SEDIMENTOLOGY, ICHNOLOGY, BIOSTRATIGRAPHY, AND SEQUENCE STRATIGRAPHY OF THE MIDDLE MIOCENE OFICINA FORMATION, ORINOCO OIL BELT, VENEZUELA

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By

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ABSTRACT

Although the middle Miocene Oficina Formation of the Orinoco Oil Belt represents most of Venezuela's hydrocarbon resource, a comprehensive and detailed sedimentary facies model for the whole belt has never been put forward. Nine facies (FA-FI), grouped in five facies assemblages (FA1-5), have been identified in the Oficina Formation in the Orinoco Oil Belt. FA1 occurs in the lower member, encompassing fluvial braided channels (FB), floodplains (FG2), swamps (FH1) and paleosols (FG3). FA2 occurs in the middle member and consist of meandering estuarine-channel deposits (FA, FC, FD, FE, and FI). FA3 occurs in the middle member, including tidal flats and tidal creeks (FC, FD, FE, FF, and FG2), swamps (FH1 and FH2), and paleosols (FG3) formed in tide-dominated estuarine systems. FA4 is present in the uppermost part of the middle members, including sandbars (FC, FD, FG1), paleosols (FG3), and swamps (FH2) formed in the outer part of estuaries. FA5 occurs in the upper member and consists of deltaic distributary channel (FC and FD), floodplain and interdistributary bay (FG2) and swamp (FH1) deposits of the lower delta plain of tide-dominated deltas.

The sedimentary succession in the Oritupano Field represents the upper member of the Oficina Formation, therefore correlating with the deltaic deposits identified in the Orinoco Oil Belt. Eleven facies (FJ-FS), grouped in four facies assemblages (FA6-9), have been recognized in the Oritupano Field. FA6 is present in the lower part and consists of deltaic distributary-channel (FJ) and interdistributary-bay (FK) deposits of the delta plain of a wave-dominated delta. FA7 is present in the middle part and consists of sandy mouth-bar (FL), proximal delta-front (FM1), storm-dominated distal delta-front (FM2), and prodelta (FN) deposits formed in an area encompassing the delta front and the prodelta of a wave-dominated delta. FA8 is present in the upper part, including upper- to middle-shoreface (FO) and lower-shoreface (FP) deposits formed in a wave-dominated shoreface. FA9 is present in the upper part, including deposits of the upper offshore (FQ), lower offshore (FR) and shelf (FS) formed in an offshore-shelf complex.

The Oficina Formation contains four softground ichnofacies (*Scoyenia*, depauperate *Cruziana*, *Skolithos*, and archetypal *Cruziana*) and two substrate-controlled ichnofacies (*Teredolites* and *Glossifungites*). The Oficina Formation in the Orinoco Oil Belt and Oritupano areas provides an ideal opportunity to study faunal distribution and ichnofacies because it comprises a wide range in depositional environments formed under variable salinity conditions

within a single stratigraphic unit. Freshwater conditions in the fluvial deposits, as well as in the inner portions of the estuary and delta plain, are further supported by the presence of *Scoyenia* Ichnofacies, whereas brackish-water segments of the estuarine and delta-plain deposits are characterized by the *Skolithos* and depauperate *Cruziana* Ichnofacies. Rapid ichnofaunal changes are distinctive of delta-front and prodelta deposits, where archetypal marine ichnofacies (i.e. *Skolithos* and *Cruziana*) alternate with stressed expressions of marine suites (i.e. depauperate *Cruziana* Ichnofacies), indicating rapid changes in salinity conditions due to times of freshwater discharge and return to fully marine conditions. Shoreface, offshore and shelf are characterized by the *Skolithos* and archetypal *Cruziana* Ichnofacies, indicating persistence of normal-marine salinity conditions. Salinity is a crucial factor in the development of benthic organisms and is independent of physical sedimentological processes. Therefore, understanding ichnofaunal distribution is very important for paleoenvironmental characterization of marginal-marine settings. In addition, the *Glossifungites* and *Teredolites* Ichnofacies indicate erosional exhumation of coastal-plain deposits, providing insights into sequence-stratigraphic interpretations.

The Oficina Formation (15.97-12.7 Ma) in the Orinoco Oil Belt comprises a single 2nd-order sequence, which is divided into two third-order depositional sequences (DS1-2). Third-order sequences provide a better understanding of reservoir distribution and are associated with sea-level changes. DS1 is bounded by sequence boundaries U-1 (15.97 Ma) and U-2 (13.82 Ma) and includes maximum flooding surface MFS-1 (14.91 Ma). It consists of thick lowstand systems tract (LST) and transgressive systems tract (TST) strata, and a thin highstand systems tract (HST) package. DS1 is associated with incised-valley systems formed during a relative sea-level fall. Fluvial valley-fill is recorded by FA1. The fluvial valleys were replaced by estuarine valleys during the Langhian relative sea-level transgressive episode. The estuarine valley-fill displays a retrogradational stacking pattern, comprising FA2, FA3 and FA4. Thin deltaic deposits also occur in the uppermost interval of DS1, forming a thin HST. DS2 is bounded by U-2 (13.82 Ma) and U-3 (12.7 Ma) and includes MFS-2 (13.53 Ma). It consists of a thin TST and a thick HST formed during the Serravallian sea-level highstand. In DS2, transgressive deposits in the lower part form a thin TST interval reflecting delta abandonment, which rests directly on top of the underlying highstand systems tract (HST) deposits of DS1, therefore mantling a flooding surface/sequence boundary. The bulk of DS2 is represented by FA5, displaying a progradational stacking pattern.

The Oficina Formation of the Orinoco Oil Belt shows similarities in sedimentologic, ichnologic and sequence-stratigraphic aspects to other marginal-marine units worldwide (most notably the Cretaceous McMurray Formation of Alberta), representing a broad spectrum of latitudinal contexts. These similarities therefore stress the importance of tidal dominance and relative sea-level changes as main controls on deposition, regardless of latitudinal controls. However, latitude may have played some role in controlling the establishment of extensive coastal wetland systems, the abundance of tidal channels and the types of burrowing organisms.

ACKNOWLEDGEMENTS

Dedicated to God and my parents Carmen and Pedro

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Chapter 1

1. Introduction

1.1. Significance of the project

This study is the first of its kind to comprehensively evaluate the sedimentary processes taking place in the Oficina Formation of the Orinoco Oil Belt through an integrated sedimentologic, ichnologic, and sequence-stratigraphic analysis. Integration of these multiple datasets is key to strengthen geological models in order to improve reservoirs characterization and performance. An appropriate understanding of the variability of sedimentary facies within fluvial, tide-dominated estuarine and deltaic environments is essential because it has major impact on exploration and field development. The relationship between organisms and substrates (as reflected by trace fossils) within a single stratigraphic unit has been scarcely documented and, in this regard, the Oficina Formation represents an excellent example to study such interactions because it contains diverse environments formed under variable salinity conditions along the depositional profile. Trace fossils are sensitive indicators of salinity fluctuations and, accordingly, ichnological studies have the potential to improve sedimentary facies characterization of fluvial, marginal-marine and open marine units. The paleoenvironmental and systems tract changes documented in the sedimentary succession of the Oficina Formation, as well as the regional recognition of sequence boundaries and maximum flooding surfaces, allow the identification of third-order depositional sequences, which are important to delineate the stratigraphic architecture at the reservoir scale in order to increase petroleum recovery through new drilling locations and improved secondary recovery schemes. On the other hand, these sequences at the exploration scale can predict the occurrence of reservoir, sources and seal facies.

1.2. Research Objectives and Hypotheses

As previously mentioned, a regional study with this scope has never been addressed in the Orinoco Oil Belt. Therefore, it is of great importance for both exploration strategies and reservoir characterization. It also will be useful for present and future geoscientists from both academia and hydrocarbon industry. The hypotheses to be tested in this thesis are the following. First, framing

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sedimentologic observations within a sequence-stratigraphic perspective indicates that the whole Oficina Formation cannot be interpreted as recording sedimentation in a deltaic system as invoked in current models, but instead represents a more complex facies mosaic comprising not only deltaic deposits but also estuarine facies. The basic concepts necessary to assess this hypothesis are presented in this chapter and the hypothesis is tested in Chapter 2. Second, analysis of trace fossil distribution allows reconstructing salinity changes along the depositional profile in the Orinoco Oil Belt and the Oritupano Field. Third, substrate-controlled ichnofacies in the Oficina Formation delineate surfaces of sequence-stratigraphic significance. Whereas the fundamentals to assess these two hypotheses are presented in this chapter, these issues are discussed in detail in Chapter 3. Fourth, third-order sequences based on biostratigraphy, sedimentology, allostratigraphic surfaces and systems tracts can be delineated within the Oficina Formation. The present chapter provides basic sequence-stratigraphic concepts and this hypothesis is tested in Chapter 4.

Based on these hypotheses, the objectives of this research project are to: (1) interpret sedimentary facies and depositional environments represented in the Oficina Formation of the Orinoco Oil Belt, using sedimentologic and ichnologic information, (2) evaluate trace-fossil distribution and ichnofacies gradients along a depositional profile to calibrate salinity-related trace-fossil models not only in the Orinoco Oil Belt, but in the Oritupano area as well, and (3) propose a third-order sequence-stratigraphic framework for the Oficina Formation in the Orinoco Oil Belt based on the integration of sedimentologic, stratigraphic, ichnologic and biostratigraphic datasets using well logs and core.

1.3. Materials and Methods

Conventional cores were described from the Boyaca, Junín, Ayacucho, and Carabobo areas of the Orinoco Oil Belt, and the Oritupano area to the northeast of the belt. The study includes the following wells with cores: 3 cores from the Boyaca area (B1, B2, and B3), 9 cores from the Junín area (J1, J2, J3, J4, J5, J6, J7, J12, and J13), 9 cores from the Ayacucho area (A4, A7, A8, A1, A2, A9, A10, A11, and A12), 8 cores from the Carabobo area (C1, C2, C3, C6, C7, C8, C9, and C10), and 3 cores from the Oritupano Field (OR1, OR2, and OR3), which together encompass 3258 m of core. Sedimentologic data were collected by detailed bed-by-bed analyses, taking into account lithology, bed thickness, bed contacts, and physical and biogenic sedimentary structures. Trace-

fossil data were collected and analyzed following a combined ichnofacies and ichnofabric approach, considering identification of ichnotaxa, ethologic groups, trophic types, population strategies, ichnodiversity, degree of bioturbation, and tiering structure. Degree of bioturbation was estimated based on the scheme of Taylor and Goldring (1993), who defined a bioturbation index (BI), ranging from 0 (no bioturbation) to 6 (complete bioturbation), after a previous scale by Reineck (1963). Additionally, 300 well logs were analyzed and correlated to evaluate changes in thickness and general facies relationships across the Orinoco Oil Belt.

The chronostratigraphic framework for the Orinoco Oil Belt was built using calcareous nannoplankton, palynomorphs, and foraminifers from previous studies (Audemard et al., 1985; Solórzano et al., 2015; Solórzano and Farias, 2017). Approximately 3000 samples from 96 wells, mostly side wall core and core, were revised and reinterpreted. The age of the strata was assigned based on the interpretation and integration of the biozones following key references, such as Martini (1971) for nannoplankton, Muller et al. (1987) and Williams and Bujak (1985) for palynomorphs, and Blow (1969, 1979) for foraminifers. Integration of the biozones was calibrated with the time scale of Ogg et al. (2008). The bioevents were interpreted based on the First Appearance Datum [FAD] and Last Appearance Datum [LAD] of the species. The maximum flooding surfaces (MFS-1, MFS-2 and MFS-3) were interpreted based on the calcareous nannoplankton and the planktonic foraminifer zones and were correlated with the maximum flooding surfaces of Haq and Schutter (2008). The sequence boundaries (U-1, U-2, U-3, and U-4) were correlated with the sequence boundaries of Haq and Schutter (2008).

1.4. Basic concepts

1.4.1. Estuary

An estuary is a transgressive coastal setting at the mouth of a river, receiving sediment from both river and sea, encompassing a wide spectrum of salinity levels (Pritchard, 1967; Dalrymple et al., 1992, 2006, 2012). The estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth. A tide-dominated estuary is formed when tidal current energy exceeds wave energy at the mouth of the estuary, displaying a typical funnel-shaped geometry. Tide-dominated estuaries consist of elongate sand bars and broad sand

flats that pass landward into a low-sinuosity (`straight´) single channel; net sand transport is headward in these areas (Dalrymple et al., 1992).

