–grained sandstones are overlain by cross–bedded medium sandstone (S x) (Figure 10a–c). The thickness of the unit succession is between 5 and 8 m, but it repeats several times to reach nearly 40 m of sands. This facies succession is common in the Oligocene basal sandstones of the C8 Member of the Carbonera Formation toward the ESLLB. In some cycles, the shallowing–upward open shoreline succession (FS6) is capped by a coastal plain–backshore compound paleosol (FS5) and then by backshore swamp facies (FS3) (Figures 10a–e, 11a1–a6, 11b3–b6). This facies succession is not present in the NMS.

FS6 is interpreted as a progradational cycle unit, but it contains sets that have a retrogradational pattern as the transgression continues to the east. This succession was deposited during high–frequency cycles of base level rise/fall that generated repeated progradational deposits (Clifton, 2006). FS6 is interpreted as a stacking of high–frequency cycles that occurred during the transgression, probably forming an estuary. This facies could be the marginal or transitional equivalent to the FS2 facies succession, which is composed of subaqueous shoreface deposits.

Its development responds to a balance between sedimentation and base level rise, when sedimentation is greater than base level rise, prograding distributary mouth bars (deltaic settings) or prograding shoreface deposits (open shoreline settings) are present. If sedimentation is less than base level rise, retrogradation of the shoreline occurs, and an estuary forms. If sedimentation is much less than base level rise, the transgression advances toward the continent, putting foreshore–shoreface sandstone over marsh to swamp or backshore deposits through a ravinement surface (Clifton, 2006).

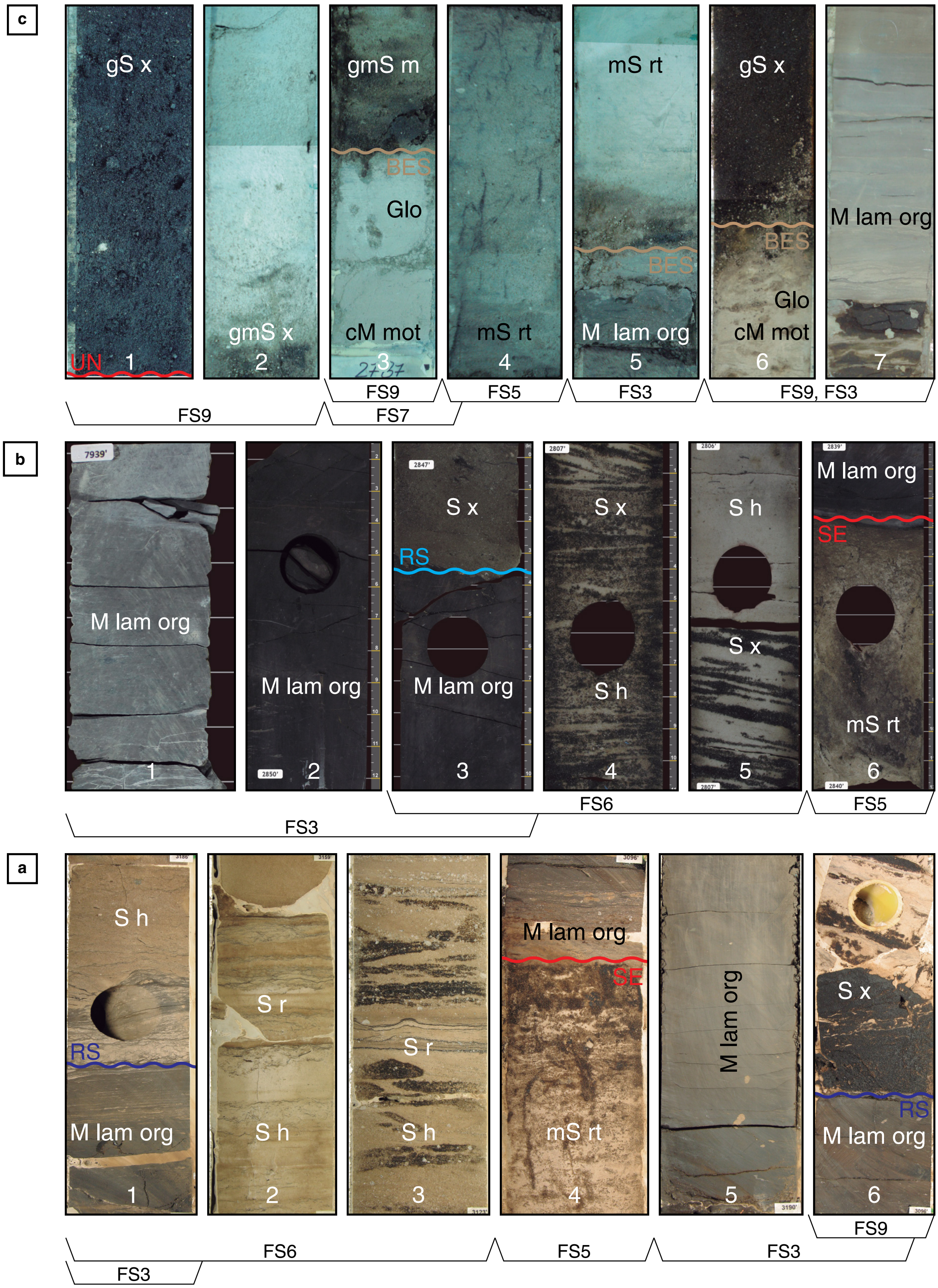
3.2.7. Facies Succession 7 (FS7): Fluvial Floodplain–Cumulative Paleosol

This succession is composed of facies F11 and F4. FS7 consists of variegated clayey mudstone (facies cM rt mot) that is one to 30 meters thick. FS7 is identified by the presence of root traces, bioturbation that masks the primary sedimentary structures, a mottled aspect, and very thick intervals. FS7 commonly includes rooted mottled muddy fine to coarse sandstone (mS rt) interlayered within variegated mudstones (Figures 5c, 6f).

In the NMS, the floodplain deposits begin to appear in the lower Eocene lower–middle section of the La Paz Formation (Figure 12a2) and continue in the lower part of the Esmeraldas Formation (Figure 12b1) FS7 resumes in the Oligocene rocks of the Mugrosa Formation and continues in the units above (Figure 13).

FS7 was deposited in a fluvial floodplain. The interlayering with rooted muddy sandstones (mS rt mot) is typical of crevasse splay and flooding events that were deposited on the floodplain. Simultaneously with the steady sedimentation, pedogenesis occurred by subaerial exposure and development of vegetation with low rates of erosion. Because floodplains are regularly flooded over geologic time, this process decreases the rate of pedogenesis (Krauss, 1999).

The varicolored or variegated color was produced by oscillation of the water table on the floodplain and concomitant oxidation or reduction of the soil, producing ferric or ferrous iron, respectively. Gray colors (reducing conditions) formed when the water table was high and the substrate was drowned, whereas red, orange, or yellow colors (oxidizing conditions) occurred when the water table was low and air entered the well–drained soil.


c
gS x
UN
1
2
gmS x
gmS m
BES
Glo
cM mot
3
mS rt
4
mS rt
BES
M lam org
5
gS x
BES
Glo
cM mot
6
M lam org
7
FS9
FS5
FS3
FS9, FS3
FS9
FS7
b
7939'
M lam org
1
M lam org
2850'
2
2847'
S x
RS
M lam org
3
2807'
S x
S h
4
2806'
S h
S x
2807'
5
2839'
M lam org
SE
mS rt
2840'
6
FS6
FS5
FS3
a
S h
RS
M lam org
1
S r
S h
2
S r
S h
3
M lam org
SE
mS rt
4
M lam org
5
S x
RS
M lam org
6
FS9
FS6
FS5
FS3
FS3

←

Figure 11. (a, b) Oligocene basal sandstones of the Carbonera Formation in the ESLLB (see location in Figures 1 and 15). **(c)** Is from the C7 Member of the Carbonera Formation. **(a)** Well 10 showing, from left to right, backshore swamp–lacustrine deposits (FS3) eroded by a ravinement surface (RS). Above the RS is a prograding shoreline succession (FS6) capped by a coastal plain–backshore compound paleosol (FS5), which indicates subaerial exposure (SE). After the SE, backshore swamp–lacustrine deposits (FS3) complete a prograding cycle. Another cycle begins at the ravinement surface below a mouth bar sandstone (FS9). These cycles are 5–8 m thick. **(b)** Well 11 showing, from left to right, the same cycle as that described previously: backshore swamp–lacustrine deposits (FS3) eroded by a ravinement surface and overlain by a prograding shoreline succession (FS6) capped by a coastal plain–backshore compound paleosol (FS5), indicating subaerial exposure, and then, backshore swamp or lacustrine mudstone (FS3). **(c)** Well 13 showing the C7 Member of the Carbonera Formation. The base of C7 is an unconformity (UN), and the unit consists of fluvial cycles that begin on a basal erosion surface (BES). From left to right, fluvial channel and bar sandstones (FS9) are capped by a coastal plain–backshore compound paleosol (FS5) and then backshore swamp or lacustrine mudstone (FS3) or floodplain cumulative paleosol (FS7). (Glo) *Glossifungites*.

3.2.8. Facies Succession 8 (FS8): Crevasse Splay to Sheetflood Deposits

This succession consists of facies F2, F3, and F4. FS8 is composed of planar–bedded, massive or small–scale cross–stratified sandstone (mS h, mS m, S x, mS rt) and sometimes rooted sandstone in gradational contact with the variegated mudstones (cM m, cM rt mot, cM lam) of the cumulative paleosol (FS7). These sandstone beds have limited lateral extents of tens of meters. Crevasse splay successions are less than 1 m thick and up to 6 m thick when stacked (Figure 13b, 13c). These deposits do not have evidence of erosion, and because they are unconfined, there is no evidence of sand bar development. The sedimentary structures change upsection from planar/massive bedding to ripple lamination.

In the lower and middle section of the Esmeraldas Formation (Figure 12b1) and Oligocene Mugrosa Formation (Figure 6f, 6i, 6j), FS8 includes beds of muddy sandstone or gravelly muddy sandstone with planar or massive bedding (mS h, mS m) over floodplain mudstones (FS7).

The association with floodplain mudstones and the limited thickness and lateral extent are interpreted as evidence of crevasse splays in a fluvial system or sheetflood deposits in alluvial fan and fluvial plain systems. Some channels form sandstone bodies in erosive contact with floodplain mudstones, and the scour and fill structures can be interpreted as distributary channels in an alluvial fan (Figure 13d). Planar bed deposits or massive muddy sand sheets between the floodplain mudstones are interpreted as sediment gravity flows, such as sheetflow deposits associated with hyperconcentrated flows (Figure 13c) (Blair & McPherson, 1994).

3.2.9. Facies Succession 9 (FS9): Fluvial Meandering Channel and Bar Deposits

This succession consists of facies F1, F2, and F5. FS9 consists of facies (gmS x or mS m) with erosive bases (in most cycles, only a conglomeratic lag) followed by trough cross–bedded, very coarse–grained sandstone to planar cross–bedded medium–grained sandstone (S x), and finally current ripple sandstone (S r) or a compound paleosol (FS5).

The progression from large–scale trough cross–bed sets to smaller–scale planar cross–bed sets in sandstone and to finer–grained ripple sandstone is attributed to waning flow on a point bar of a meandering channel. These point bars form along the concave part of a meander by helicoidal flow in the channel that erodes the outer concave bank toward the inner convex bank. This helical flow component transports sediment up the sloping bank and adjacent point bars. Only gravel is deposited in the base of the channel; the remaining sediment is transported laterally to construct a point bar (Boggs, 1987).

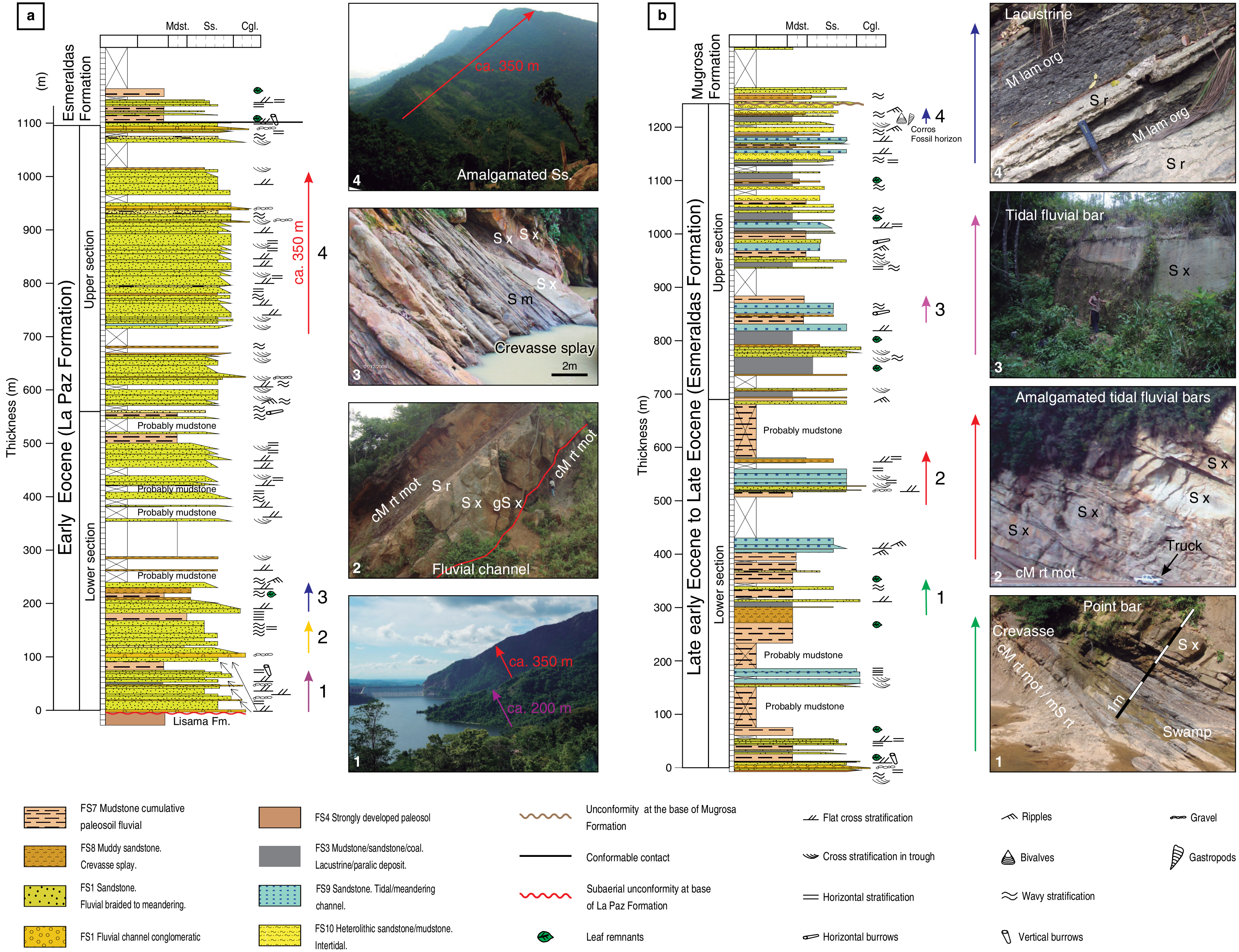
This facies succession was interpreted in the C7 Member of the Carbonera Formation in the ESLLB (Figure 11c), which contains a typical fining–upward succession from erosional lag, channel, floodplain, and/or crevasse deposits.