1.4.2. Delta

Galloway (1975) defined a delta as "a contiguous mass of sediment, partially subaerial, deposited around the point where a stream enters a standing body of water", where the interaction between fluvial and marine processes may produce diverse kinds of deltas. A tide-dominated delta occurs if tidal currents are stronger than river discharge. These bidirectional currents can redistribute river-mouth sediments, producing sand-filled, funnel-shaped distributaries. The distributary mouth bar may be reworked into a series of linear tidal ridges, extending from within the channel mouth out onto the subaqueous delta-front (Boggs, 2006; Bhattacharya, 2010). A tide-dominated delta is a prograding coastal environment that receives clastic sediment from a river source, being mostly reworked by tidal currents (Hori et al., 2001; Coleman, 1981).

1.4.3. Tide-dominated physical sedimentary structures

Tidal currents affect both estuaries and deltas. Tidal action is revealed by the presence of physical sedimentary structures, such as heterolithic inclined stratification or IHS and mudstone drapes, which are the most common structures recorded in the Oficina Formation. The mudstone drapes are formed during a brief slack-water period in the tide-dominated point bars (Choi et al., 2004; Hovikoski et al., 2008; Rodriguez, 2015; Gingras et al., 2016). IHS represents tidally generated deposits due to lateral accretion of point bars in meandering channels (Thomas et al., 1987; Hovikoski et al., 2008; Gingras et al., 2016). Although more commonly recorded in estuarine settings, IHS may be produced in deltaic systems as well (Choi et al., 2004; Martinius et al., 2012; Rodríguez, 2015; Solórzano et al., 2017).

1.4.4. Ichnofacies

Ichnofacies are based on the recognition of distinctive characteristics shared by different ichnocoenoses of variable ages formed under similar paleoenvironmental conditions (Buatois and Mángano, 2011). The ichnofacies model was introduced and published in German by Seilacher (1954, 1955, 1958, 1963) and later published in English (Seilacher 1964, 1967). The *Skolithos* Ichnofacies was proposed by Seilacher (1963, 1967) and comprises vertical, cylindrical, simple or

U-shaped spreiten burrows. It is dominated by dwelling burrows of suspension feeders or predators, displaying low ichnodiversity and variable abundance (Buatois and Mángano, 2011). The *Skolithos* Ichnofacies illustrates marginal-marine to shoreface environments, having been recognized locally in deep-marine and continental settings (Buatois and Mángano, 2011) The C*ruziana* Ichnofacies was proposed by Seilacher (1954, 1955, 1958) for molasse deposits and later referred as the *Cruziana* facies (Seilacher 1963, 1964, 1967). It consists of horizontal, vertical and inclined burrows, including locomotion, feeding, resting, dwelling, and grazing burrows of detritus feeders, suspension feeders and predators, displaying high ichnodiversity and high abundance (Buatois and Mángano, 2011). The C*ruziana* Ichnofacies records marginal-marine to shelf environments (Pemberton et al., 1992; Buatois and Mángano, 2011). The *Scoyenia* Ichnofacies was introduced for nonmarine sediments by Seilacher (1963, 1967), including meniscate trace-fossils produced by mobile deposit feeders, arthropod trackways and bilobed traces, typically associated with desiccation cracks and raindrop imprints. It displays low to moderate ichnodiversity and high abundance (Buatois and Mángano, 2011). The *Scoyenia* Ichnofacies records fluvial and lacustrine environments, but also may be present eolian subsettings as well (Buatois and Mángano, 2011; Krapovickas et al., 2016). The *Scoyenia* Ichnofacies is also present in the inner zone of the tide-dominated deltaic and estuarine systems (Buatois et al., 1997; Buatois and Mángano, 2011). The *Teredolites* and *Glossifungites* Ichnofacies have been used in sequence stratigraphy to identify and characterize discontinuity surfaces (i.e., transgressive surfaces of erosion) (MacEachern et al., 1992; Pemberton et al., 2004; Buatois and Mángano, 2011). These surfaces develop substrate-controlled ichnofacies because the exhumed surfaces originate within a marine or marginal marine environment, favoring colonization by organisms before deposition of the overlying sediment (MacEachern et al., 1992). The *Glossifungites* Ichnofacies was introduced by Seilacher (1967) and redefined by Frey and Seilacher (1980). It is manifested by sharp-walled, unlined, passively filled, dwelling traces of suspension-feeding organisms or passive predators. These burrows are robust, vertical to subvertical, simple and spreite U-shaped; this ichnofacies tend to display high abundance and low ichnodiversity (Buatois and Mángano, 2011). The *Glossifungites* Ichnofacies is developed in firm but unlithified substrates (MacEachern et al., 1992; Pemberton et al., 2004; Buatois and Mángano, 2011) being preferentially associated to transgressive settings (Gingras et al., 2004). The *Teredolites* Ichnofacies was proposed by Bromley et al. (1984) and revised by Gingras et al. (2004). It consists of clavate boring (ichnogenus

Teredolites) produced by pholadid bivalves with very low ichnodiversity and high density of boring (Buatois and Mángano, 2011), but other trace fossils, including *Thalassinoides,* also may be present (Buatois et al., 2002; Gingras et al., 2004; Solórzano et al., 2017). The *Teredolites* Ichnofacies consists of borings emplaced in marginal-marine woodgrounds, normally swamps and bays and is formed in resistant xylic substrates that may be preserved as coal or lignite in the stratigraphic record (Pemberton et al., 2001).

1.4.5. Sequence stratigraphy

Sequence stratigraphy is the study of rock relationships within a time-stratigraphy framework of repetitive, genetically related strata limited by surfaces of erosion or nondeposition, or their correlative conformities (Posamentier et al., 1988; Van Wagoner, 1995). A sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977). Whereas depositional systems represent three-dimensional assemblages of lithofacies, genetically associated by modern or ancient processes and environments (Fisher and McGowan, 1967; Van Wagoner, 1995), systems tracts comprise a connection of contemporaneous depositional units, which subdivide a sequence. They are also manifested by strata formed in the basin during a particular stage of shoreline shifts. Systems tract are interpreted based on stratal stacking pattern, position within the sequence, and types of bounding surfaces. The timing of systems tracts is inferred relative to a curve that describes the base-level fluctuations at the shoreline (Brown and Fisher, 1977).

1.5. Thesis structure

This is a paper-based thesis. Therefore, each of the three main chapters corresponds to a manuscript submitted for a publication venue. This thesis is organized into five chapters.

Chapter 1 underscores the significance of this research, outlining the research hypotheses, objectives and methods in this thesis, as well as providing a brief review of the basic conceptual framework.

Chapter 2 provides a comprehensive and detailed sedimentary facies model of the Oficina Formation and establishes comparisons with other marginal-marine units worldwide in order to emphasize the importance of tidal dominance and eustatic changes as main controls on

sedimentation, regardless of latitudinal controls. This manuscript will be submitted to Sedimentary Geology.

Chapter 3 evaluates trace-fossil distribution and ichnofacies gradients along a depositional profile for the Oficina Formation from the Orinoco Oil Belt to the Oritupano Field. This manuscript was published in Palaeogeography, Palaeoclimatology, Palaeoecology, v.482, p. 30-47.

Chapter 4 includes the third-order sequence-stratigraphic model, based on the integration of sedimentologic, stratigraphic, ichnologic, and biostratigraphic datasets. This manuscript is under review in AAPG Bulletin.

Chapter 5 provides final remarks, and a summary of main findings and conclusions obtained during this research.

Transition

The previous chapter (Chapter 1) underscores the significance of this research, outlining the research hypotheses, objectives and methods in this thesis, as well as providing a brief review of the basic conceptual framework. The aim of the next chapter (Chapter 2) is to provide a comprehensive and detailed sedimentary facies model of the Oficina Formation as well as to establish comparisons with other marginal-marine units worldwide in order to empahsize the importance of tidal dominance and eustatic changes as main controls on sedimentation, regardless of latitudinal controls.

I have built a paleoenvironmental model for the Oficina Formation in the Orinoco Oil Belt using sedimentary facies and trace-fossil distribution. Therefore, nine facies (FA-FI) were identified and grouped into five facies associations (FA1-5), namely fluvial braided channels (FA1), meandering estuarine channels (FA2), tidal flats and creek complex (FA3), outer-estuarine sandbar complex (FA4), and lower delta plain of a tide-dominated delta (FA5). These facies assemblages allowed me to recognize fluvial, estuarine and deltaic deposits. I also compared the environments of the Oficina Formation with other marginal-marine units formed under a wide variety of latitudinal settings. Supervisors Luis A. Buatois and M. Gabriela Mángano checked facies descriptions and interpretations and edited the manuscript. Co-author Williams Rodríguez helped with core logging.

2. Sedimentary facies and depositional environments of a tide-dominated estuarine and deltaic complex: The middle Miocene Oficina Formation of the Orinoco Oil Belt, Venezuela

Solórzano, E.J., Buatois, L.A., Rodríguez, W.J., Mángano, M.G., Sedimentary facies and depositional environments of a tide-dominated estuarine and deltaic complex: The middle Miocene Oficina Formation of the Orinoco Oil Belt, Venezuela. To be submitted to Sedimentary Geology.

2.1. Abstract

Although the middle Miocene Oficina Formation of the Orinoco Oil Belt represents most of Venezuela's hydrocarbon resource, a comprehensive and detailed sedimentary facies model for the whole belt has never been put forward. Based on the analysis of cores and well logs, nine sedimentary facies (FA-I), forming five facies assemblages (FA1-5), have been characterized. Both sedimentologic and ichnologic datasets have been integrated in this study. FA1 consists of fluvial-braided channel (FB), floodplain (FG2), and swamp (FH1) deposits, as well as paleosols (FG3). This facies assemblage occurs in the lower member, representing the infill of lowstand fluvial valleys. FA2 consists of meandering estuarine-channel deposits (FA, FC, FD, FE, and FI). FA2 occurs in the middle member, representing the infill of tide-dominated estuarine valleys during the early stages of the Langhian transgression. FA3 consists of tidal-flat and tidal-creek (FC, FD, FE, FF, and FG2) and swamp (FH1 and FH2) deposits, together with paleosols (FG3). This facies assemblage is present in the middle member, revealing backstepping and retrogradation within the estuarine system during a continuing transgression. FA4 consists of outer-estuarine sandbar (FC, FD, FG1) and swamp (FH2) deposits, as well as paleosols (FG3). It occurs in the uppermost part of the middle members, representing a late stage of the Langhian transgression, culminating in a maximum flooding surface. FA5 consists of deltaic distributary channel (FC and FD), floodplain and interdistributary-bay (FG2), and swamp (FH1) deposits. FA5 occurs in the upper member, recording sedimentation in the lower delta plain of a tide-dominated delta during a highstand. Freshwater conditions in the fluvial system, as well as in the inner portions of the

estuary and the delta plain are further supported by the presence of the *Scoyenia* Ichnofacies, whereas brackish-water segments of the estuary are characterized by the *Skolithos* and depauperate *Cruziana* Ichnofacies. The substrate-controlled *Teredolites,* and *Glossifungites* Ichnofacies occur in connection to erosional exhumation during ravinement. The absence of fully marine ichnofaunas is consistent with the embayed nature of the Orinoco Oil Belt. Comparisons with other marginal-marine units worldwide underscore the importance of tidal dominance and relative sea-level changes as main controls on deposition, regardless of latitudinal controls. However, latitude may have played some role in controlling the establishment of extensive coastal wetland systems and on the types of burrowing organisms.

Keywords: fluvial braided channels, meandering estuarine channels, deltaic distributary channels, ichnofacies, marine-marginal

2.2. Introduction

The oil sandstone deposits of the Orinoco Oil Belt represent most of Venezuela's hydrocarbon resource (Magna Reserva Project, 2012). The middle Miocene Oficina Formation in the Orinoco Oil Belt has been traditionally considered to record deposition within fluvio-deltaic systems (Latreille et al., 1983; Audemard et al., 1985; Toro et al., 2001, Martinius et al., 2012, 2013). However, recent work is suggesting a more nuanced depositional setting based on the fact that the deltaic interpretation is not consistent with the retrogradational stacking pattern recorded in its middle member (Rodríguez et al., 2018). In particular, deposition in fluvial to tide-dominated estuarine settings has been proposed for the lower and middle members, whereas deltaic deposition has been suggested to be restricted to the upper member based on detailed analysis in the Junín and Boyacá areas (Rodríguez et al., 2018). Unfortunately, despite its economic importance, a comprehensive and detailed sedimentary facies model for the Oficina Formation along the whole Orinoco Oil Belt has never been put forward. This is unfortunate because a proper understanding of the variability of sedimentary facies in these tide-dominated depositional environments is important for both exploration strategies and reservoir characterization. Characteristic sedimentary structures of tide-influenced environments, such as mudstone drapes and inclined heterolithic

stratification (IHS) (Hori et al., 2001; Choi et al., 2004; Crerar and Arnott, 2007; Rodríguez, 2015, 2018; Gingras et al., 2016; Solórzano et al., 2017), commonly impact on reservoir heterogeneity. The purposes of this paper are to: (1) document the different sedimentary facies and depositional environments in the Oficina Formation in the Orinoco Oil Belt, (2) discuss changes in thickness/general facies relationship, (3) study the tidal signature and reconstruct paleosalinity conditions, using sedimentologic and ichnologic information, (4) place facies information within a sequence-stratigraphic framework, and (5) compare our observations with those in similar deposits elsewhere in order to discuss controlling factors on deposition. The widespread extension of the Oficina Formation in the subsurface allows us to delineate the regional architecture of these marginal-marine strata, further refining facies models of tide-influenced settings.