FS9 was observed in the NMS at the top of the lower section of the La Paz Formation, where it is 5 to 14 m thick (Figure 12a2). In the Esmeraldas Formation, it is 3 to 30 m thick and is tidally influenced (Figure 12b2, 12b3), and in the Oligocene Mugrosa Formation, it is 1 to 3 m thick (Figure 13f).

3.2.10. Facies Succession 10 (FS10): Estuarine Intertidal Deposits

This succession consists of facies F5, F7, and F10. FS10 is composed of current ripple–laminated fine sandstone (S r) in beds less than 1 m thick, sometimes with bidirectional cross–laminations (Figure 5e). FS10 contains layers of heterolithic sandstone/mudstone (S/M), which consists of fine– to very fine–grained well–sorted sandstones interlayered with medium gray mud and rhythmic with wavy (S/M w), lenticular (S/M l), and flaser laminations (S/M f) approximately 1 to 10 m thick. This facies also includes thick layers of carbonaceous mudstone (M lam org) (Figure 5f).

This facies was deposited in an estuarine intertidal flat environment, where sand layers accumulated during periods of current activity, and mud accumulated during slack water periods


a
Thickness (m)
Early Eocene (La Paz Formation)
Esmeraldas Formation
Upper section
Lower section
Mdst.
Ss.
Cgl.
Probably mudstone
Lisama Fm.
ca. 350 m
Amalgamated Ss.
S x
S m
Crevasse splay
2m
cM rt mot
S r
gS x
Fluvial channel
ca. 200 m
b
Late early Eocene to Late Eocene (Esmeraldas Formation)
Mugrosa Formation
Corros Fossil horizon
Lacustrine
M lam org
Tidal fluvial bar
Amalgamated tidal fluvial bars
Truck
Point bar
Crevasse
cM rt mot / mS rt
Swamp
1m
FS7 Mudstone cumulative paleosoil fluvial
FS8 Muddy sandstone. Crevasse splay.
FS1 Sandstone. Fluvial braided to meandering.
FS1 Fluvial channel conglomeratic
FS4 Strongly developed paleosol
FS3 Mudstone/sandstone/coal. Lacustrine/paralic deposit.
FS9 Sandstone. Tidal/meandering channel.
FS10 Heterolithic sandstone/mudstone. Intertidal.
Unconformity at the base of Mugrosa Formation
Conformable contact
Subaerial unconformity at base of La Paz Formation
Leaf remnants
Flat cross stratification
Cross stratification in trough
Horizontal stratification
Horizontal burrows
Ripples
Bivalves
Wavy stratification
Vertical burrows
Gravel
Gastropods

←

Figure 12. Fluvial facies successions of the La Paz and Esmeraldas Formations in the Sucio River, eastern flank of the NMS. **(a)** La Paz Formation fluvial facies successions, including from the base to the top: (1) stacked cycles of single–story to multistory braided channels and bars (FS1); (2) single channel fill and floodplain cumulative paleosol (FS9, FS7); (3) crevasse splay floodplain swamp facies succession (FS8, FS7); and (4) stacked braided channel and bar facies successions (FS1). **(b)** Esmeraldas Formation coastal plain to lacustrine successions. From base to top: (1) fluvial meandering point bar crevasse and floodplain swamp facies (FS9, FS7); (2, 3) 4–8 m thick meandering tidal unit bar; and (4) backshore swamp–lacustrine fill deposit (FS3) in a lacustrine to fluvial tidal environment (FS10). (Mdst.) mudstone; (Ss.) sandstone; (Cgl.) conglomerate; (Fm.) Formation.

(Reineck & Singh, 1973, Nio & Yang, 1991). In the NMS, FS10 is described in the Esmeraldas Formation. The interpretation of an estuarine environment is strengthened by the discovery of stromatolitic structures in the sandstones of the Esmeraldas Formation (Figure 5i). In the Llanos Basin, this facies succession is present in the C8 Member of the Carbonera Formation (Figure 10i).

The deposition of mud and sand in these strata requires that both sand and mud were available in the environment and that periods of current activity alternated with periods of still water (Reineck & Singh, 1973). These environments occur when base level rises near a river mouth, the mouth is flooded, and the deposits are tidally influenced (Boyd et al., 2006).

The difference with the laminated and bioturbated sandstone/mudstone (S/M lam biot) described previously is the preservation and type of sedimentary structures. In the S/M lam biot facies, organic structures predominate over the physical structures, which are wavy to horizontal laminations, whereas in the S/M w, l, f facies, physical structures predominate over organic structures, and the physical structures are flaser, lenticular, and wavy bedding. Another difference is the ichnogenera present in the S/M lam biot, which is not present in the S/M w, l, f facies.

3.3. Distribution of Facies, Stratigraphic Surfaces, and Facies Trends

We first identify and describe the correlation surfaces that have stratigraphic significance because these surfaces mark changes in facies and define the architecture of the bodies of the rocks in the Llanos Basin and MMB. Facies trends refer to how facies change over time, and the changes are recorded in the bounding surfaces; these changes could be from erosion, aggradation, progradation, or retrogradation. All of these changes are responses of the sedimentary system to the controls of tectonics, eustasy, and climate as reflected in base level change or relative sea level change (Catuneanu, 2006).

The distributions of the facies in the two study areas were determined by sequence stratigraphic correlations supported by available biostratigraphy data (biozones) and the facies analysis and successions described previously to develop a sequence stratigraphic framework.

3.4. Stratigraphic Surfaces and Markers

3.4.1. Interfluvial Paleosol below the Subaerial Unconformity

The strongly developed paleosol (FS4) is a stratigraphic marker in the studied basins. The strongly developed paleosol is located below the subaerial unconformity at the base of the Lower Mirador and La Paz Formations. The paleosol drapes an interfluvial ancient landscape in the southern Llanos Basin and NMS and was identified on the Paleocene, Cretaceous, Paleozoic, and older rocks in the southern Llanos Basin (Figure 15) and over Jurassic and Cretaceous rocks on the La Cira–Infantas–Sogamoso Paleohigh in the MMB (Figure 18). This paleosol may have been eroded in the main trunk valleys in the ancient fluvial landscape.

3.4.2. Subaerial Unconformity at the Base of the Mirador and La Paz Formations

The subaerial unconformity (SU) at the base of the Mirador Formation is present in all of the wells studied in the southern Llanos Basin and foothills of the Eastern Cordillera. This surface is located above the mature, well–developed FS4 paleosol. The subaerial unconformity is diachronous because it puts upper Paleocene rocks in contact with lower Eocene rocks in the foothills and WSLLB, but in the ESLLB, it puts upper Paleocene rocks in contact with middle Eocene or younger rocks to the east (Figures 14, 15).

The subaerial unconformity at the base of the La Paz Formation is identified by its lacuna with the units below, especially in the western part of the MMB (Rodriguez–Forero et al., 2012). In the NMS, the basal conglomerates of FS1 from the La Paz Formation are in erosive contact with the Lisama Formation (Figures 16, 17). In the MMB, the unconformity is an erosive and diachronous surface that truncates Paleocene, Jurassic, and Cretaceous rocks on the axial La Cira–Infantas–Sogamoso Paleohigh (LCISP) in the Magdalena Valley and the basement rocks in the Central Cordillera (Figure 18) (Suárez, 1997; Gómez et al., 2003, 2005a).

3.4.3. Transgressive Ravinement Surface

The transgressive erosion surface or transgressive ravinement surface (Catuneanu, 2006) puts the fining–upward facies suc-

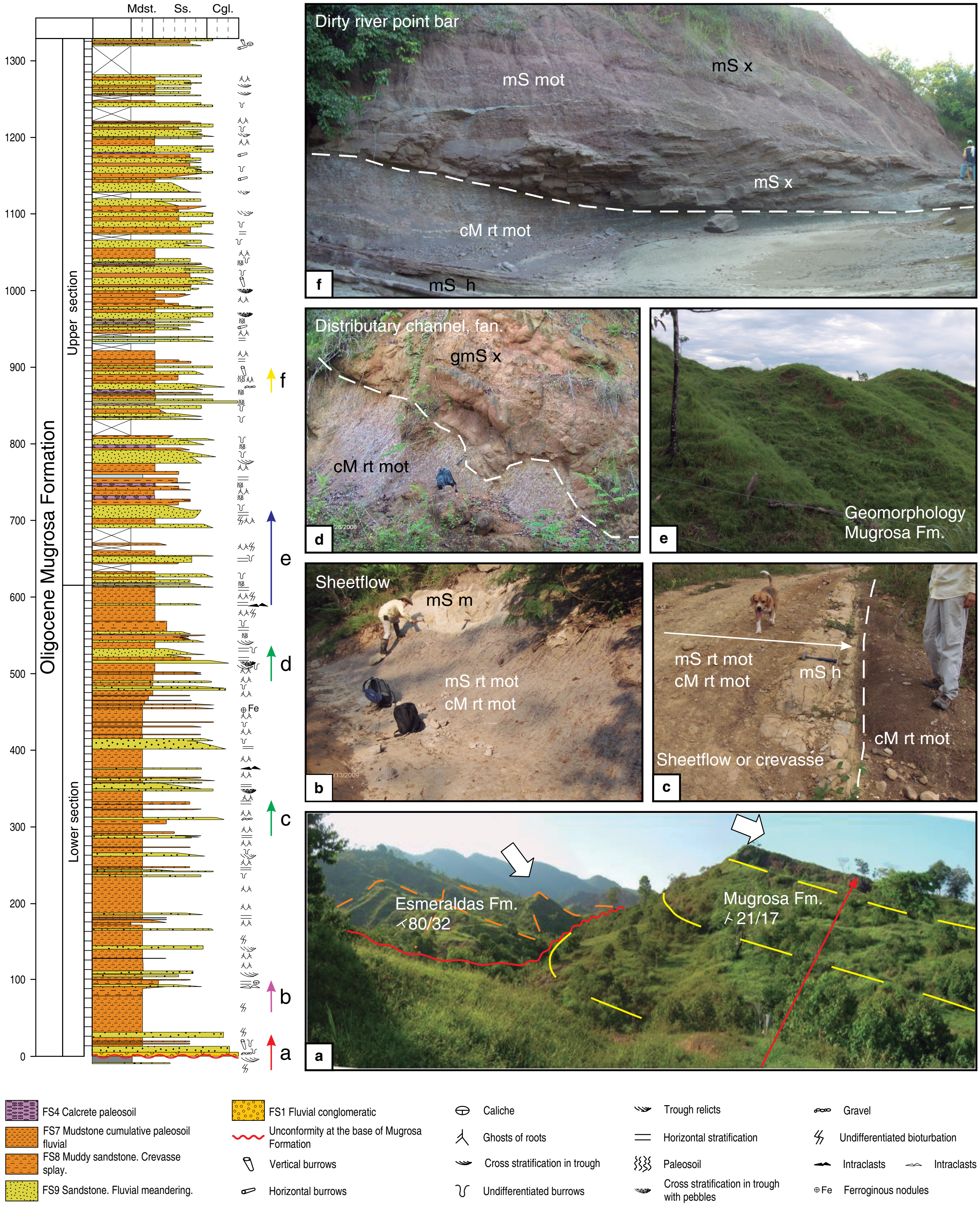

Mdst.
Ss.
Cgl.
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Oligocene Mugrosa Formation
Upper section
Lower section
Fe
f
e
d
c
b
a
Dirty river point bar
mS mot
mS x
mS x
cM rt mot
mS h
f
Distributary channel, fan.
gmS x
cM rt mot
d
e
Geomorphology
Mugrosa Fm.
Sheetflow
mS m
mS rt mot
cM rt mot
b
mS rt mot
cM rt mot
mS h
cM rt mot
Sheetflow or crevasse
c
Esmeraldas Fm.
80/32
Mugrosa Fm.
21/17
a
FS4 Calcrete paleosoil
FS7 Mudstone cumulative paleosoil fluvial
FS8 Muddy sandstone. Crevasse splay.
FS9 Sandstone. Fluvial meandering.
FS1 Fluvial conglomeratic
Unconformity at the base of Mugrosa Formation
Vertical burrows
Horizontal burrows
Caliche
Ghosts of roots
Cross stratification in trough
Undifferentiated burrows
Trough relicts
Horizontal stratification
Paleosoil
Cross stratification in trough with pebbles
Gravel
Undifferentiated bioturbation
Intraclasts
Intraclasts
Fe Ferroginous nodules