2.3. Geologic setting

The Orinoco Oil Belt (Fig. 2.1) covers an area of approximately 55,314 km^2, being located in the southern part of the Eastern Venezuela Basin, sub-parallel to the Orinoco River. The Hato Viejo fault system subdivides the Orinoco Oil Belt into two provinces, the western and eastern provinces (Latreille et al., 1983; Audemard et al., 1985). The western province consists of the Boyaca and Junín areas where the Cenozoic succession overlies Cretaceous and Paleozoic strata. The eastern province includes the Carabobo and Ayacucho areas, where the Cenozoic succession rests on top of the Precambrian basement (Fig. 2.2).

Based on an integrated study of foraminifers, calcareous nannoplankton and palynomorphs, the Oficina Formation is considered of middle Miocene age (Audemard et al., 1985; Solórzano et al., 2015; in review). The Oficina Formation in the Orinoco Oil Belt was divided into three informal members: lower, middle and upper, representing fluvial, estuarine and deltaic deposits, respectively (Rodríguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). This formation consists of one single second-order depositional sequence, encompassing lowstand (LST), transgressive (TST) and highstand (HST) systems tracts (Rodríguez et al., in press). The lower member consists of fining-upward, massive to planar or trough cross-stratified, pebbly, and very coarse- to medium-grained sandstone. It records fluvial channel-fills of a lowstand systems tract. The middle member is characterized by interbedded coarse- to very fine-grained sandstone and mudstone with IHS locally capped by coal. Flaser, wavy and lenticular bedding are common.

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The bulk of this member records deposition in a tide-dominated estuarine system formed within a transgressive systems tract.
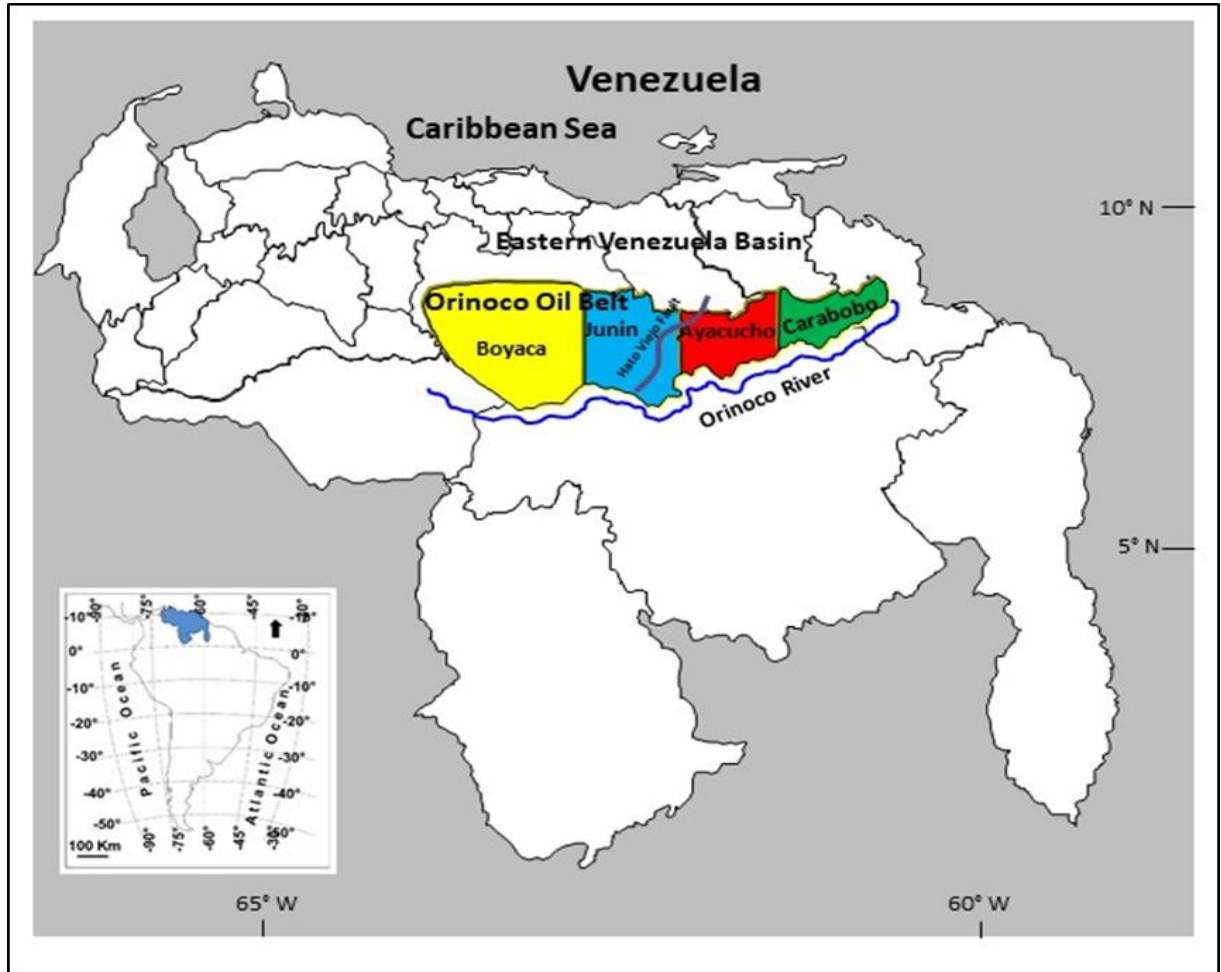
Figure 2.1. Map of Venezuela outlining the location of the Orinoco Oil Belt.

The upper member is represented by fining- and thinning-upward, planar and trough cross-stratified medium- to fine-grained sandstone with mudstone drapes, as well as inclined heterolithic stratified coarse- to fine-grained sandstone units. Desiccation and syneresis cracks, siderite nodules and bands, and coal beds also are present. The upper member mostly represents highstand systems tract deltaic progradation. Whereas deposits of the Oficina Formation in the Orinoco Oil Belt represent sedimentation in a broad, tide-dominated, marginal-marine embayment, coeval strata formed further to the northeast in the Oritupano Oil Field characterize open marine environments affected by wave reworking (Solórzano et al., 2017). turn, the Oficina Formation is subdivided

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into two third-order depositional sequences (DS1-2) which match the middle Miocene global eustatic curve of Haq and Schutter (2008) (Solórzano et al., 2017, in review). These third-order depositional sequences have been delineated based on the integration of biostratigraphy, sedimentology, allostratigraphic surfaces and systems tracts and provide a better understanding of reservoir distribution (Solórzano et al., 2017, in review). DS1 is bounded by sequence boundaries U-1 (15.97 Ma) and U-2 (13.82 Ma) and includes maximum flooding surface MFS-1 (14.91 Ma). It is associated with thick fluvial and estuarine valleys and thin deltaic deposits. DS2 is bounded by U-2 (13.82 Ma) and U-3 (12.7 Ma) and includes MFS-2 (13.53 Ma). It consists of thin transgressive deposits and thick lower delta plain deposits.
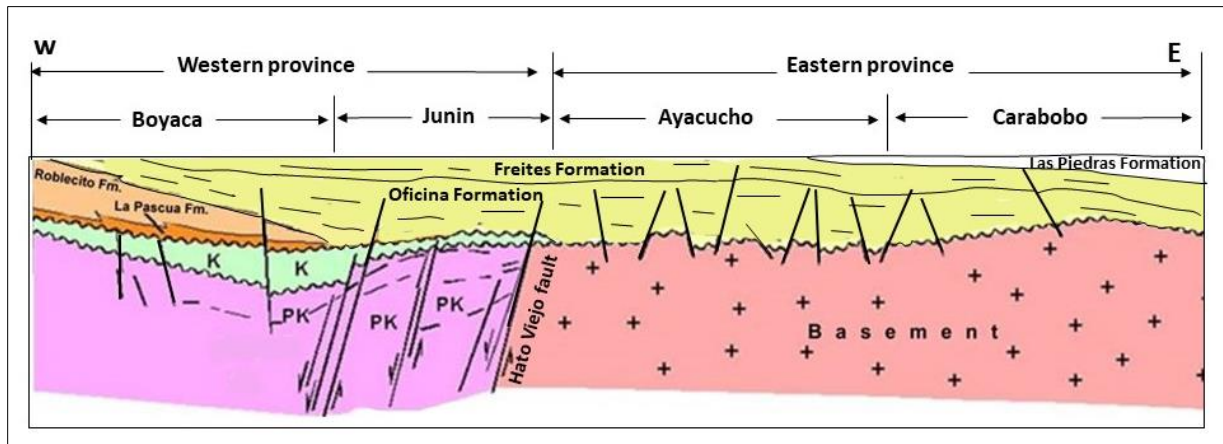
Figure 2.2. West to east structural section showing Cenozoic stratigraphy across the Orinoco Oil Belt (modified from Audemard et al., 1985).

2.4. Sedimentary facies and trace fossil content

Twenty-eight cored wells from the Oficina Formation in the Orinoco Oil Belt were described (B1, B2, and B3 from the Boyacá area, J1, J2, J3, J4, J5, J6, J7, J12 and J13 from the Junín area, A4, A7, A8, A1, A2, A9, A10, A11, and A12 from the Ayacucho areas, and C1, C2, C3, C6, C7, C8, C9, and C10 from the Carabobo area), totalizing 3055 m. Core-based facies were characterized by identifying lithology, sedimentary structures, textural characteristics, bed and bedset thicknesses, bed contacts, bioturbation index, trace-fossil distribution, and ichnologic suites (Figs. 2.3-2.5). Additionally, 300 well logs (resistivity, density, neutron and gamma ray) were analyzed and correlated to evaluate changes in thickness and general facies relationships across the Orinoco Oil

Belt (Fig. 2.6). Table 2-1 summarizes the main characteristics of nine sedimentary facies (FA-FI) present in the Oficina Formation, forming five facies associations, labeled FA1 to FA5.
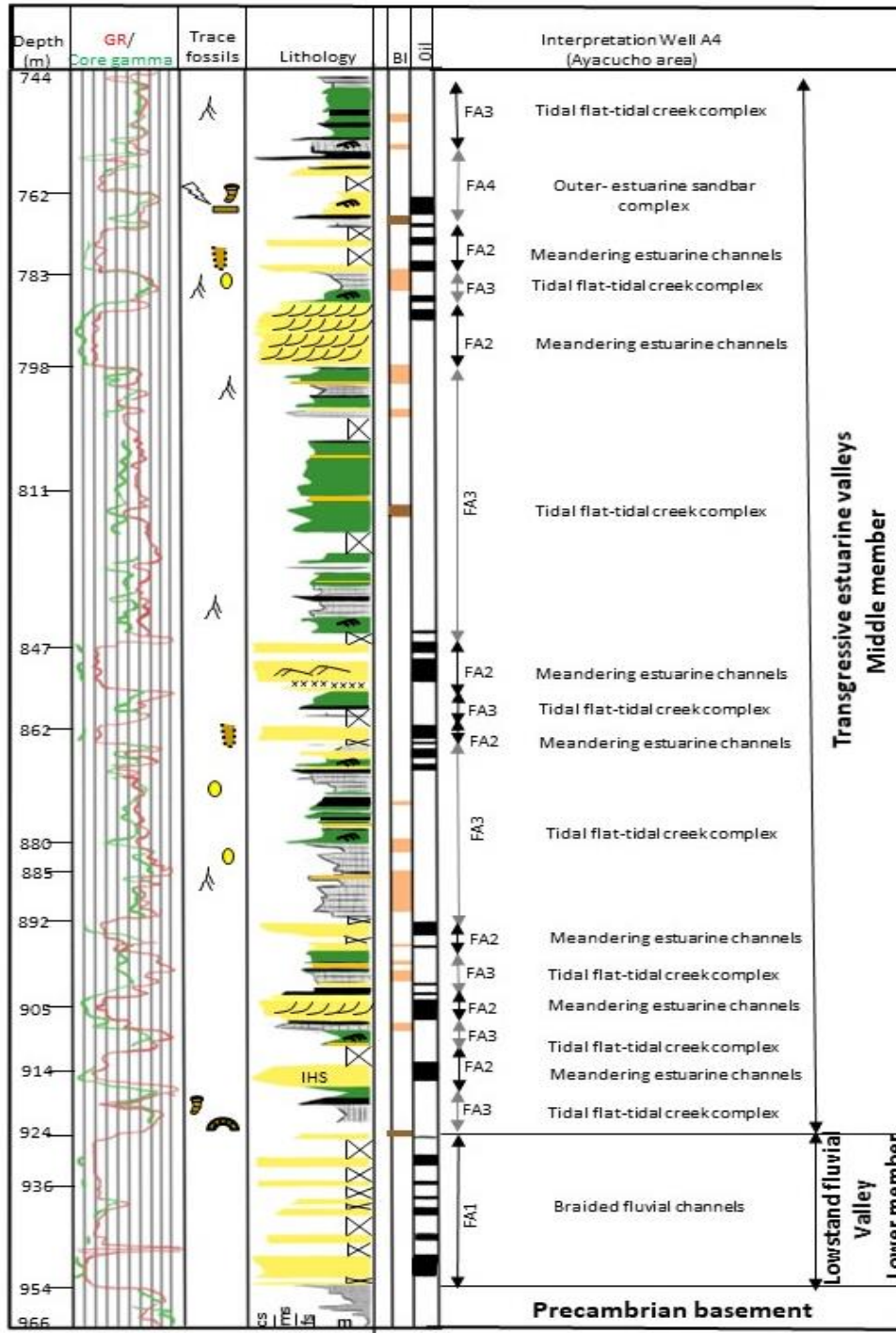
Figure 2.3. Sedimentological and ichnological log for well A4.
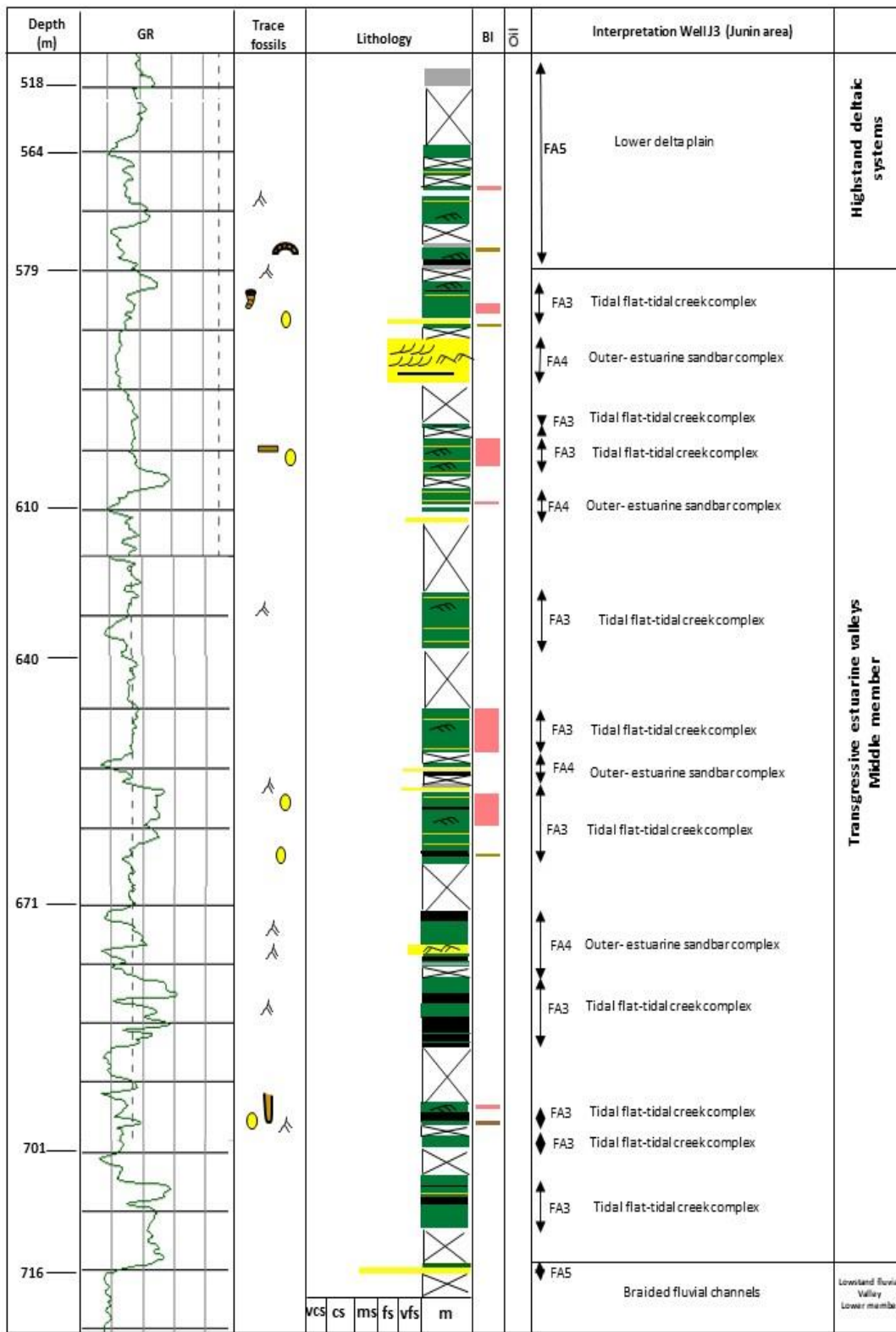
Figure 2.4. Sedimentological and ichnological log for well J3.
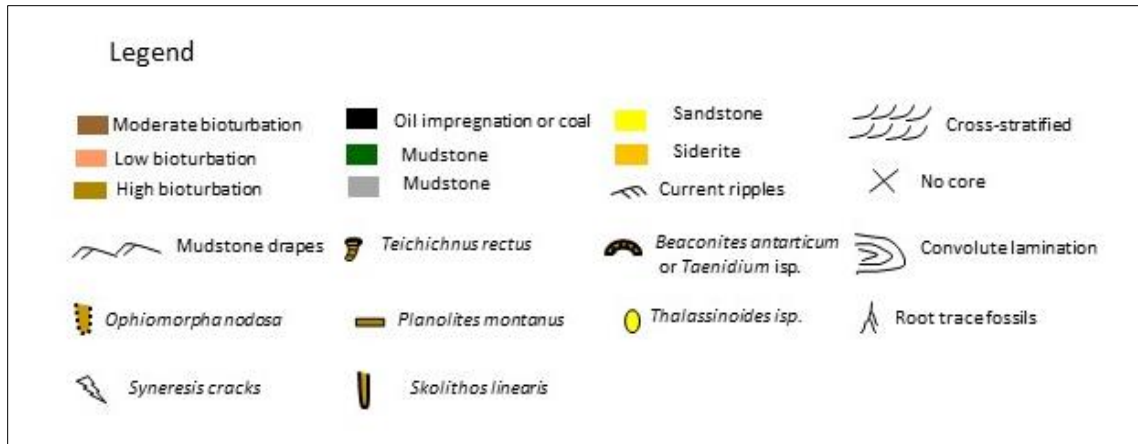
Figure 2.5. Lithology, sedimentary structures and trace fossils legend for well J3 and A4.
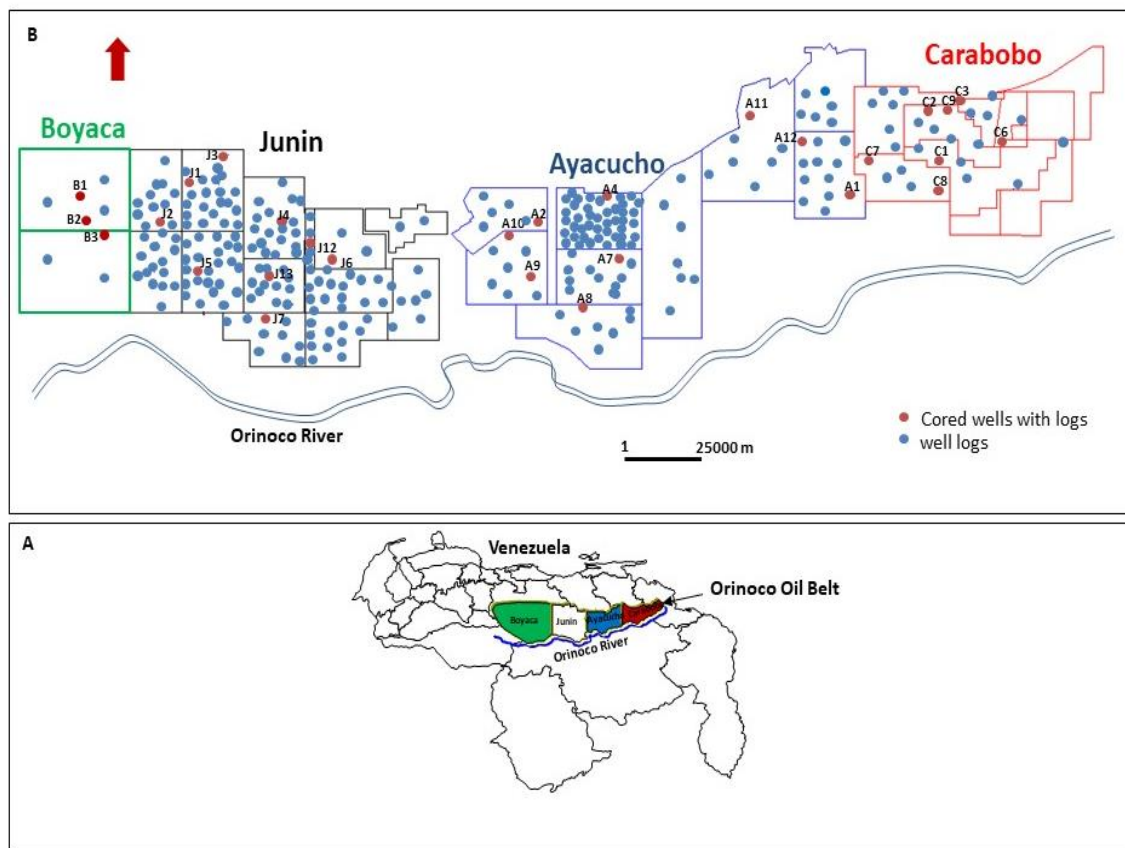
Figure 2.6. Map showing the wells used in this study. A) Map of Venezuela outlining the Orinoco Oil Belt. B) Map of the Orinoco Oil Belt showing the location of wells both with and without cores.

Table 2-1. Sedimentary Facies of the Oficina Formation in the Orinoco Oil Belt (modified from Rodríguez, 2015).

Facies			Lithology and Texture	Dominant physical sedimentary structures	Ichnology	Bed thickness (cm)	Other characteristics	Interpretation
FA Intraclast breccia			Mudstone breccia, medium- to fine-grained sandstone and mudstone, poorly sorted	Microfaults and planar cross stratification	No trace fossils	10-50		Lag deposits, cut bank margins of meandering estuarine channels
FB Cross-Stratified very coarse-to medium-grained sandstone	FB1	Massive to Planar cross-stratified sandstone with granules	Very coarse- to medium-grained gravel-rich sandstone with dispersed granules, poorly sorted	Massive to planar cross-stratification	No trace fossils	10-50	Locally parallel-laminated mudstone, mudstone and coal clasts, generally oil impregnated, argillaceous	Braided fluvial channels
	FB2	Massive to trough cross-stratified sandstone with pebbles and mudstone clast	Coarse- to medium-grained gravel- rich sandstone, poorly sorted	Massive to trough cross-stratification	No trace fossils	20-70		
FC Cross-stratified medium- to fine-grained sandstone with mudstone drapes			Medium- to fine-grained fine sandstone, well sorted	Trough and planar cross stratification	No trace fossils	10-120	Mudstone drapes	Tidal channels, tidal flat, and tidal sandbars
FD Inclined heterolithic stratified coarse- to fine-grained sandstone and mudstone			Coarse- to fine-grained sandstone	Inclined heterolithic cross-stratification	Scarce *Rosselia socialis*, *Teichichnus rectus*, *Ophiomorpha nodosa* BI: 0-1 *Beaconites antarcticum* (BI: 4-6)	30-200	Mudstone intraclasts, mudstone drapes	Estuarine and distributary channel pointbars, tidal flat, and tidal sandbars
FE Convoluted fine- to very fine-grained sandstone and mudstone			Fine- to very fine-grained sandstone, well sorted	Convolute lamination	Scarce *Ophiomorpha nodosa* BI: 0-1	10-50		Estuarine channels and tidal flats