Figure 13. Oligocene fluvial to alluvial facies successions in the NMS. The lower section of the Mugrosa Formation is mainly composed of variegated to reddish brown floodplain deposits (FS7) with embedded thin fluvial channel sandstones (FS9) and a crevasse splay or sheetflood succession (FS8). In general, the Mugrosa Formation is a coarsening–upward alluvial plain succession. **(a)** Field view of the unconformity between the Mugrosa Formation and the overlying Esmeraldas Formation (red line) on the western limb of the NMS. **(b, c)** Solitary sheetflow deposit (FS8) interbedded with floodplain deposits (FS7). **(d)** Fluvial channel facies FS9 scouring and filling fluvial flood plain cumulative paleosol FS7. **(e)** Present geomorphology after subaerial exposure of the Mugrosa Formation. **(f)** Meander point bar deposit FS9 eroding fluvial floodplain cumulative paleosols of FS7 which overlay crevasse splay deposits FS8. (Mdst.) mudstone; (Ss.) sandstone; (Cgl.) conglomerate; (Fm.) Formation.

cession of the Lower Mirador below (Figures 7, 8) in contact with coarsening–upward, shallow marine facies successions of the Upper Mirador Formation and the lower C8 Member of the Carbonera Formation above. The transgressive ravinement surface is a diachronous surface. In the WSLLB, this event occurs in the middle Eocene and erodes lower Eocene fluvial deposits, whereas in the ESLLB, it occurs during the late Eocene and reworks the previous subaerial unconformity in wells 5, 6, and 8 (Figures 14, 15).

In the Middle Magdalena Valley, the facies contact between the La Paz and Esmeraldas Formations corresponds stratigraphically to the ravinement surface in the southern Llanos Basin. However, in the NMS, the contact is conformable and marks a change in facies and stacking pattern from multistory braided fluvial sandstones to floodplain cumulative paleosols. This change is from facies successions deposited under low accommodation conditions in the La Paz Formation to a facies succession deposited under high accommodation conditions in the Esmeraldas Formation.

3.4.4. Flooding Surfaces

Three maximum flooding events formed maximum flooding surfaces (MFSs) in the southern Llanos Basin. The MFSs can be identified in wells and delineated by identifying the maximum peaks in the gamma ray logs and by changes in the log patterns. These maximum flooding surfaces occur in the lower and upper parts of the C8 Member and the upper part of the C6 Member of the Carbonera Formation. At least two of them are truncated by the overlying unconformities.

The MFS in the lower C8 Member of the Carbonera Formation coincides roughly with the Eocene – Oligocene boundary. This MFS is truncated by the unconformity at the base of the Oligocene basal sandstones (Figure 15). The MFS in the upper C8 Member of the Carbonera Formation is truncated by the unconformity at the base of the C7 Member (Figure 15). The latest Oligocene MFS within the C6 Member of the Carbonera Formation is at the top of the sandstones of the C6 Member of the Carbonera Formation. Its continuity eastward was not determined in this work, but it may be truncated to the east.

In the Nuevo Mundo Syncline, the maximum flooding surface was interpreted to occur during a period of high accommodation space within the lacustrine coastal plain facies (FS3) and estuarine intertidal facies (FS10) of the Esmeraldas Formation, roughly corresponding with the Los Corros fossil horizon (Figures 12b4, 16). The fossil markers of Los Corros, Mugrosa, and Cira have been reported as flooding events in the MMB (Morales, 1958; Gómez et al., 2005a).

3.4.5. Oligocene Unconformities in the Carbonera and Mugrosa Formations

The lower lower Oligocene unconformity at the base of the basal sandstones of the C8 Member of the Carbonera Formation in the ESLLB is an erosive contact between the Oligocene basal sandstones above the shales of the lower segment of the C8 Member of the Carbonera Formation (Figure 14). This surface marks a change in the stacking patterns and a transposition of facies from coarsening–upward marine facies to fining–upward open shoreline to fluvial and estuarine facies in the basal sandstones. This unconformity was previously identified in the foothills and in the WSLLB at the base of the T1, an operational name for the basal sandstones of the Carbonera Formation (Malagón, 1997) (Figure 15).

The upper lower Oligocene unconformity is at the base of the C7 Member of the Carbonera Formation and corresponds to an erosive contact, a transposition of facies, and a change in the stacking pattern from coarsening–upward shelf mudstones and sandstones (FS2) of the upper C8 Member to fining–upward fluvial facies (FS1–FS5) of the C7 Member. This unconformity is observed in the GR pattern, especially in the eastern part of the Llanos Basin (Figure 15). This surface is not well constrained in the central part of the basin and the ESLLB.

The Mugrosa–Esmeraldas contact is an unconformity that occurs at the Eocene – Oligocene boundary. On the eastern limb of the NMS, this unconformity is erosive with the Esmeraldas Formation truncated by fluvial facies (FS1) of the overlying Mugrosa Formation (Figure 6a). There is a facies transposition from lacustrine and tidal flat estuarine facies (FS3–FS9) of the Esmeraldas Formation to alluvial facies (FS1, FS7, FS8) of the Mugrosa Formation. On the western limb, the Mugrosa Formation overlaps the Esmeraldas Formation on what has been reported as a growth unconformity (Gómez et al., 2005a) (Figure 13a). In the MMB, this unconformity was previously identified as a regional unconformity at the base of tectonosequence 2 of Suárez (1997) (Figure 17a, 17b, 17c).

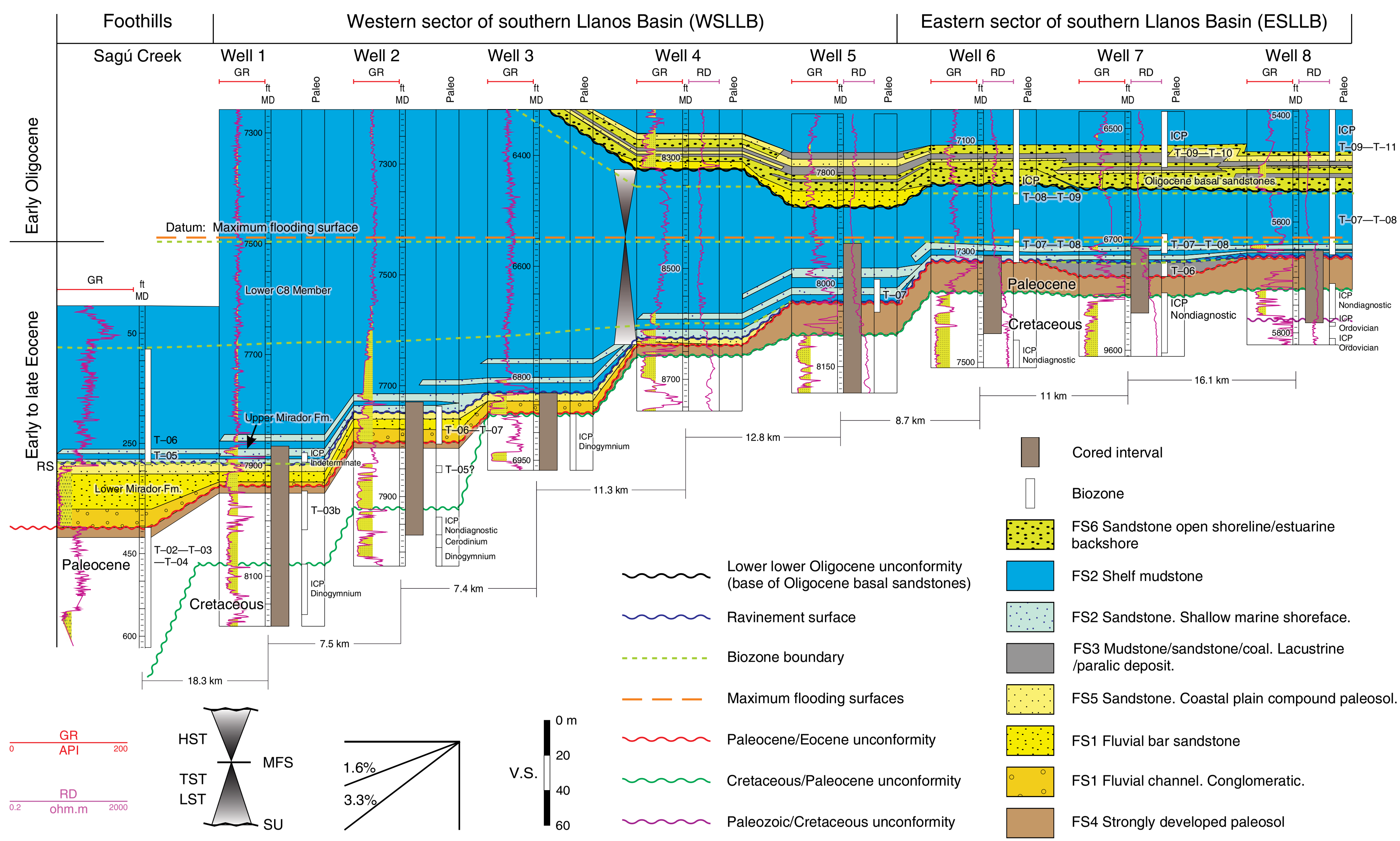


Figure 14. Distribution of facies in the southern Llanos Basin. The strongly developed paleosol (FS4) is diachronous and puts upper Paleocene rocks in contact with lower Eocene rocks in the WSLLB and upper Paleocene rocks in contact with Oligocene rocks in the ESLLB. The Lower Mirador Formation becomes younger to the east and includes fluvial to marginal sediments (FS1, FS5) of early – middle Eocene age. The middle Eocene backshore swamp and lacustrine facies cover the relief of the unconformity in well 7. The ravinement surface erodes the Lower Mirador Formation and records the onset of a marine transgression across the basin. The marine facies include facies successions (FS2) that preserved a pre–Eocene landscape. In the earliest Oligocene, several foreshore–backshore facies successions (FS6, FS3), called the Oligocene basal sandstones here, advanced westward. These are part of the C8 Member of the Carbonera Formation in the WSLLB. The correlation datum is the maximum flooding surface at the Eocene – Oligocene boundary. (GR) gamma ray; (MD) measured depth; (RD) deep resistivity; (ICP) Instituto Colombiano del Petróleo; (Fm.) Formation; (HST) highstand systems tract; (MFS) maximum flooding surface; (TST) transgressive systems tract; (LST) lowstand systems tract; (SU) subaerial unconformity.

3.5. Facies Trends in the Eocene – Oligocene

3.5.1. Early Eocene: Lower Mirador and La Paz Formations

The Lower Mirador and La Paz Formations consist of amalgamated braided channel–fill sandstones (FS1) above a subaerial unconformity. FS1 fines upward and forms an aggradational multistory sandstone complex with scarce floodplain deposits (Figures 7, 8, 12a1). The Lower Mirador and La Paz Formations lap onto (fluvial onlap; Catuneanu, 2006) the subaerial unconformity (Figures 14, 18). The Lower Mirador Formation is capped by an erosion surface, which is the ravinement surface. In the southern Llanos Basin, these braided facies are covered by a sandy coastal plain backshore compound paleosol (FS5), and in the NMS, the fluvial facies of the La Paz Formation are covered by a muddy floodplain cumulative paleosol (FS7) (Figures 14, 16).

The Lower Mirador wedge is 35 m thick at Sagú Creek and pinches out in well 4, 38 km to the east (Figure 14). In the MMB, the La Paz Formation was deposited on both margins of the basin and pinches out above the axial La Cira–Infantas–Sogamoso Paleohigh. The western wedge is 580 m thick near the Cantagallo Fault and pinches out above the LCISP, approximately 18 km to the east. The eastern wedge is 1090 m thick on the eastern limb of the NMS and pinches out 38 km to the west above the axial LCISP (Figure 18) (Suárez, 1997; Gómez et al., 2005a; Caballero, 2010).

The porosity and permeability were measured in several conglomerates of the Lower Mirador Formation in the southern Llanos Basin. The porosity of the basal muddy conglomerates of the Mirador Formation varies from 6.4 to 9.1%, and the permeability is very low (0.8–0.81 mD). These properties are very different in the fluvial multistory sandstones of the Lower Mirador Formation; the porosity is 10–20 %, and the permeability is 100–10 000 mD.

The porosity and permeability in the La Paz Formation in the eastern part of the MMB vary from 10 to 20% and from 100 to 1500 mD, respectively. In the Provincia Field, these properties vary from 8 to 16.7% and from 13.6 to 409.2 mD, respectively (Suarez, 1997). The Cantagallo sandstones, which are the equivalent of the La Paz Formation in the western part of the MMB, have porosities of 15–25 % and permeabilities of 100–1000 mD.

The porosity of the fluvial facies of the Mirador Formation in the Cusiana Field varies from 7.7 to 11.7%, and the permeability varies between 33.4 and 402 mD, although these values differ in different high–frequency cycles (Fajardo, 1995).