FF Interbedded mudstone and middle- to very fine-grained sandstone	Sandstone dominated	FF1 Parallel-laminated sandstone and mudstone	Fine- to very fine-grained sandstone, well sorted, rounded clasts; mudstone	Wavy lamination (rhythmic appearance)	*Planolites montanus, Teichichnus rectus, Rosselia socialis, Skolithos linearis, Diplocraterion habichii*, escape trace fossils BI: 0-1	1-200	Mudstone drapes and flaser bedding	Tidal sand to mixed flats
		FF2 Muddy sandstone	Fine- to very fine-grained sandstone mixed with mudstone	Sandstone is interlaminated to interbedded with light to medium grey mudstone	*Ophiomorpha nodosa* (BI:0-1), undeterminate bioturbation mottling (BI: 4-5)	1-90		Tidal sand to mixed flats
	Mudstone dominated	FF3 Parallel-laminated sandy mudstone and siltstone	Mudstone with scarce very fine sand grains, well sorted	Sand grains dispersed in mudstone- and siltstone-dominated intervals	*Bergaueria* isp., *Planolites montanus, Thalassinoides* isp. BI: 2-3	1-100		Tidal mud flats
		FF4 Bioturbated siltstone and mudstone	Siltstone and mudstone	Massive appearance	*Teichichnus rectus, Thalassinoides* isp., indeterminate bioturbation mottling BI: 4-5	1-180		Tidal mud flats
		FF5 Calcareous massive mudstone with scarce limestone layers	Massive calcareous mudstone with scarce limestone layers	Massive appearance	No trace fossils	10-30	Shell remains	Tidal mud flats
FG Carbonaceous, rooted silty mudstone and thinly laminated mudstone		FG1	Mudstone	Massive to parallel-laminated, locally current ripples and flaser bedding	*Planolites montanus, Teichichnus rectus, Thalassinoides* isp., root trace fossils BI: 3-4	30-150	Syneresis cracks, abundant organic debris, and scarce mudstone clasts	Outer -estuary margin
		FG2	Mudstone and silstone	Massive to parallel-laminated, white to light gray	*Beaconites antarcticum, Planolites montanus, Taenidium* isp. BI: 4-6	30-120	Siderite nodules and bands, desiccation cracks	Floodplains, interdistributary bays and tidal flats
		FG3	Mudstone	Massive to parallel-laminated, white to light gray	Firmground *Thalassinoides* isp., *Planolites montanus*, root trace fossils BI: 1-4	50-200	Siderite nodules and bands, desiccation cracks	waterlogged paleosols
FH Coal		FH1	Coal		No trace fossils	1-60		Swamps in fluvial, estuarine and delta plain settings
		FH2	Bioturbated Coal		Woodground *Thalassinoides* isp. BI: 3-5	10-50		Swamps in estuarine system

FI Cross-Stratified very coarse- to very fine-grained sandstone	FI1	Very coarse- to medium-grained sandstone, poorly sorted	Massive sandstone	*Ophiomorpha nodosa* BI: 0-1	50-100	Sandy deposits are limited in their top or base by mudstone deposits or heterolithic zones, containing benthic foraminifera and dinoflagellates	Meandering tidal channels
	FI2	Very fine- to medium-grained sandstone with shells	Massive to planar cross-stratified	No trace fossils	10-60		Meandering tidal channels
	FI3	Very coarse- to fine-grained sandstone, poorly sorted	Massive to planar cross-stratified	No trace fossils	50-300		Meandering tidal channels

2.4.1 Facies A: Intraclast breccia

Description: Facies A consists of 10-50 cm thick, mudstone breccia, medium- to fine-grained sandstone and mudstone. The sandstone is poorly sorted (Fig. 2.7A). Beds are stacked forming facies intervals up to 1.2 m thick. This facies is barren of ichnofauna. Facies A is present in the middle member.

Interpretation: Facies A delineates the base of meandering estuarine channels. It was formed from the collapse of the associated muddy cut-bank deposits (Musial et al., 2012; Gingras et al., 2017; Brekke et al., 2017). These breccias overlie the erosional bases of the estuarine channels and indicate the thalweg position of the channels.

2.4.2 Facies B: Cross-stratified very coarse- to medium-grained sandstone

Description: Facies B consists of trough and planar cross-bedded very coarse- to medium-grained sandstone, locally displaying a structureless aspect. Beds are stacked forming facies intervals up to 12 m thick. It has been subdivided into subfacies B1 and B2. Subfacies B1 consists of 10-50 cm thick, poorly sorted, massive to planar cross-stratified, very coarse- to medium-grained, gravel-rich sandstone with dispersed granules (Fig. 2.7B). No trace fossils occur in this subfacies. Subfacies B1 occurs in the lower member.

Subfacies B2 consists of 20-70 cm thick, poorly sorted, massive to trough cross-stratified, coarse- to medium-grained gravel- rich sandstone. Trace fossils have not been recorded in this subfacies. Subfacies B2 occurs in the lower member.

Interpretation: Facies B represents the infill of braided-fluvial channels. The fluvial braided

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channel-fills are represented by stacked sandstone successions of multiple depositional units or storeys. Grain size suggests high energy conditions. These channels are characterized by two and three-dimensional dunes that migrated along the bottoms of river channels (Miall, 2010; Brekke et al., 2017), representing subfacies B1 and B2, respectively.

2.4.3 Facies C: Cross-stratified medium- to fine-grained sandstone with mudstone drapes

Description: Facies C consists of 10-120 cm thick, well-sorted, trough and planar cross-stratified, medium- to fine-grained sandstone (Fig. 2.7C-D), forming facies intervals up to 15 m thick. Mudstone drapes mantling foresets are ubiquitous. These sandstone units do not present trace fossils. Facies C is present in the middle member.

Interpretation: Facies C represents a wide variety of tidal-influenced deposits, such as meandering estuarine channels, tidal creeks, tidal sandbars and deltaic interdistributary channels. The former three record sedimentation in transgressive estuarine systems and the latter records deposition in the lower delta plain of a tide-dominated delta. The mudstone drapes suggest tidal influence and are formed during a brief slack-water period in the tide-dominated point bars (Choi et al., 2004; Hovikoski et al., 2008; Rodríguez, 2015; Gingras et al., 2016). The presence of the cross-stratal sets in the channel infills suggests migration of two and three-dimensional dunes during periods of high river discharge when the maximum tidal limit migrated seaward. FC is interpreted as a subordinate component within tidal creeks. FC also records sedimentation in outer estuarine sandbars, but facies units tend to be thinner than those representing the meandering estuarine channels. These bars are formed by the migration of two and three-dimensional dunes reflecting a high-energy setting.

2.4.4 Facies D: Inclined heterolithic stratified coarse- to fine-grained sandstone and mudstone.

Description: Facies D consists of 30-200 cm thick, coarse- to fine-grained sandstone with IHS (Fig. 2.8A-C), forming facies intervals up to 6 m thick. Trace fossils, such as *Rosselia socialis*, *Ophiomorpha nodosa, Teichichnus rectus* and *Beaconites antarcticum*, are present. Elements of the *Scoyenia* Ichnofacies (*Beaconites antarcticum)* may be overprinting elements of the depauperate *Cruziana* Ichnofacies (*Teichichnus rectus).* Facies D is present in the middle and upper members.

Interpretation: Facies D represents deposits formed in estuarine channel point bars, tidal

creeks, tidal sandbars, and distributary channel point bars. The former three record sedimentation in tide-dominated estuarine systems and the latter records deposition in the lower delta plain of a tide-dominated delta. IHS represents tidally generated deposits due to lateral accretion of point bars in meandering channels (Thomas et al., 1987; Hovikoski et al., 2008; Gingras et al., 2016). Although more commonly recorded in estuarine settings, IHS may be produced in deltaic systems as well (Choi et al., 2004; Martinius et al., 2012; Rodríguez, 2015; Solórzano et al., 2017). Trace fossil cross-cutting relationships occur in the fluvial-tidal transition area, evidencing channel abandonment and a freshwater-terrestrial infauna overprinting elements of the brackish-water suite (Diez-Canseco et al., 2015).
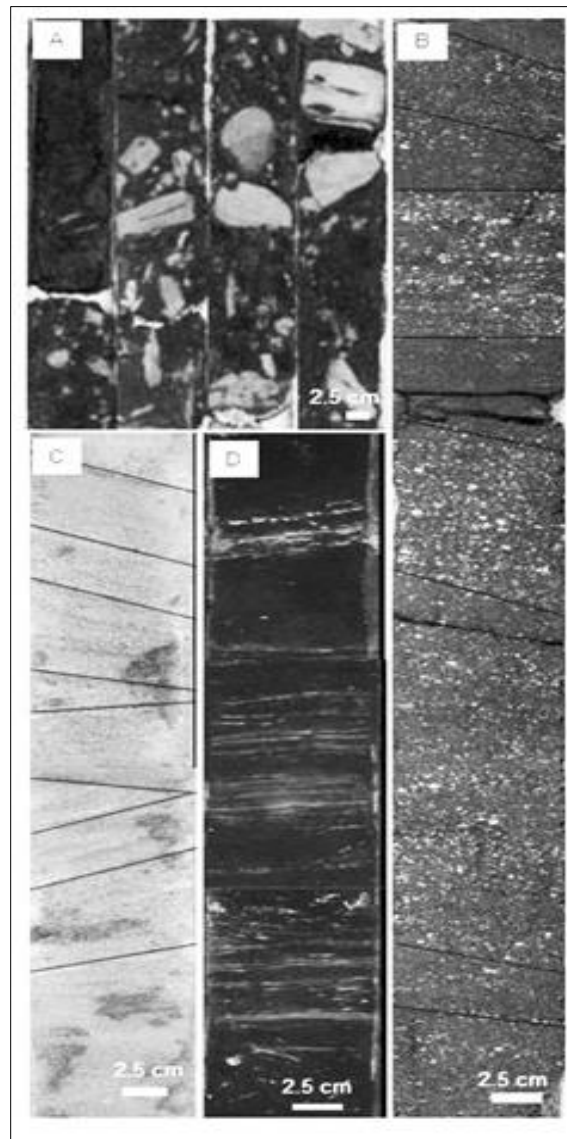
Figure 2.7. Sedimentary facies A, B and C. A: Facies A (mudstone breccias indicating the base of meandering estuarine channel deposits and formed from the collapse of the associated muddy cut-bank deposits). Well C2 (Carabobo area), depth 982.37 m. B: Facies B (braided fluvial channel deposits consisting of cross-stratified pebbly, very coarse- to medium-grained sandstone and recording migration of two and three-dimensional dunes). Well A8 (Ayacucho area), depth 514 m. C: Facies C (meandering estuarine channel deposits consisting of cross-stratified medium- to fine-grained sandstone and characterized by migration of two and three-dimensional dunes). Wells J1 (Junín area) A9 (Ayacucho area), depths 569.06 m and 372 m. D: Facies C (meandering estuarine channel deposits with mudstone drapes, which are formed during a brief slack-water period, and provide evidence of tide-dominated estuarine settings). Well A9 (Ayacucho area), depth 372 m.

FD is interpreted as a subordinate component within the tidal creeks. The absence of bioturbation in distributary-channel deposits is probably due to a combination of salinity conditions and hydrodynamic energy, namely severe brackish-water conditions and rapid migration of two and three-dimensional dunes. In contrast, the presence of trace fossils in meandering estuarine-channel deposits with IHS reflects pauses in sedimentation or slower rates of sedimentation during times of reduced energy conditions.

2.4.5 Facies E: Convoluted fine- to very fine-grained sandstone and mudstone

Description: Facies E consists of 10-50 cm thick, well-sorted, fine- to very fine-grained sandstone and mudstone with convolute lamination (Fig. 2.8D-E), forming facies intervals up to 1.5 m thick. *Ophiomorpha nodosa* is locally present, forming monospecific trace-fossil suites suggestive of the *Skolithos* Ichnofacies. Facies E is present in the middle member.

Interpretation: Facies E mostly represents meandering-channel deposits within tide-dominated estuarine systems and, to a lesser extent, tidal-flat deposits. Convolute lamination may have been formed as result of loading, rapid sedimentation or slumping (Bridge et al., 2000; Plink-Bjorklund, 2005; Hubbard et al., 2011) or may be interpreted as seismically induced (seismites) (Toro and Pratt, 2015a, b).