3.5.2. Middle to Late Eocene and Earliest Oligocene: Upper Mirador Formation, Lower C8 Member of the Carbonera Formation

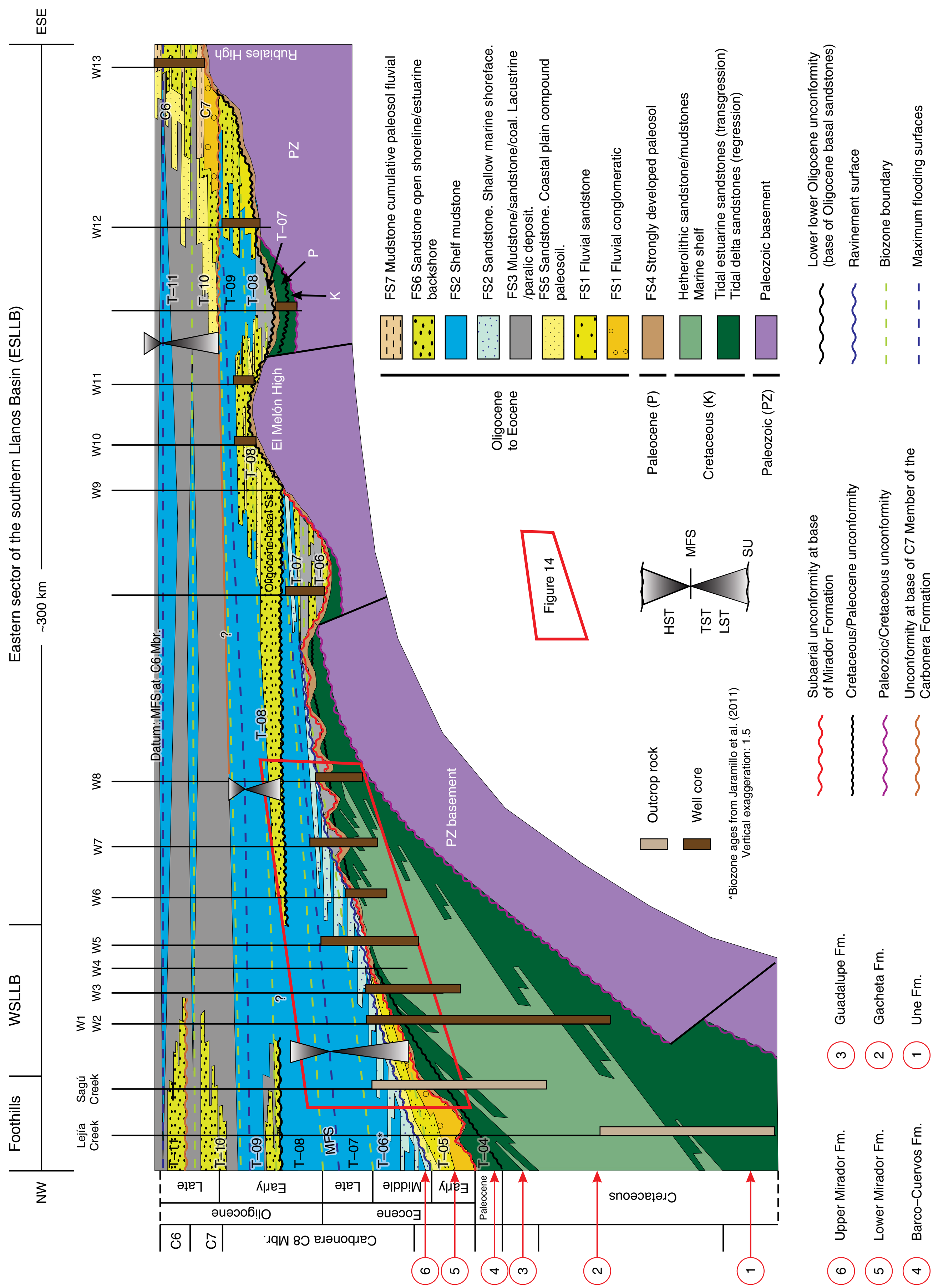
During the middle Eocene, coarsening–upward, shallow marine low–energy shoreface facies (FS2) were deposited in the foothills and the WSLLB, whereas backshore swamp to lacustrine facies (FS3) were deposited in the topographic lows of the interfluvial area of the ESLLB (see well 7 in Figure 14). The marine facies lap onto the ravinement surface above the Lower Mirador Formation in the WSLLB, and the backshore swamp to lacustrine facies lap onto the subaerial unconformity above the strongly developed paleosol (FS4) in the eastern part of the ESLLB. By the late Eocene and earliest Oligocene, FS2 reached the El Melón High to the east, onlapping the previous backshore facies and the paleosol (FS4) on the topographic highs. The maximum flooding surface formed at the end of the Eocene. After the maximum flooding surface, deposition of progradational facies (FS2) of the C8 Member of the Carbonera Formation resumed, but they were truncated by the lower lower Oligocene unconformity at the base of the Oligocene basal sands in the El Melón High (Figures 14, 15).

This landward shift of the facies forms a transgression with a retrogradational stacking pattern, in which high–order coarsening–upward facies (FS2) lap onto the ravinement surface and advance toward the margins of the basin. These lithologies preserve part of a previous landscape that was created in the late Paleocene in the ESLLB (Figures 14, 15). This wedge–shaped transgressive unit is 213 m thick in well 1 and pinches out on the El Melón High (Well 9) approximately 110 km to the east (Figure 15).

The porosity varies from 5 to 7%, and the permeability varies from 1 to 60 mD in the medium– to fine–grained, cross–bedded, bioturbated sandstones facies of the Upper Mirador Formation in the Cupiagua Oil Field (Ramon & Fajardo, 2006). In the southern Llanos Basin, the Upper Mirador sandstones have porosities between 5 and 15% and permeabilities of 0.1–100 mD. Adjacent to the El Melón High in the ESLLB, the porosity of FS2 in the upper Eocene sandstones is 20–25 %, and the permeability is 100–10 000 mD.

3.5.3. Middle – Upper Eocene: Esmeraldas Formation

In the Middle Magdalena Valley, the Esmeraldas Formation consists of fluvial meandering channel and bar sandstones (FS1) and fluvial floodplain–cumulative paleosols (FS7), which transition to very thick fluvial tidally influenced meandering channels and bar sandstones (FS9) intercalated with fluvial tidally influenced floodplain or intertidal deposits (FS7, FS10) with a retrogradational trend. These facies then transition to intertidal sandstones/mudstones (FS10) and lacustrine mudstones (FS3) with channelized tidal meandering sandstones (FS9). These tidally influenced fluvial deposits are temporally equivalent to marine maximum flooding surfaces. Near the top, meandering sandstones (FS9) intercalated with lacustrine and intertidal mudstones (FS3, FS10) are observed in a progradational trend until the contact with the Mugrosa Formation (Figures 12b2, 16).



Eastern sector of the southern Llanos Basin (ESLLB)
~300 km
NW
ESE
Foothills
WSLLB
Lejía Creek
Sagú Creek
W1 W2 W3 W4 W5 W6 W7 W8 W9 W10 W11 W12 W13
Datum: MFS at C6 Mbr.
Oligocene basal Ss.
El Melón High
Rubiales High
PZ basement
PZ
P
K
T–04 T–05 T–06* T–07 MFS T–08 T–09 T–10 T–11
C6 C7
Carbonera C8 Mbr.
Oligocene Eocene Paleocene Cretaceous
Late Early Late Middle Early
Figure 14
HST MFS TST LST SU
Outcrop rock
Well core
*Biozone ages from Jaramillo et al. (2011)
Vertical exaggeration: 1.5
Oligocene to Eocene
FS7 Mudstone cumulative paleosol fluvial
FS6 Sandstone open shoreline/estuarine backshore
FS2 Shelf mudstone
FS2 Sandstone. Shallow marine shoreface.
FS3 Mudstone/sandstone/coal. Lacustrine /paralic deposit.
FS5 Sandstone. Coastal plain compound paleosoil.
FS1 Fluvial sandstone
FS1 Fluvial conglomeratic
Paleocene (P)
FS4 Strongly developed paleosol
Cretaceous (K)
Hetherolithic sandstone/mudstones Marine shelf
Tidal estuarine sandstones (transgression) Tidal delta sandstones (regression)
Paleozoic (PZ)
Paleozoic basement
Subaerial unconformity at base of Mirador Formation
Cretaceous/Paleocene unconformity
Paleozoic/Cretaceous unconformity
Unconformity at base of C7 Member of the Carbonera Formation
Lower lower Oligocene unconformity (base of Oligocene basal sandstones)
Ravinement surface
Biozone boundary
Maximum flooding surfaces
6 Upper Mirador Fm.
5 Lower Mirador Fm.
4 Barco–Cuervos Fm.
3 Guadalupe Fm.
2 Gacheta Fm.
1 Une Fm.

Figure 15. Regional schematic stratigraphic correlation showing the facies trends and depositional sequences in the southern Llanos Basin (see well location in Figure 1d). Three depositional sequences are shown in the correlation: (i) Between the unconformity above the strongly developed paleosol and the lower lower Oligocene unconformity; the LST is the Lower Mirador Formation, the TST is the Upper Mirador Formation and lower C8 Member, the MFS is in the shales of the C8, and the HST is the shales of the lower C8 Member eroded in the ESLLB. (ii) Between the lower lower Oligocene unconformity and the base of the C7 unconformity; the LST is the Oligocene basal sandstones, the TST is the shales of the upper C8 Member, and the HST is the progradational shales of the C8 Member. The MFS is between these shales. (iii) Only the LST–TST that comprises the C7 and C6 Members of the Carbonera Formation is shown. The MFS is on the shales of the upper part of the C6 Member. The Eocene – Oligocene wedge is 1044 thick in the foothills and 93 m thick on the Rubiales High. Graphic is not to scale. (WSLLB) western sector of the Llanos Basin; (MFS) maximum flooding surface; (Mbr.) Member; (Fm.) Formation; (Ss.) sandstone; (HST) highstand systems tract; (TST) transgressive systems tract; (LST) lowstand systems tract; (SU) subaerial unconformity.

During the middle to late Eocene, the Esmeraldas Formation drapes and pinches out toward the Central Cordillera, and it was deposited in most of the MMB. This wedge reaches a thickness of 1255 m in the NMS and thins to 50 m in well Yariguí–1 in the western of the MMB (Suárez, 1997). This wedge fossilized the landscape throughout which the fluvial system of the La Paz Formation established in early Eocene (Figure 18) (Suárez, 1997; Gómez et al., 2005a; Caballero et al., 2013b; Reyes–Harker et al., 2015). The reservoir sandstones of the Esmeraldas Formation have porosity between 10–20 % and 100–200 mD of permeability.

3.5.4. Oligocene

3.5.4.1. Early Oligocene: Oligocene Basal Sandstones and Upper C8 Member of the Carbonera Formation

Above the lower lower Oligocene unconformity, several fining–upward high–order cycles and facies successions (FS6–FS5–FS3) were deposited in the ESLLB, whereas in the WSLLB, these shallowing–upward facies successions are separated by subaerial exposure surfaces and minor ravinement surfaces, as described in the cores from wells 10 and 11 (Figures 10, 11a, 11b). This basal high–frequency cycle was deposited in erosional contact as a progradational wedge above the unconformity, whereas the upper sets have a retrogradational pattern until the MFS. These facies are sandier over the El Melón and Rubiales Highs.

At the end of the early Oligocene and the beginning of the late Oligocene, FS2 of the upper part of the C8 Member of the Carbonera Formation retrograded over the basal sandstones. The thickness of this unit between the lower lower Oligocene unconformity and the base of the C7 Member of the Carbonera Formation unconformity is 277 m in the WSLLB, 120 m on the El Melón High, and it pinches out on the Rubiales High 210 km to the east (Figure 15). The average porosity of the Oligocene basal sandstones around the El Melón High varies between 20 and 30%, and the permeability varies between 1000 and 10 000 mD.

3.5.4.2. Late Oligocene: C7 and C6 Members of the Carbonera Formation

Several fining–upward fluvial cycles were deposited above the upper lower Oligocene unconformity; these cycles form the C7 Member of the Carbonera Formation. The fluvial cycles consist of granule sandstones (FS9) capped by a coastal plain compound paleosol (FS5), backshore swamp–lacustrine fill (FS3), and/or fluvial floodplain deposits (FS7). The fining–upward fluvial to coastal plain cycles of the C7 Member of the Carbonera Formation were deposited in a progradational pattern, but the upper C6 cycles are coarsening–upward in a retrogradational pattern until the MFS at top of the C6 Member of the Carbonera Formation (Figures 11c, 15).

The C7 and C6 Members of the Carbonera Formation are fluvial and sandier toward the easternmost part of the southern Llanos Basin and muddier and paralic toward the center of the basin. In the southern part of the LLB, the thickness varies from 554 m in well 1 to 150 m on the El Melón High and 93 m in well 13 on the Rubiales High (Figure 15).

In the fluvial sandstones of the C7 Member of the Carbonera Formation on the Rubiales High, the porosity varies from 25 to 30%, and the permeability varies between 100 and 10 000 mD.

3.5.4.3. Oligocene: Mugrosa Formation

The Mugrosa Formation begins with fluvial sandstones that unconformably overlie the Esmeraldas Formation on the eastern and western flanks of the NMS (Figures 13, 17). The Mugrosa Formation consists mainly of a fluvial floodplain cumulative paleosol (FS7) with embedded fluvial channel sandstones (FS1). The cumulative paleosol includes levels of calcareous calcrete paleosol and sheetflood deposits (FS8) in a coarsening–upward, progradational stacking pattern (Figures 13, 16).

In the southern MMB, the Mugrosa Formation consists of decimeter– to meter–scale cross–bedded sandstone beds that grade upward into thick layers of variegated mudstones with caliche and paleosols (Gómez et al., 2003). In the northern part of the basin, floodplain variegated mudstones (cumulative pa-

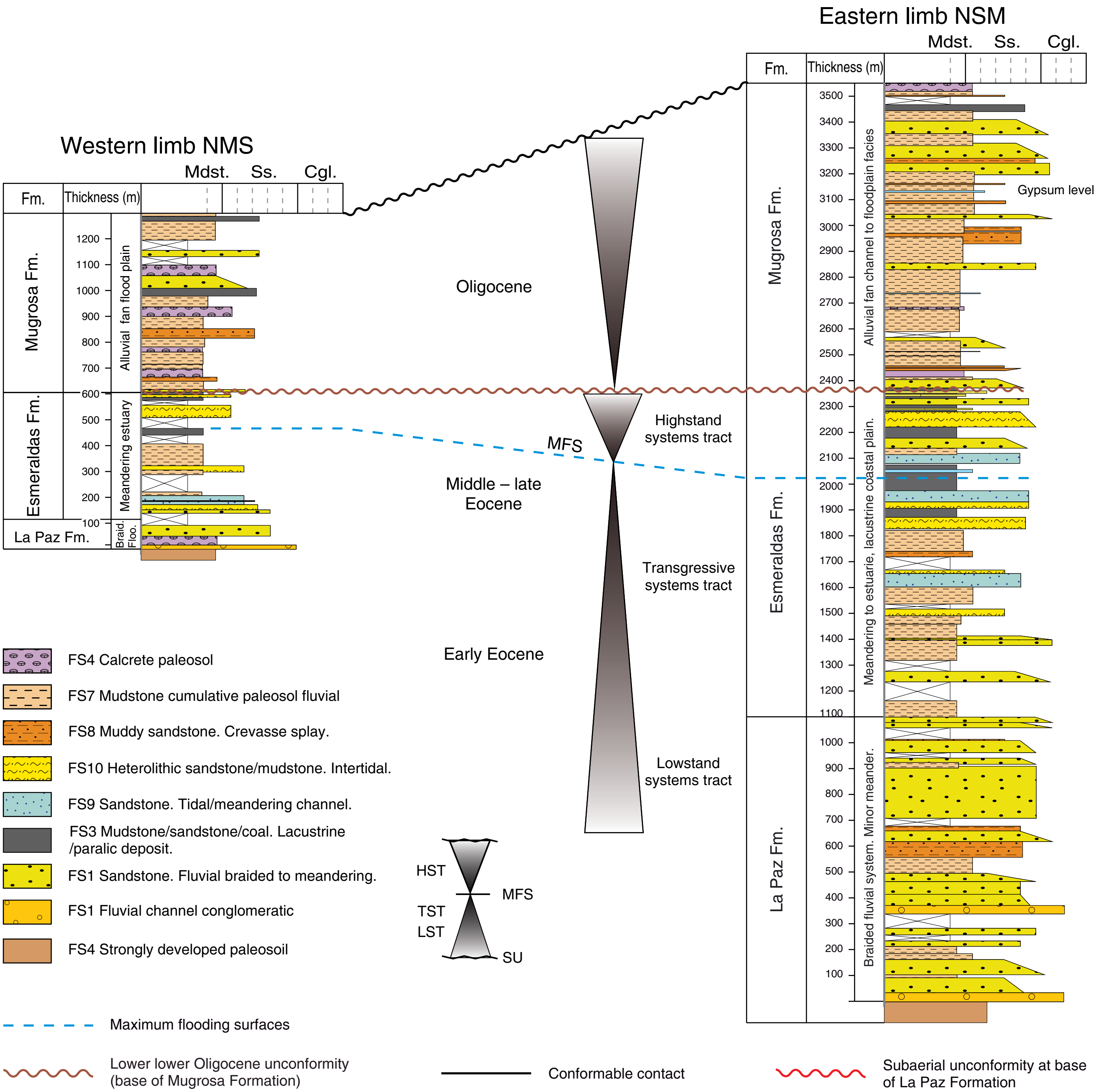


Figure 16. Correlation of Eocene to Oligocene units in the NMS. One depositional sequence and a nonmarine HAST are shown. (i) Braided to meandering facies successions (FS1, FS7, and FS8) in the lower Eocene La Paz Formation form the LST; these fluvial facies transition to floodplain, fluvial to estuarine and lacustrine facies (FS1/FS9, FS7, FS10, FS3) of the Lower–Middle Esmeraldas Formation and compose the TST. The MFS is on estuarine–lacustrine facies in the upper part of the Esmeraldas Formation; the HST is composed of the progradational upper part of the Esmeraldas Formation. (ii) The HAST is composed of the Oligocene Mugrosa Formation, which is composed of sheet sandstones, a cumulative paleosol, distributary channels in alluvial bajadas, calcrete paleosols in the fluvial plain, and a few meandering channel and crevasse splay facies successions (FS7, FS4, FS9). The wedge–shape geometry of the units indicates tectonic control on deposition with more accommodation space on the eastern limb. The location of the correlation is shown in Figure 1c. (HAST) high–accommodation systems tract (Catuneanu, 2006); (Mdst.) mudstone; (Ss.) sandstone; (Cgl.) conglomerate; (Fm.) Formation; (MFS) maximum flooding surface; (HST) highstand systems tract; (TST) transgressive systems tract; (LST) lowstand systems tract; (SU) subaerial unconformity.

leosol) with channelized sands were deposited in the Mugrosa Formation (Suárez, 1997). The thickness of the Mugrosa Formation varies from 1330 m on the eastern limb of the NMS to 700 m on the eastern limb of the NMS and 580 m in the Yariguí Field, and it pinches out to the northwest (Suárez, 1997) (Figure 17a).

The porosity in the Mugrosa Formation in the Cantagallo area varies between 15 and 25%, and the permeability varies from 10 to 1000 mD; in the provincial area, the Mugrosa Formation has porosities of 8–15 % and permeabilities of 70–150 mD.

4. Discussion

4.1. Latest Paleocene – Earliest Eocene Fluvial Landscape

The subaerial unconformity identified at the base of the Lower Mirador Formation in the southern Llanos Basin records a time interval of subaerial exposure, nondeposition, or erosion (lacuna) as well as intense weathering. The unconformity at the base of the La Paz Formation in the MMB records the same conditions that were previously identified (Gómez et al., 2003, 2005a) and is equivalent in age and stratigraphic position to the unconformity in the southern Llanos Basin.

The strongly developed paleosol identified in this study records subaerial exposure with intense weathering in the interfluvial areas of a fluvial landscape at the end of the Paleocene. The paleosol is well preserved in the interfluvial sectors and is ubiquitous in the southern Llanos Basin, although it varies in thickness based on its topographic position in the landscape in the latest Paleocene. Erosion or deposition halted its development along trunk valleys and incised valleys where it was truncated, but it was preserved in the interfluves, where pedogenic processes were dominant and erosion was not significant. The strongly developed paleosol at the base of the La Paz Formation on the western limb of the NMS is called the Toro shale (Caballero, 2010; Caballero et al., 2010); this soil corresponds to that described by Morales (1958) in the MMB. Several similar cases have been studied in other basins and different geological periods, in which interfluvial paleosols are correlated with incised valley fills along strike (Aitken & Flint, 1996; O'byrne, & Flint, 1996) and form a sequence boundary.

The unconformity was initially identified in the central foothills of the Eastern Cordillera. In the Cusiana area, this unconformity is present at the base of the Lower Mirador Formation (Fajardo, 1995; Ramon & Fajardo, 2006) and above a deep paleosol (Pulham et al., 1997). Recently, a paleosol in the same stratigraphic position was reported in a well core in the northern foothills (Bayona et al., 2015). The paleosol was reported to be late Paleocene – early Eocene in age and developed on volcanoclastic deposits.

Previous studies have identified tectonic deformation and uplift during the late Paleocene and earliest Eocene in the Central Cordillera, MMB, and western flank of the Eastern Cordillera (Gómez et al., 2003, 2005a; Parra et al., 2012; Bayona et al., 2013; Caballero et al., 2013b). Other studies have identified the reactivation of older structures on the eastern flank of the Eastern Cordillera (Bayona et al., 2013; Mora et al., 2013) and within the southern Llanos Basin and Llanos Foothills, where the Mirador Formation unconformably overlies Cretaceous rocks (Mora et al., 2013).

We interpret that the tectonic activity during the latest Paleocene – earliest Eocene resulted in the development of a subaerial fluvial landscape over the MMB, EC, and Llanos Basin. The landscape consisted of paleohighs in the MMB (La Cira–Infantas–Sogamoso Paleohigh) and low–relief highs on the western and eastern flanks of the Eastern Cordillera, the axial Eastern Cordillera, and the southern Llanos Basin and Llanos Foothills. This tectonic activity caused a fall in base level, and by the early Eocene, at least three trunk fluvial incised valleys (main trunk valleys) flowed north to northeast. These fluvial valleys were located in the Middle Magdalena Valley, the axial Eastern Cordillera, and the WSLLB (Figure 18). This fluvial system configuration was proposed previously (Bayona et al., 2013).

4.2. Early Eocene Lowstand Systems Tract

The Paleocene tectonic activity continued into the early Eocene (Parra et al., 2012; Mora et al., 2013, Bayona et al., 2013). Accommodation space was available along the main trunk valleys and localized incised valleys on the flanks of the growing tectonic structures. The La Paz, Upper Socha–Picacho, and Lower Mirador Formations were deposited in these incised fluvial valleys. The incised valley model was previously interpreted for the Cusiana area to the north (Pulham et al., 1997). This model is supported by the fluvial onlap of the Lower Mirador and La Paz Formations onto a truncated, strongly developed paleosol, the geometry and stacking pattern of the sandstones, and the low rate of accommodation space generation, as indicated by the fluvial braided facies.

Compound and cumulative paleosols were deposited at the top of the Lower Mirador and La Paz Formations; these paleosols suggest that the accommodation space was slowly increasing and that the sedimentation was almost constant. This slow increase in accommodation space was likely due to the large volumes of sediment from the increasing influence of the exhumed La Cira–Infantas Paleohighs in the axial Magdalena Basin, the low–amplitude uplifts in the axial Eastern Cordillera and the uplifts in the southern Llanos Basin. These conditions promoted progradation of facies onlap onto the paleotopography. The configuration of the lowstand systems tract (LST) and the compound and cumulative paleosols

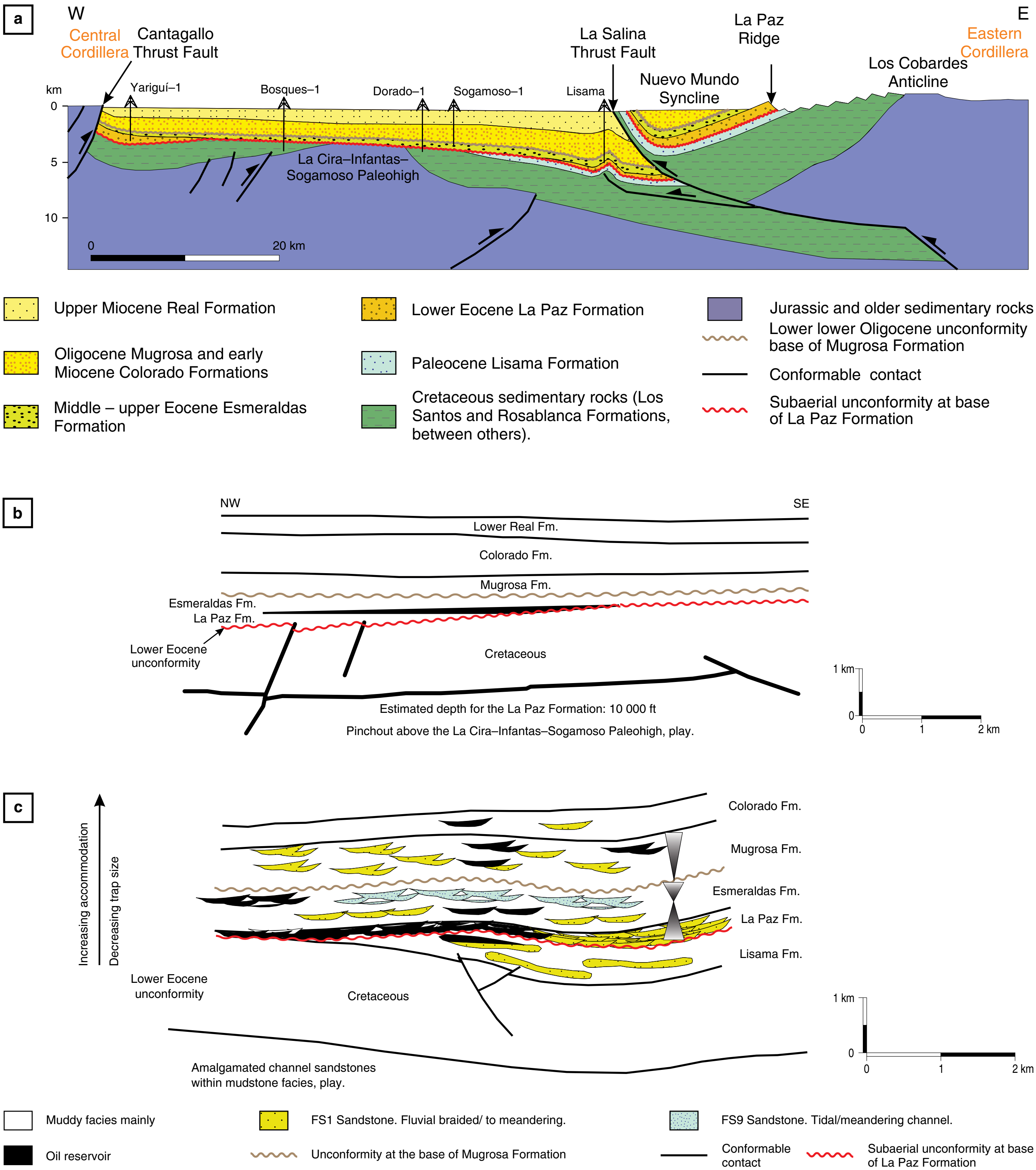


Figure 17. Regional schematic stratigraphic sections showing the facies trends and depositional sequences in the MMB. **(a)** Stratigraphic section between the eastern and western areas of the MMB. (a) The La Paz Formation was deposited above a subaerial unconformity on the two margins of the MMB and by a topographic high, the La Cira–Infantas–Sogamoso Paleohigh (LCISP). The Esmeraldas Formation covers and preserves the pre–existing topography. The Mugrosa was deposited after a period of erosion represented by the lower lower Oligocene unconformity (after Gómez et al., 2005a). (b, c) Types of stratigraphic plays in the Eocene – Oligocene units. **(b)** Pinchout of amalgamated sandstones FS1 of the La Paz Formation above the LCISP. Modified from Suárez (1997). **(c)** Amalgamated channel belts (FS1 or FS9), embedded within mudstones of: cumulative paleosol in Mugrosa and Colorado Formations and swamp to lacustrine or estuarine intertidal in Lisama and Esmeraldas Formations. Location in Figure 19. Modified from Suárez (1997). (Fm.) Formation.