2.4.6 Facies F: Interbedded mudstone and medium- to very fine-grained sandstone

Description: Facies F consists of mudstone intervals or alternations of mudstone and medium- to very fine-grained sandstone. Facies F forms intervals up to 12 m thick. It has been subdivided into subfacies F1, F2, F3, F4, and F5. Subfacies F1 (Fig. 2.8F-I) consists of 1-200 cm thick, fine- to very fine-grained sandstone and mudstone. Mudstone drapes and flaser, wavy and lenticular bedding are present. In places, wave-ripple cross-lamination and low-angle cross-lamination are

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present. Ripple foresets are commonly mantled by mudstone drapes. This subfacies contains *Planolites montanus*, *Skolithos linearis* (Fig. 2.8F), *Rosselia socialis* (Fig. 2.8H), *Teichichnus rectus* (Fig. 2.8I), *Diplocraterion habichii*, and escape trace fossils (FIG. 2.8G), reflecting the presence of both th*e Skolithos* and the depauperate *Cruziana* Ichnofacies. Subfacies F1 is present in the middle member.

Subfacies F2 (Fig. 2.9A-D) consists of 1-90 cm thick, interlaminated to interbedded fine- to very fine-grained sandstone with mudstone. This subfacies contains *Ophiomorpha nodosa* (Fig. 2.9C) and indeterminate bioturbation mottling, indicative of the *Skolithos* Ichnofacies. Subfacies F2 is present in the middle member.

Subfacies F3 (Fig. 2.9E-H) consists of 1-100 cm thick, mudstone with dispersed, scarce very fine sand grains. This subfacies contains *Bergaueria* isp., *Planolites montanus* (Fig. 2.9G), and *Thalassinoides* isp. (Fig. 2.9G), reflecting the presence of the depauperate *Cruziana* Ichnofacies. Subfacies F3 is present in the middle member.

Subfacies F4 (Fig. 2.9I-M) consists of 1-180 cm thick, massive siltstone and mudstone. This subfacies contains *Teichichnus rectus*, *Thalassinoides* isp. (Fig. 2.9J and L), and indeterminate bioturbation mottling, suggestive of the depauperate *Cruziana* Ichnofacies. Subfacies F4 is present in the middle member.

Subfacies F5 (Fig. 2.10A-E) consists of 10-30 cm thick, massive calcareous mudstone (Fig. 2.10C) with scarce limestone layers (Fig. 2.10D-E) and shell remains (Fig. 2.10AB). This subfacies is barren in ichnofauna. Subfacies F5 is present in the middle member.

Interpretation: Overall, facies F represents deposition in estuarine tidal flats locally dissected by tidal creeks. In particular, subfacies F1 and F2 record deposition in tidal sand to mixed flats and subfacies F3, F4, and F5 record sedimentation in tidal mud flats. Flaser, wavy and lenticular bedding are common in, although not exclusive of, tidal-flats environments (Weimer et al., 1981; Reineck and Wunderlich, 1968; Hovikoski et al., 2008; Sisulak and Dashtgard, 2012; Gingras et al., 2016, 2017). Siderite nodules and bands, such as those present in the Oficina Formation, are particularly abundant in environments affected by fluctuating salinity (Plummer and Gostin, 1981; Postma, 1982; MacEachern et al., 2005; Hovikoski et al., 2008; Buatois et al., 2012; Martinius et al., 2012). A wide variety of mechanisms has been proposed for the generation of syneresis cracks (Fig. 2.9H), including sediment compaction and expulsion of water (White, 1961; Burst, 1965), microbial-mat stabilization (see Seilacher, 1999; Seilacher et al., 2005;

Harazim et al., 2013), clay contraction and expansion due to fluctuating salinity (Plummer and Gostin, 1981; Hovikoski et al., 2008; Martinius et al., 2012).

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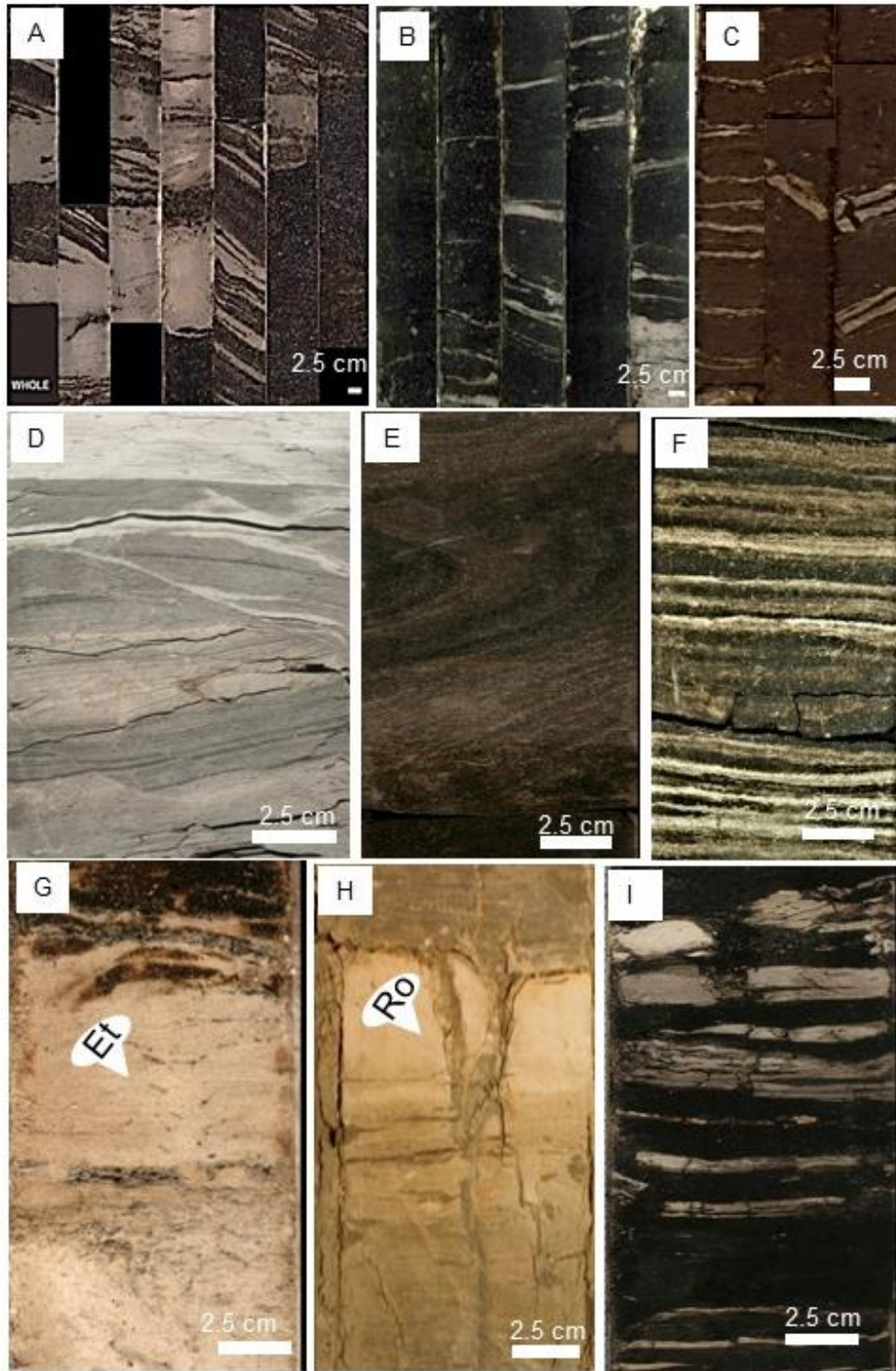
Figure 2.8. Sedimentary facies D and E and sedimentary subfacies F1. A, B and C: Facies D (meandering estuarine channel deposits with inclined heterolithic stratification formed by lateral accretion of point bars, mostly reflecting the influence of tidal currents). Wells A9, A8 (Ayacucho area), and C2 (Carabobo area), depths 374 m, 347.77 m and 890 m. D and E: Facies E (tidal flat and meandering estuarine channel deposits with convolute lamination). Wells A10 and J1 (Junín area), depths 410 m and 538 m. F, G, H, and I: Subfacies F1 (tidal flat deposits consisting of interbedded sandstone and mudstone). Wells J12 (Junín area), A12 (Ayacucho area), C1 (Carabobo area), and J1 (Junín area), depths 506 m, 891 m, 614 m, and 426 m. G shows escape trace fossil (Et) displaying the classic cone-in-cone morphology, representing rapid changes in sedimentation and H shows *Rosselia socialis* (Ro). The trace-fossil assemblage illustrates the depauperate *Cruziana* Ichnofacies, which implies formation in the estuarine valley under brackish-water conditions. Sandstone is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

Syneresis cracks also are interpreted as seismically induced (seismites), and in this context they are referred to as small dikes (Pratt, 1998, Toro and Pratt, 2015a, b; 2016). Limestone and shells indicate marine influence. *Thalassinoides* isp. forms tubular tidalites, further supporting tidal influence in these deposits (Fig. 2.9L). Tubular tidalites of inclined laminae occur only in open framework burrows, such as *Thalassinoides* (Gingras et al., 2012, 2015; Wetzel et al., 2014). Tubular tidalites have been observed in subtidal point-bar, intertidal-flat, or tidal-channel-thalweg (Gingras et al., 2015). *Thalassinoides* isp. forming tubular tidalites could be misinterpreted as *Teichichnus rectus*. However, *Teichichnus rectus* displays concave-up laminae, representing spreite. A distinct horizontal, circular to sub-circular, burrow is always present at the upper or lower end of the laminae (Pemberton et al., 1992, 2001). In addition, *Teichichnus rectus* tends to be smaller than *Thalassinoides* isp.. The presence of the *Skolithos* and depauperate *Cruziana* Ichnofacies suggest that these deposits were formed under brackish-water conditions (Solórzano et al., 2017).

2.4.7 Facies G: Carbonaceous, rooted silty mudstone and thinly laminated mudstone

Description: Facies G consists of massive mudstone and parallel- to ripple cross-laminated siltstone. Facies intervals are up to 4 m thick. It has been subdivided into subfacies G1, G2, and G3. Subfacies G1 (Fig. 2.10F-G) consist of 30-150 cm thick, massive to parallel-laminated mudstone, siltstone and sandstone, locally with current ripples, flaser bedding and syneresis cracks. This subfacies contains *Planolites montanus*, *Teichichnus rectus*, *Thalassinoides* isp., and root trace fossils, illustrative of the depauperate *Cruziana* Ichnofacies. Subfacies G1 is present in the middle member.

Subfacies G2 (Fig. 2.10I-O) consists of 30-120 cm thick, massive to parallel-laminated mudstone and siltstone with siderite nodules and bands (Fig. 2.10I-J), and desiccation cracks. This subfacies contains *Beaconites antarcticum* (Fig. 2.10L-M), *Planolites montanus*, and *Taenidium* isp. (Fig. 2.10N and O), indicative of the *Scoyenia* Ichnofacies. Subfacies G2 is present in the lower, middle and upper members.

Subfacies G3 (Fig. 2.11A-B) consists of 50-200 cm thick, massive to parallel-laminated mudstone with siderite nodules and bands, syneresis cracks. This subfacies contains firmground *Thalassinoides* isp. (Fig. 2.11A-B) overprinted to a fabric dominated by *Planolites montanus* and root trace fossils. The former reflects the presence of the *Glossifungites* Ichnofacies. Subfacies G3 is present in the lower and middle members.

Interpretation: Overall facies G represents a wide variety of coastal-plain subenvironments such as floodplains, interdistributary bays, tidal flats, and soils formed either along the margins of the estuary or in the innermost areas of the estuarine and deltaic complex.

Subfacies G1 represents low-energy deposits formed along the margins of the outer estuarine area. This subfacies displays ichnologic and sedimentologic evidence of tidal influence (e.g. flaser bedding) and salinity fluctuations. In particular, the depauperate *Cruziana* Ichnofacies suggests that these deposits were formed under brackish-water conditions (Solórzano et al., 2017). The presence of root trace fossils suggests waterlogged paleosols.