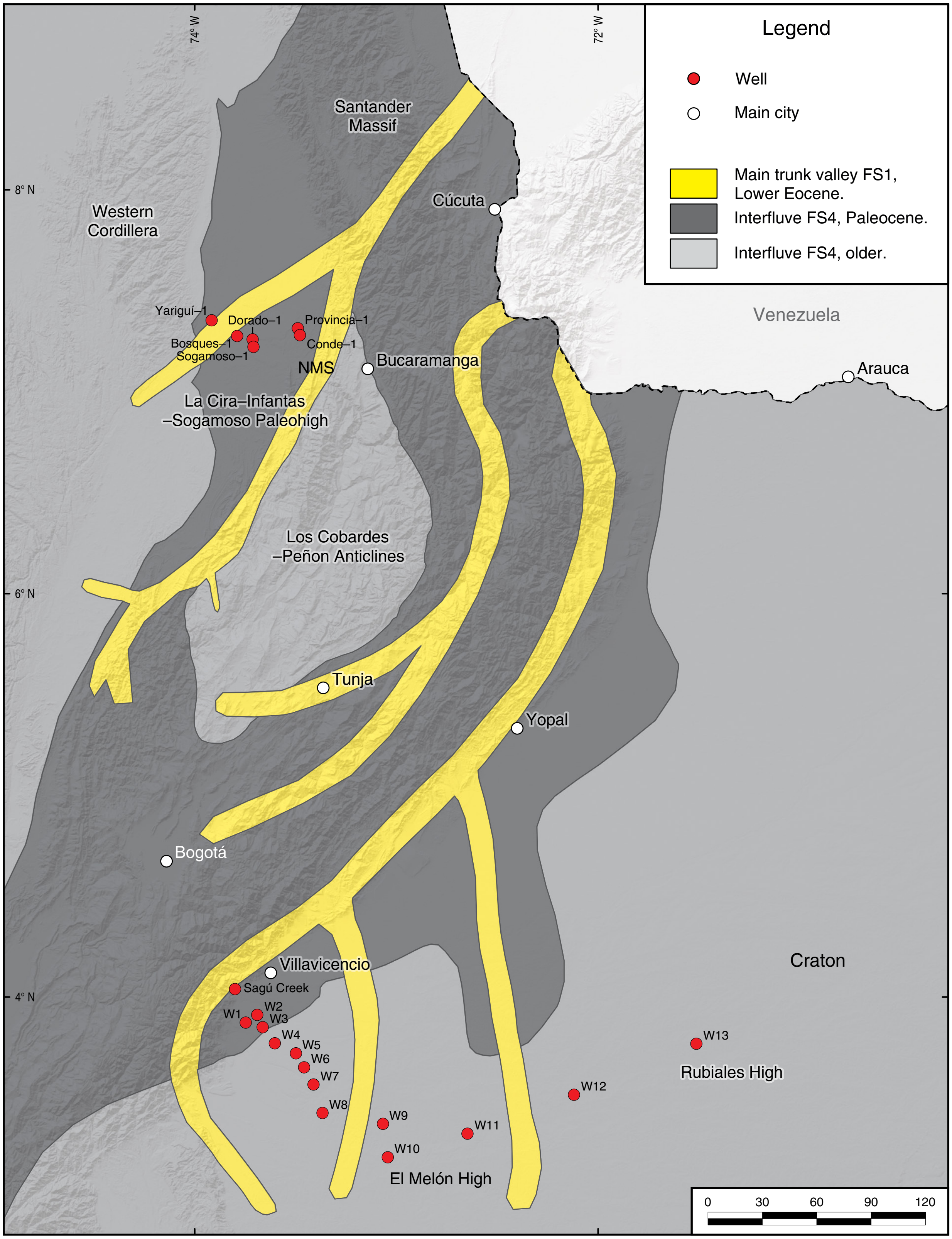


Figure 18. Interpreted paleogeographic configuration at the end of the Paleocene. As the result of tectonic uplift and the resulting base level fall, three incised trunk valleys developed in a fluvial continental landscape; these valleys were located in the MMB, the axial Eastern Cordillera, and the Llanos Basin. Between the fluvial valleys, the subaerially exposed interfluvial area allowed the development of the strongly developed paleosol (FS4) over Paleocene and older rocks. Modified from Bayona et al. (2013). (NMS) Nuevo Mundo Syncline.

Paleogene

indicate subaerial exposure at the end of the early Eocene, likely due to the progradation of fluvial facies over the preexisting topography.

The LST was completely deposited by the end of the early Eocene and occupied two depocenters, one in the Eastern Cordillera and the western Llanos Basin and the other in the Magdalena Basin. The morphology at the end of the early Eocene was a wider coastal – fluvial plain in the southern Llanos Basin and NMS (Figure 19).

4.3. Middle – Late Eocene Transgressive Systems Tract

According to previous studies, during the middle – late Eocene, tectonic deformation and loading advanced to the Eastern Cordillera (Bayona et al., 2008, 2013; Parra et al., 2009b; Mora et al., 2010; Saylor et al., 2012b), and the Santander Massif began to be uplifted, initially from the northwestern area toward the southeastern area of the massif (Caballero et al., 2013a; 2013b; Mora et al., 2015). The tectonic loading prompted flexural subsidence on both flanks of the Eastern Cordillera and established the conditions for the base level to rise and allow the marine waters to transgress into the southern Llanos Basin. On the western margin of the EC, the base level rose, and marine tidal waters eventually drowned the fluvial system to form an estuarine and then lacustrine system during the late Eocene in the NMS and Middle Magdalena Valley Basin (Caballero et al., 2013a, 2013b; Mora et al., 2013; Reyes–Harker et al., 2015). This lacustrine system is recorded in the Los Corros fossil horizon (Morales et al., 1958; Gómez et al., 2005a). The change in facies succession between the La Paz and Esmeraldas Formations indicates a base level rise from a fluvial plain to a coastal plain with a meandering tidally influenced estuarine system and finally intertidal flats with lacustrine deposition systems in the NMS (Figure 20).

In the southern Llanos Basin, the Upper Mirador Formation and the lower part of the C8 Member of the Carbonera Formation recorded the marine transgression. These units form the transgressive systems tract (TST) in the MMB and Llanos Basins. The TST is limited by the ravinement surface and the MFS in the lower C8 Member of the Carbonera Formation. The highstand systems tract (HST) of this first sequence is the least well preserved by the erosion of the earliest Oligocene unconformity, but it consisted of prograding marine facies of the lower section of the C8 Member (Figure 20).

The integration of facies analysis and depositional trends and the sedimentary environments support previous interpretations of the configuration of the middle – late Eocene paleogeography (Bayona et al., 2013; Caballero et al., 2013b; Silva et al., 2013; Reyes–Harker et al., 2015) and its extent toward the Maracaibo Basin and to the Maracaibo shoreline (Figure 21). The middle – late Eocene marine ingression was also previously identified in the central Llanos Foothills and the axial Eastern Cordillera (Cooper et al., 1995; Villamil, 1999; Bayona et al., 2008; Santos et al., 2008). The connection of this marine–lacustrine embayment system with the sea was discussed previously (Santos et al., 2008; Jaramillo et al., 2011; Rodríguez–Forero et al., 2012).

4.4. Oligocene Divergent Stratigraphic Histories

Accelerated exhumation of the Floresta and Santander Massifs (Bayona et al., 2008; Parra et al., 2009b; Mora et al., 2015) and the entire Mesozoic ancestral graben in the Eastern Cordillera (Parra et al., 2009a, 2009b; Mora et al., 2010; Saylor et al., 2011, 2012a) occurred during the Oligocene. At this time, the MMB became a closed basin between the Santander Massif, the western flank of the Eastern Cordillera, and the Central Cordillera. The Oligocene facies record in the MMB indicates tectonic and climate controls on deposition of the alluvial Mugrosa Formation and no control of the regional base level by the Maracaibo Sea (Caballero et al., 2013a, 2013b) (Figure 21).

In the foothills and the Llanos Basin, the tectonic loads of the Eastern Cordillera resulted in accelerated flexural subsidence and increased accommodation space. The previous shallow marine conditions of the late Eocene continued through the Oligocene. The subsidence in the foothills and WSLLB drove the deposition of the upper part of the C8 Member of the Carbonera Formation under shallow marine shelf conditions, whereas in the ESLLB, the basal Oligocene sandstones were deposited above an unconformity. These deposits likely indicates that increased flexural subsidence occurred in the western part of the southern Llanos Basin (foredeep), whereas to the east, flexural uplift (forebulge) is recorded in the unconformity at the base of the Oligocene basal sandstones (Figure 21).

The second depositional sequence is composed of Oligocene basal sandstones and shales of the upper C8 Member of the Carbonera Formation between the lower lower Oligocene unconformity and the unconformity at the base of the C7 Member of the Carbonera Formation. The LST–TST corresponds to the Oligocene basal sandstones of the Carbonera Formation between the lower lower Oligocene unconformity and the maximum flooding surface; the HST corresponds to the shales (FS2) of the upper part of the C8 Member of the Carbonera Formation between the MFS and the upper lower Oligocene unconformity at the base of the C7 Member of the Carbonera Formation.

The rapid subsidence and prevailing marine conditions during the early Oligocene were also interpreted in previous studies in the northern Llanos Basin and Medina Basin (Bayona et al., 2008; Parra et al., 2009a).

The fluvial – coastal plain and lacustrine conditions reached the southern Llanos Basin by the late Oligocene with the deposition of the C7 and C6 Members of the Carbonera Formation

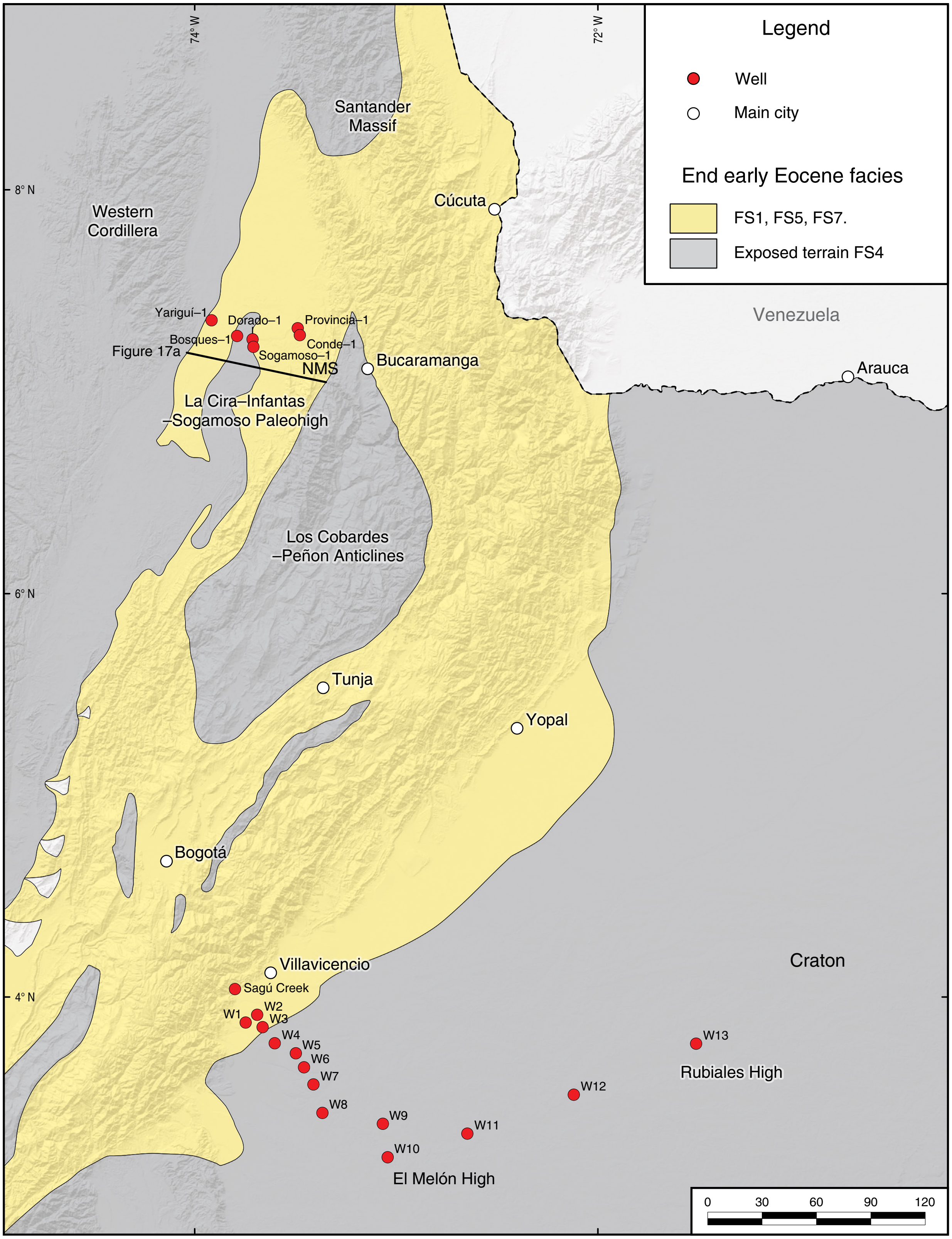


Figure 19. Early Eocene facies distribution. Through the early Eocene, as the tectonic activity gradually decreased, the base level transitioned from falling to rising, and the accommodation space slowly increased, likely because of the high sediment supply from the uplifted terrains. The previous landscape began to fill with a fluvial coastal plain wedge that onlapped onto the previous paleotopography. At the end of the early Eocene, these fluvial coastal plain facies (FS1, FS7, FS5) prograded and extended to form two depocenters, one in the MMB and the other covering the axial Eastern Cordillera and the western part of the Llanos Basin. These rocks correspond to the lowstand systems tract of the first depositional sequence. Modified from Reyes–Harker et al. (2015). (NMS) Nuevo Mundo Syncline.