Subfacies G2 represents various environments, including floodplains in the fluvial systems, tidal flats in the fluvial-tidal transition zone of estuaries, and floodplains and interdistributary bays in the tide-dominated deltaic systems. The presence of the *Scoyenia* Ichnofacies indicates that the bulk of these deposits were formed under freshwater conditions. Although this ichnofacies is common in continental settings, it also is present in freshwater settings located between the maximum salinity and the maximum tidal limit, such as the inner estuarine and deltaic environments (Buatois et al., 1997; Mángano and Buatois, 2004; Diez-Canseco et al., 2015, 2016; Rodriguez, 2015; Solórzano et al., 2017). The local presence of desiccation cracks indicates that periodic subaerial exposure took place occasionally. The occurrence of siderite bands is consistent with freshwater environments that present low chloride concentrations as well as no dissolved sulfide and high ferrous iron content. However, siderite is not exclusive of freshwater environments, but may be present in minor proportions in brackish or fully marine settings because the presence of iron remains results in complete sulfate reduction (Postma, 1982).
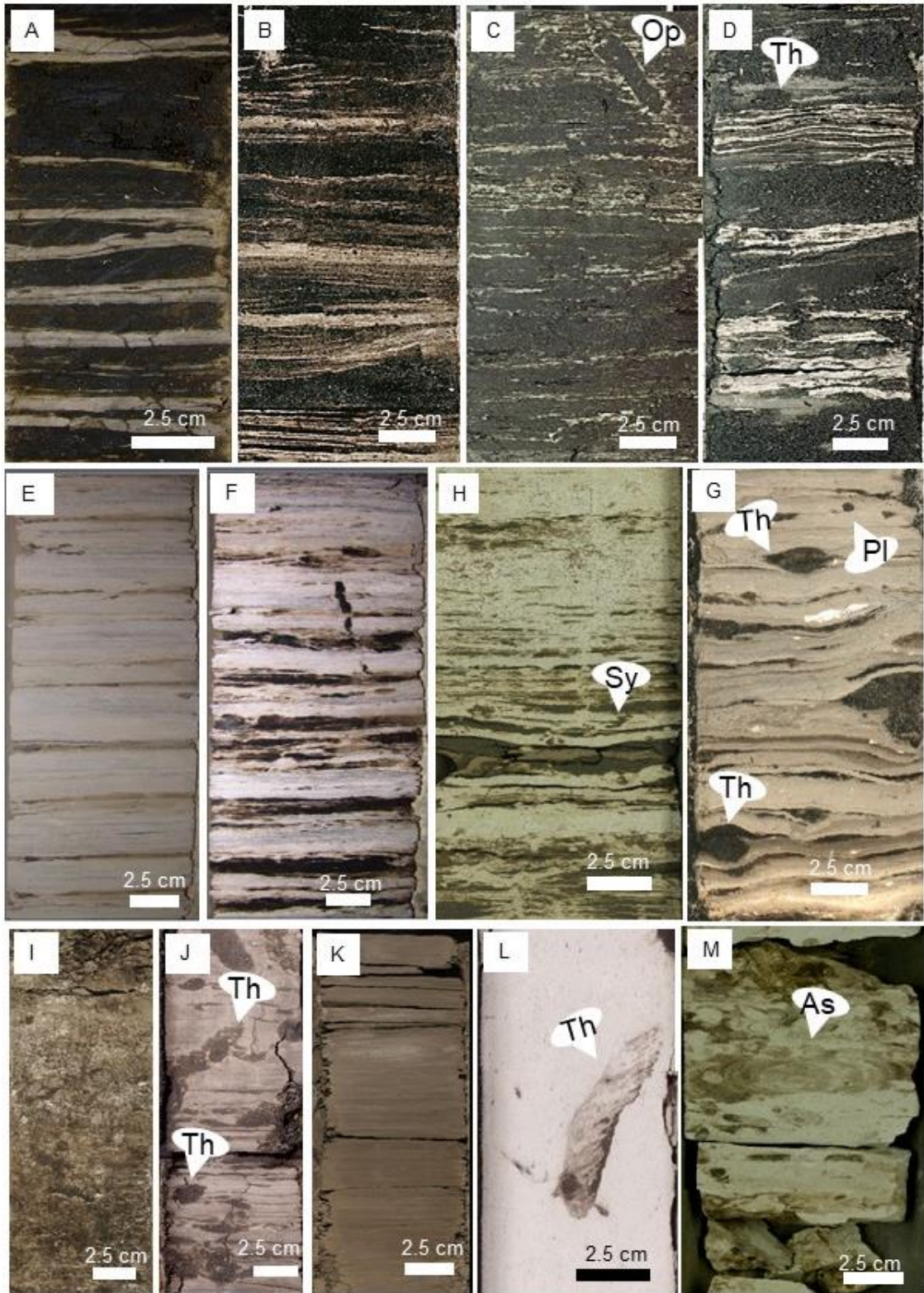
Figure 2.9. Sedimentary subfacies F2, F3, and F4. A, B, C, and D: Subfacies F2 (tidal flat deposits consisting of interbedded sandstone and mudstone, suggestive of alternating traction and suspension fallout). Wells A11 (Ayacucho area), J1 (Junín area), C8, and A8 (Ayacucho area), depths 1323 m, 506 m, 438 m, and 335 m. *Ophiomorpha nodosa* (Op) and *Thalassinoides* isp. (Th) are present in the figures C and D. The former illustrates the *Skolithos* Ichnofacies, whereas the latter indicates the presence of the depauperate *Cruziana* Ichnofacies, both ichnofacies occur under brackish-water conditions. E, F, H, and G: Subfacies F3 (tidal flat deposits consisting of mudstone-dominated heterolithics). Wells A2 (Ayacucho area), J12 and J13 (Junín area), depths 737 m, 735 m, 434 m, and 352 m. Synaeresis crack (Sy) is present in the figure H and *Thalassinoides* isp. (Th) is present in figure G indicating the presence of the depauperate *Cruziana* Ichnofacies. I, J, K, L, and M: Subfacies F4 (tidal flat deposits consisting of massive silstone and mudstone). Wells A9 (Ayacucho area), C9 (Carabobo area), J1 (Junín area), C9, J12 (Junín area), depths 449 m, 980 m, 510 m, 988m and 518 m. *Thalassinoides* isp. (Th) is present in the figures J and L, the latter with rhythmic tidal infill, and *Asterosoma* isp. (AS) is present in the figure M, reflecting the presence of the depauperate *Cruziana* Ichnofacies. Sandstone is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

Subfacies G3 represents waterlogged paleosols within fluvial and estuarine systems. In places, paleosols display the *Glossifungites* Ichnofacies, which represents transgressive surfaces of erosion (Solórzano et al., 2017). This suggests that these soils were emplaced in areas of the coastal plain that were subjected to significant wave erosion during ravinement.

2.4.8 Facies H: Coal

Description: Facies H represents coal layers, forming intervals up to 2 m thick. This facies has been subdivided into subfacies H1 and H2. Subfacies H1 consists of 1-60 cm thick, coal layers without trace fossils. Subfacies H1 is present in the lower, middle and upper members.

Subfacies H2 (Fig. 2.11D and E) consists of 10-50 cm thick, bioturbated coal layers that are penetrated by *Thalassinoides* isp., representing the *Teredolites* Ichnofacies. Subfacies H2 is present in the middle member.

Interpretation: Overall facies H records swamp deposits. The presence of coal layers indicates a high-water table. Subfacies H1 represents swamps formed in a wide variety of settings, such as fluvial, estuarine and deltaic. In contrast, subfacies H2 records swamps restricted to estuarine systems in direct association with a relative sea-level rise. In these settings, the presence of crustacean galleries attributed to the *Teredolites* Ichnofacies delineates transgressive surfaces of erosion (Solórzano et al., 2017). Following erosional exhumation of the swamp deposits during ravinement, decapod crustaceans were able to penetrate the underlying coal layer.
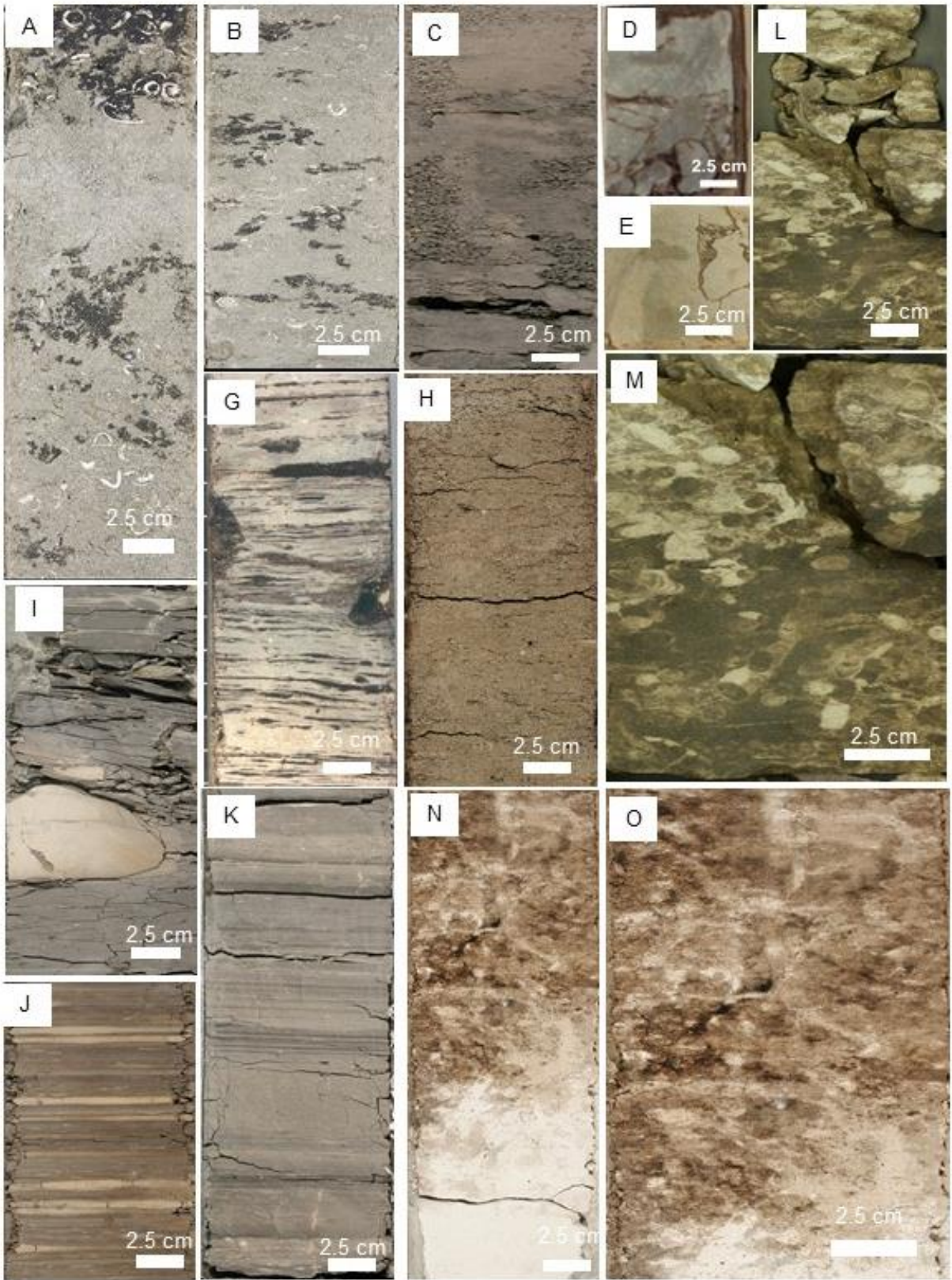
Figure 2.10. Sedimentary subfacies F5, G1, and G2. A, B, C, D, and E: Subfacies F5 (tidal flat deposits consisting of calcareous mudstone with shells and thin limestone beds). Wells A11 (Ayacucho area), A1 (Ayacucho area), and C1 (Carabobo area), depths 793 m, 794 m, 623 m, 555 m, and 549 m. A, B and C represent calcareous mudstone with shell remains, suggesting marine influence. C displays limestone layers, indicating marine influence. G and H: Subfacies G1 (outer-estuarine margin deposits consisting of massive to parallel-laminated mudstone). Wells A4, A4 and A12 (Ayacucho area), depths 807 m, 763 m and 831 m. I, J and K: Subfacies G2 (tidal flat deposits consisting of massive to parallel-laminated mudstone with siderite nodules and bands, supporting fluctuating salinity). Wells A10 (Ayacucho area), J1 (Junín area) and A10 (Ayacucho area), depths 401 m, 523 m and 410 m. L and M: Subfacies G2 (tidal flat deposits consisting of bioturbated mudstone with *Beaconites antarcticum,* indicating the presence of the *Scoyenia* Ichnofacies developed in a setting located beteween the maximum salinity limit and the maximum tidal limit). Well J12, depth 518 m. N and O: Subfacies G2 (floodplain deposits consisting of bioturbated mudstone with *Taenidium* isp., reflecting the presence of the depauperate *Scoyenia* Ichnofacies and further supporting freshwater conditions in the fluvial systems).

2.4.9 Facies I: Cross-stratified very coarse- to very fine-grained sandstone

Description: Facies I comprises massive to cross-stratified very coarse- to very fine-grained sandstone. This facies forms intervals up to 12 m thick and is restricted to the middle member.

It has been subdivided into subfacies I1, I2 and I3. Subfacies I1 (Fig. 2.11F and G) consists of 50-100 cm thick, poorly sorted, massive, very coarse- to medium-grained sandstone with *Ophiomorpha nodosa,* representing the *Skolithos* Ichnofacies.