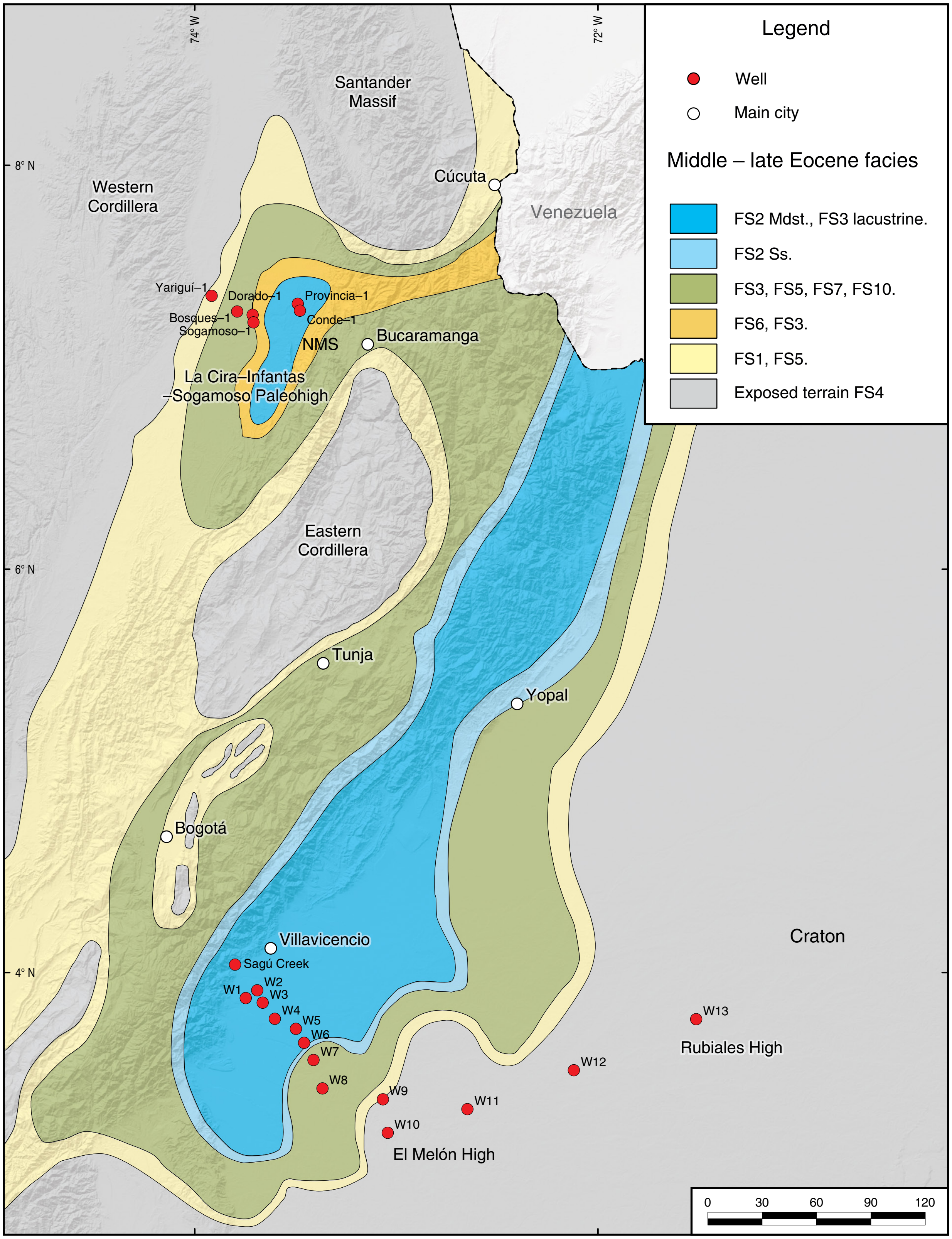


Figure 20. Middle to late Eocene facies distribution. Tectonic deformation translated to the Eastern Cordillera and Santander Massif during the middle Eocene. This deformation generated tectonic loads and flexural subsidence along both margins of the EC and the Santander Massif. The subsidence allowed marine waters to mainly enter the Llanos Basin; in the MMB, the tidal influence likely occurred as a result of overall base level rise and formed a tidally influenced fluvial to lacustrine system before the end of the Eocene. The distribution of facies shown in this map forms the TST and HST of the first depositional sequence. Modified from Reyes–Harker et al. (2015). (Mdst.) mudstone; (Ss.) sandstone; (NMS) Nuevo Mundo Syncline.

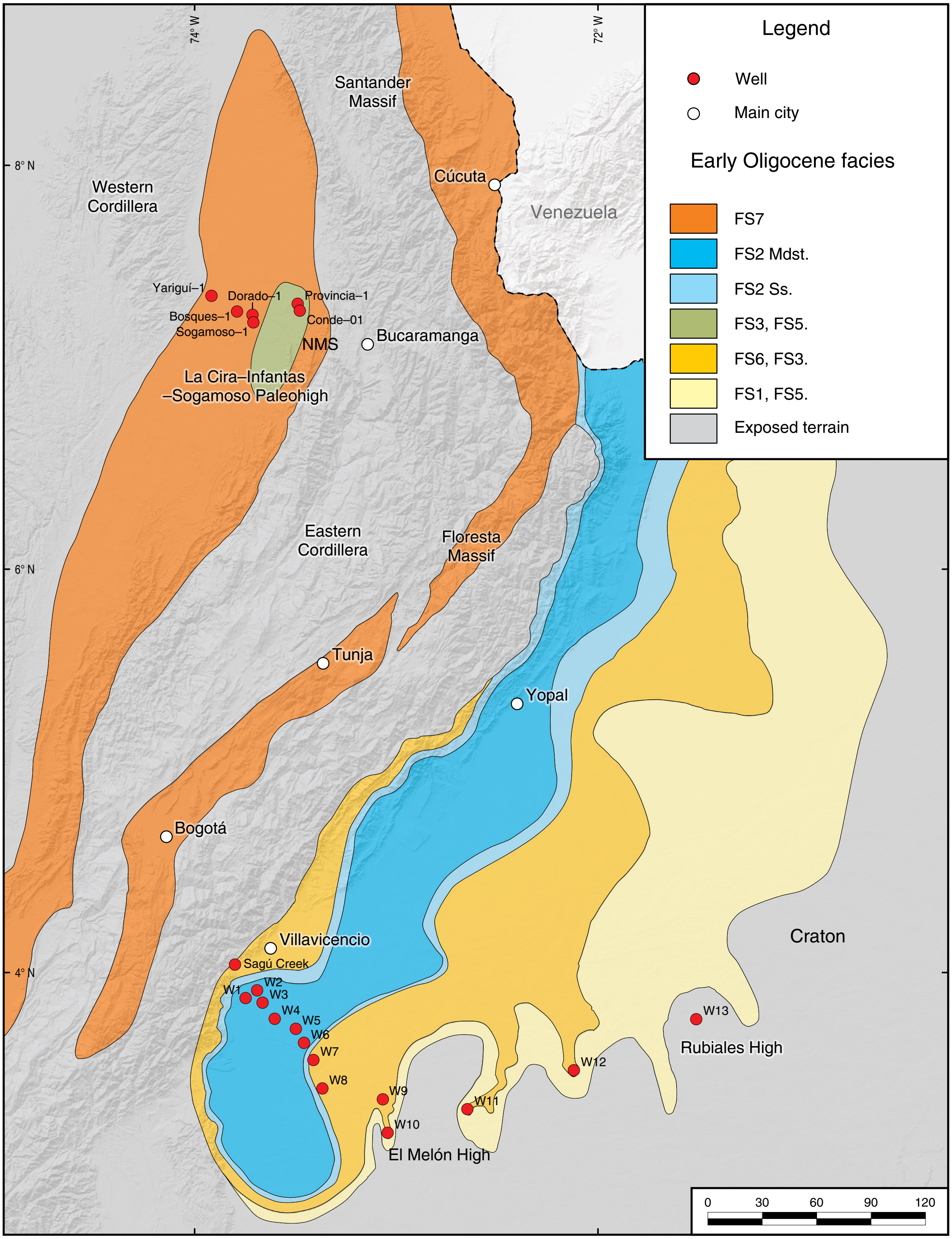


Figure 21. Early Oligocene facies distribution. By the early Oligocene, accelerated exhumation of the Floresta and Santander Massifs and the entire EC took place. The MMB became a closed basin, and an alluvial–fluvial system was established. In the Llanos, flexural subsidence continued in the foothills and WSLLB, where marine mudstones were mainly deposited, whereas in the ESLLB, low accommodation space, likely caused by forebulge migration, set the conditions for deposition of the Oligocene basal sandstones. The transgression continued into the early Oligocene. In the southern LLB, these deposits compose the second depositional sequence. Modified from Reyes–Harker et al. (2015). (Mdst.) mudstone; (Ss.) sandstone; (NMS) Nuevo Mundo Syncline.

(Figure 22). The third depositional sequence is composed of the C7–C6 Members of the Carbonera Formation between the upper lower Oligocene unconformity at the base of the C7 Member and an unconformity at the base of the C5 Member of the Carbonera Formation (Caycedo & Catuneanu, 2018).

The fluvial sandstones and organic lacustrine mudstones of the C7 and C6 Members of the Carbonera Formation between the upper lower Oligocene unconformity and the MFS make up the lowstand–transgressive systems tract. The HST is composed of the upper part of the C6 Member through the unconformity at the base of C5 Member of the Carbonera Formation.

4.5. Tectonic Controls on Deposition in the Llanos and Middle Magdalena Basins

Thickness differences of an order of magnitude were identified between the Eocene to Oligocene units in the southern Llanos Basin and those in the MMB. From the Chichimene area to the Rubiales area, the Lower Mirador Formation varies in thickness from 35 m to 0 m over a distance of 38 km. In the Middle Magdalena Basin, the thickness of the La Paz Formation varies from 1090 m in the NMS to 0 above the axial La Cira–Infantas–Sogamoso Paleohigh 38 km to the west. The western wedge of the La Paz Formation varies from 580 m thick in the Yariguí Field to 0 m above the axial LCISP (Figure 18).

The total thickness of the middle Eocene – Late Oligocene deposits in the southern Llanos Basin varies from 1044 m in the WSLLB to 93 m above the Rubiales High, 250 km to the east (Figure 15). In the MMB, the thickness varies from 2585 m on the eastern border (NMS) to approximately 630 m in the Yariguí Oil Field, and it laps onto the Cachira High 68 km to the northwest (Suárez, 1997; Gómez et al., 2005a).

The wedge–shaped geometry of these deposits is evidence of differential subsidence of the basin, which is indicative of tectonic control on the deposition (Figures 15, 18). The large difference in thickness of the units between the basins indicates a significant difference in the mechanism that generated the accommodation space during the early Eocene to Oligocene in both basins. Based on the tectonic setting at that time, it can be inferred that the orogenic loads were located near the MMB, which generated more accommodation space than in the LLB, as has been suggested in previous studies (e.g., Gómez et al., 2005a; Horton et al., 2010a, 2010b; Mora et al., 2013; Reyes–Harker et al., 2015).

These tectonic factors controlled the lateral extent and thickness of the reservoir rocks in the MMB and southern Llanos Basin. The reservoir rocks in the LLB have greater lateral extents than those in the MMB (hundreds of km versus tens of km), but the reservoirs in the LLB are thinner than those in the MMB (several m to hundreds of m). This study documents that the reservoir facies in both areas are different. They are more fluvial (i.e., more muddy sandstones and continental mudstones and less lateral continuity) in the NMS, versus more marginal to marine facies in the LLB (i.e. sandstones are more laterally continuous, they have less muddy matrix and shale horizons are, in general regional flooding events, instead of subaerial flood plain deposits).

The tectonic events that controlled the rate of subsidence, the amount and type of sediment and, indirectly, the rate of sedimentation influenced the porosity and permeability of the sandy units in both basins (e.g., Ramon & Fajardo, 2006; Cooper et al., 1995).

Based on the porosity and permeability, the best reservoirs in the MMB and southern Llanos Basin are as follows:

1. The Lower Mirador amalgamated sandstones (FS1) in the foothills and WSLLB, the lower Oligocene basal sandstones (FS6) toward the ESLLB and the fluvial channel sandstones (FS9) of the C7 Member of the Carbonera Formation have the best reservoir properties, with porosities of 10–30 % and permeabilities of 100–10 000 mD.
2. The transgressive marine shoreface sandstones of the Upper Mirador Formation in the WSLLB have porosities of 5–15 % and permeabilities of 0.1–100 mD; these sandstones are sandier and thicker in the ESLLB, with porosities of 20–25 % and permeabilities of 100–10 000 mD.
3. In the western MMB, the lower Eocene amalgamated sandstones (FS1) of the La Paz Formation (Cantagallo sandstones) have porosities of 15–25 % and permeabilities of 100–1000 mD, the Mugrosa Formation has porosities of 15–25 % and permeabilities of 10–1000 mD, and the La Paz Formation in the eastern part of the MMB has porosities of 10–20 % and permeabilities of 100–1500 mD.
4. The Esmeraldas Formation in the eastern MMB has porosities of 10–20 % and permeabilities of 100–200 mD.
5. The Mugrosa Formation in the eastern MMB has porosities of 8–15 % and permeabilities of 70–150 mD.

The Oligocene Mugrosa Formation was deposited in a closed intermountain basin. We interpret that the conditions of high accommodation space and large sediment supply from the uplifting terrains around the basin led to an increase in the mud and silt available to form the matrix of the sandstones, which decreased the porosity and permeability.

4.6. Potential for Stratigraphic Plays

There is enormous potential for stratigraphic traps in the MMB and Llanos Basin. As we illustrated in this study, we identified lateral facies changes, pinchouts, unconformities with resulting truncated beds, and buried landscapes that include buried erosional hills and incised valleys on older reservoir rocks covered by thick strongly developed paleosols, which were then flooded and draped by marine shale facies. Several types of stratigraphic traps have been postulated in the southern Llanos

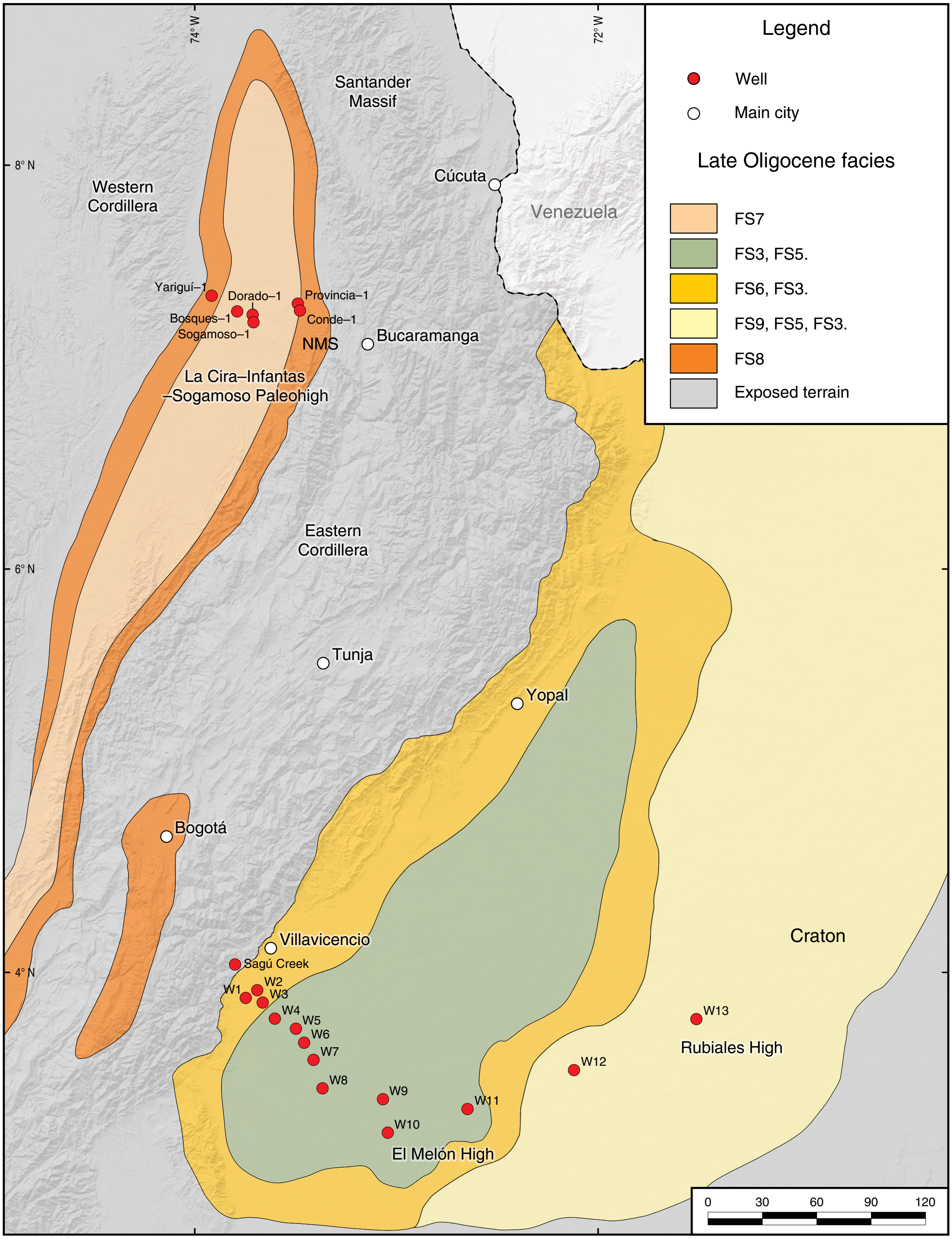


Figure 22. Late Oligocene facies distribution. The fluvial and coastal plain facies of the C7 and C6 Members of the Carbonera Formation were deposited in the Llanos Basin, and the MMB continued to be filled by alluvial–fluvial facies. The depositional limit migrated eastward. These deposits form the third depositional sequence. Modified from Reyes–Harker et al. (2015). (NMS) Nuevo Mundo Syncline.

Basin (Mora et al., 2018). In Figures 15 and 17, we identify several of these plays for detailed study:

1. Geomorphic features: The preserved landscape that formed at the end of the Paleocene on Cretaceous and Paleocene reservoir rocks, such as the Guadalupe and Barco–Cuervos Formations (Figures 14, 15) and the sandstones of the Jurassic Girón Formation and basal Los Santos, Rosablanca, and Lisama Formations on both flanks of the La Cira–Infantas–Sogamoso intrabasinal paleohigh (Figure 17a), have potential for underlying geomorphic features, such as buried hills, unconformity traps, and fluvial incised valleys.
2. The impermeable strongly developed paleosol (FS4) below the unconformity that is in direct contact with the reservoirs and the lacustrine (FS3) or marine (FS2) shales above the unconformity provides an effective seal for the underlying reservoir sandstones, forming buried hills or unconformity traps in the southern Llanos Basin and MMB. The Camoa Field in Colombia is an example of a buried hill play (Mora et al., 2018). Detailed work must be performed to search for these plays in other areas of the Llanos Basin and MMB. These traps are common and have been discovered around the world (Zhai & Zha, 1982).
3. Erosional pinchouts or erosional truncations of reservoir units of the Lower Mirador Formation and Barco and Guadalupe sandstones by the transgressive ravinement surface, which were later overlain by transgressive shales, form stratigraphic traps (see wells 1 to 5 in Figure 15), such as the stratigraphic trap of the T2 operational unit in the southern Llanos Basin.
4. Depositional pinchouts, such as the Oligocene basal sandstones against the preserved landscape in the southern Llanos Basin (see wells 6–12 in Figure 15), which were sealed during the later marine transgression and deposition of the Upper Mirador and C8 shales of the Carbonera Formation; an example is the pinchout of the La Paz Formation against the LCIS Paleohigh in the MMB and sealing by mudstones of the Esmeraldas Formation (Figure 17b).
5. Stratigraphic traps, such as amalgamated channel belt sandstones or shoreline strips of sandstones sealed by floodplain, lacustrine, tidal, or marine mudstones. The Oligocene basal sandstones in the southern Llanos Basin (Figure 15) and the Esmeraldas and Mugrosa Formations in the MMB (Figure 17c) have this potential.
6. Incised valleys. We believe that there is potential for incised valley sandstones reservoirs to be discovered in the Llanos Basin and in the MMB. In addition to the main trunk valleys that formed at the beginning of the Eocene, there should be incised valleys on Paleocene rocks in the basins, which are tributaries of these main trunk fluvial valleys. This play concept was exploited previously in the Cusiana and Cupiagua Oil Fields (Pulham et al., 1997; Ramon & Fajardo, 2006).

5. Conclusions

This study presents a comprehensive illustration and analysis of facies and facies successions of Eocene to Oligocene rocks in the NMS and southern LLB. The facies analysis allowed the identification of unconformity–bounded depositional sequences and systems tracts. The geometries and depositional trends allowed the common stratigraphic processes that occurred in these basins to be identified.

The LLB and the MMB likely shared the same stratigraphic base level and stratigraphic history during the Eocene, as indicated by the synchronicity in facies, facies successions, and stacking patterns from fluvial braided incised valley fills to meandering, estuarine, and lacustrine sediments in the MMB and low–energy shallow marine sediments in the LLB. From the Oligocene onwards, the MMB was isolated from the LLB as an intermontane closed and internally drained basin.

This fundamental change from a foreland to intermontane setting was associated with a stronger influence of the orogenic loads and close proximity to the source areas in the Middle Magdalena Basin and weaker influence of the orogenic loads and increased distance to the source areas in the Llanos Basin. We document that these factors controlled the facies and their properties, such as the porosity and permeability. Therefore, starting in the Oligocene, the sandy units were less laterally continuous and muddier in the MMB and interbedded with thick floodplain sandy mudstones, in contrast to the continuous, sandier, and marine–influenced units in the LLB, while the total thickness of the sedimentary record was greater in the MMB.

The lower Eocene sandstones in both basins are subtly fining–upward, single–story to multistory, aggradational to progradational, braided amalgamated sandstone wedges. These sandstones form excellent reservoirs and have very high porosities and permeabilities (10–25 % and 100–10 000 mD, respectively). This facies is thicker in the La Paz Formation in the MMB than it is in the Mirador Formation in the southern Llanos Basin.

The middle – late Eocene transgressive sandstones in the WSLLB are coarsening–upward mudstones and sandstones that were deposited in shoreface strips parallel to the shoreline in a retrogradational pattern. At least two important strips were identified; in the WSLLB, they are they are up to 20 m thick but are muddier (5–15 % porosity and 0.1–100 mD permeability) than in the ESLLB, where these strips are up to 12 m thick but are sandier around the El Melón and Rubiales Highs with excellent reservoir properties (20–25 % porosity and 100–10 000 mD).

The Eocene Esmeraldas Formation facies are fluvial tidally influenced meandering point bar and channel facies belts, which are wide laterally and continuous in the axial direction of the river system. These sandstones have fair to good continuity and thickness, as is observed in outcrops, and they are embedded between cumulative clayey mudstone paleosols or intertidal muddy flats. These sandstones are good reservoirs (10–20 % porosity and 100–200 mD permeability) in the eastern part of the MMB.

The lower Oligocene basal sandstones (Carbonera basal sandstones) are shallowing–upward, progradational open shoreline to backshore estuarine cycles that are 5–8 m thick. Several cycles of these facies successions are up to 40 m thick and are in a retrogradational stacking pattern forming sandstone strips parallel to the shoreline. These sandstones have excellent porosities and permeabilities (20–30 % and 1000–10 000 mD, respectively).

The Oligocene Mugrosa Formation sandstone facies are fluvial meandering point bar and channel facies belts embedded between cumulative clayey mudstone paleosols. These sandstones are good reservoirs (8–15 % porosity and 70–150 mD permeability) in the eastern part of the MMB and amalgamated sandstones (15–25 % porosity and 10–1000 mD permeability) in the western part of the MMB.

The upper Oligocene C7 and C6 Members of the Carbonera Formation are meandering fluvial systems with channel and bar sandstone belts between cumulative paleosol and paralic mudstones and coals. These sandstones are excellent reservoirs (10–30 % porosity and 100–10 000 mD permeability).

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Explanation of Acronyms, Abbreviations, and Symbols:

EC	Eastern Cordillera	MMB	Middle Magdalena Basin
ESLLB	Eastern sector of the Southern Llanos Basin	NMS	Nuevo Mundo Syncline
FS	Facies successions	SLLB	Southern Llanos Basin
HAST	High–accommodation systems tract	SU	Subaerial unconformity
HST	Highstand systems tract	T2	Amalgamated reservoirs sandstones of the Mirador, Barco, and Guadalupe Formations
ICP	Instituto Colombiano del Petróleo	TST	Transgressive systems tract
LCISP	La Cira–Infantas–Sogamoso Paleohigh	WSLLB	Western sector of the Southern Llanos Basin
LLB	Llanos Basin		
LST	Lowstand systems tract		
MFS	Maximum flooding surface		

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