Subfacies I2 (Fig. 2.11I and J) consists of 10-60 cm thick, unbioturbated, poorly sorted, massive to planar cross-stratified, very fine- to medium-grained sandstone with shells.

Subfacies I3 consists of 50-300 cm thick, unbioturbated, poorly sorted, massive to planar cross-stratified, very coarse- to fine-grained sandstone. Subfacies I1, I2, and I3 are intercalated within mudstone deposits that contain foraminifers, calcareous nannoplankton and dinoflagellates.

Interpretation: Overall, facies I represents meandering channels within estuarine systems. Facies I is distinguished from similar deposits formed in the fluvial segment of the Oficina Formation based on paleontologic evidence. In Subfacies I1, the presence of *Ophiomorpha nodosa* at the top of channel fill units indicates that these channels were marine influenced during their abandonment, most likely as a result of a relative sea-level rise. In Subfacies I2, marine influence is evidenced by the occurrence of remains of shells associated to transgressive events. These channels were characterized by the migration of two-dimensional dunes during periods of high river discharge when the maximum tidal limit migrated seaward. In subfacies I3, the key evidence to detect marine influence is the presence of a marine microfauna and plankton in interbedded mudstone deposits. As in the case of subfacies I2, migration of two-dimensional dunes is apparent.
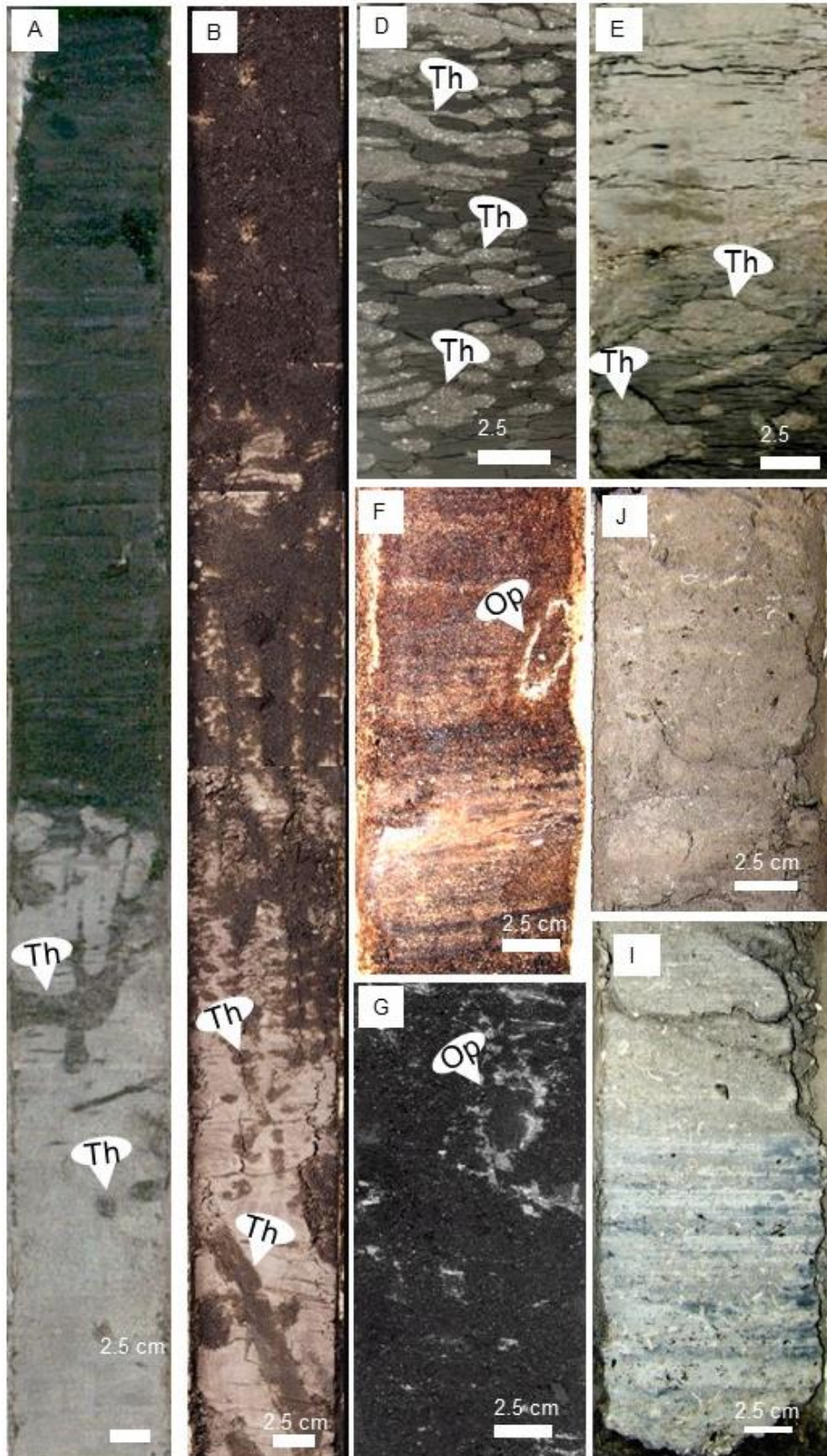
Figure 2.11. Sedimentary subfacies G3, H1, H2, I1, and I2. A and B: Subfacies G3 (firmground *Thalassinoides* isp. (Th) penetrating into paleosol and tidal flat deposits, respectively, from an overlying transgressive surface). Wells A4 (Ayacucho area) and C9 (Carabobo area), depths 862 m and 979 m. D and E: Subfacies H2 (woodground *Thalassinoides* isp. (Th) penetrating from an overlying transgressive surface into a coal layer of swamp origin). Well A8 (Ayacucho area), depths 326.44 m and 301 m. F and G: Subfacies I1 (meandering estuarine channels with *Ophiomorpha nodosa* (Op) indicating marine influence). Wells A9 (Ayacucho area) and C-10 (Carabobo area), depths 376.73 m and 908 m. I and J: Subfacies I2 (meandering estuarine channel deposits with calcareous sandstone and shells, further supporting marine influence in the estuarine systems). Well A2 (Ayacucho area), depths 698.60 m and 706 m. Sandstone (A, B, and G) is impregnated with hydrocarbon resulting in dark color, mudstone (A, B, and E) is light color, and coal (D and E) is from gray to brown color.

2.5. Facies Associations, Depositional Environments and Relative Sea-level Changes

The sedimentary facies (FA-I) of the Oficina Formation along the Orinoco Oil Belt allow recognition of five facies associations, labeled FA1 to FA5. These are stacked forming a single second-order depositional sequence.

2.5.1. FA1: Fluvial braided channels

FA1 (Fig. 2.12 and 2.13A) consists of fluvial braided channels (FB), floodplains (FG2), swamps (FH1), and paleosols (FG3), and is present in the lower member. The fluvial braided channel-fills are represented by high-energy stacked sandstone successions of multiple depositional units. Scarce mudstone and siltstone layers record limited development of floodplain settings, indicating fluvial channels of low sinuosity. The lack of lateral accretion beds and the coarse grain size of the channel fills also suggest that the rivers were of relatively low sinuosity (Bridge et al., 2000; Plink-Bjorklund, 2005). Pebbly mid-channel bars and channel bifurcation may have been dominant in these fluvial systems, most likely resulting from a local decrease in flow velocity or a change of slope (Rodríguez et al., 2018). Channel bars are represented by thick accumulations of cross-stratified sands formed mostly by frontal accretion due to unidirectional currents. Amalgamation of sandstone indicates multy-storey channels. Root trace fossils and waterlogged paleosols suggest that the areas between the channels may have been characterized by some ponded and vegetated areas (Plink-Bjorklund, 2005). The presence of swamp deposits is also consistent with a high water table in the alluvial plain. In these fluvial deposits, the *Scoyenia* Ichnofacies occurs in floodplains located above fluvial braided-channels, further supporting freshwater conditions. These floodplain deposits are strongly bioturbated, reflecting long colonization windows in overbank settings

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(Buatois and Mángano, 2004). The presence of palynomorphs and the absence of foraminifers and calcareous nannoplankton is consistent with freshwater conditions. FA1 is restricted to paleotopographic lows where it represents the infill of incised fluvial valleys, recording the LST.
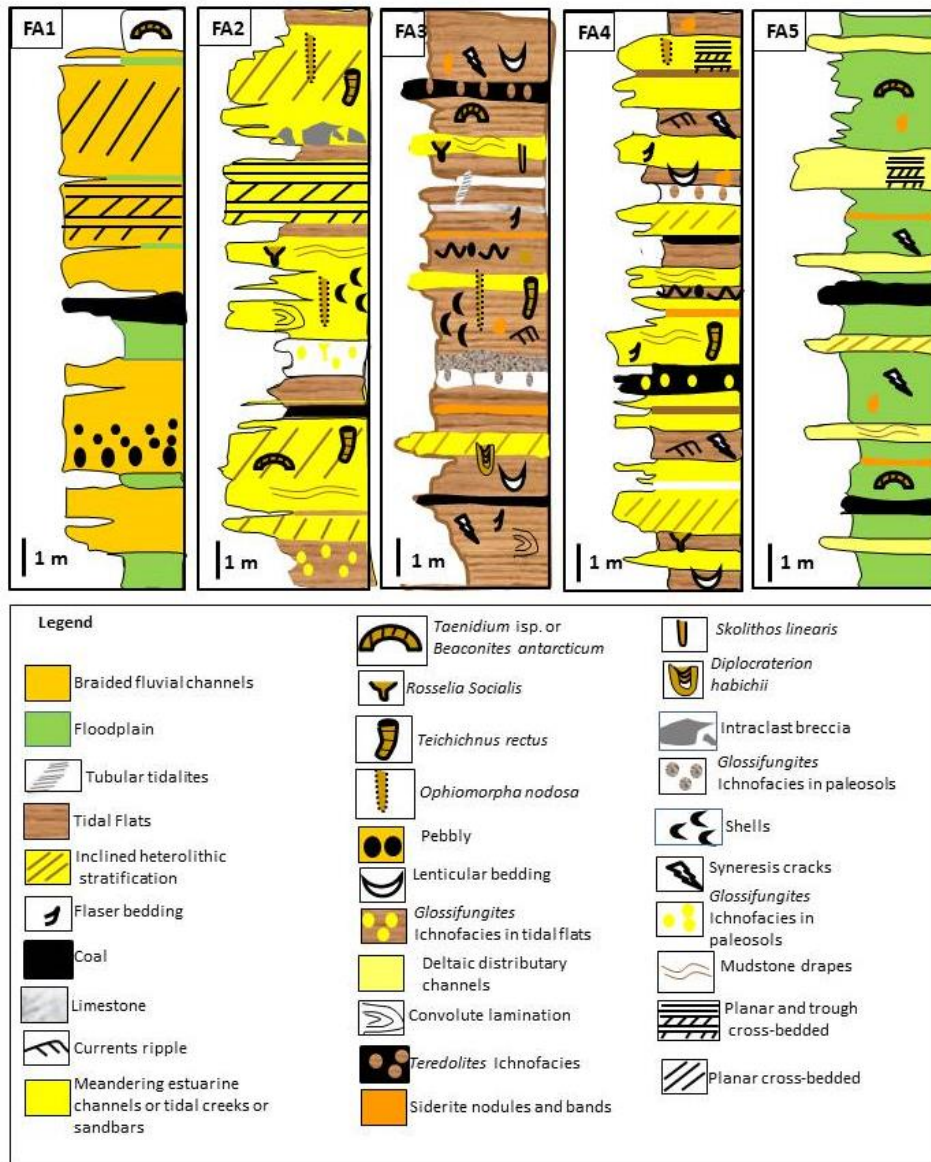
Figure 2.12. Idealized sedimentary columns for each facies association. FA1: (fluvial systems). FA2, FA3 and FA4: (estuarine deposits). FA5: (deltaic systems).

2.5.2. FA2: Meandering estuarine channels

FA2 (Fig. 2.12 and 2.13A) consists of meandering estuarine channels (FA, FC, FD, FE, and FI), and is present in the middle member. Estuarine channels from the Oficina Formation were mostly

formed by IHS resulting from lateral accretion of point bars (Thomas et al., 1987; Plink-Bjorklund, 2005; Hovikoski et al., 2008; Gingras et al., 2016, 2017). Associated mudstone drapes and marine/brackish trace fossils suggest tidal influence (Buatois et al., 2002; Plink-Bjorklund, 2005; Lettley et al., 2009; Musial et al., 2011; Hovikoski et al., 2008; Hubbard et al., 2011; Gingras et al., 2016; Solórzano et al., 2017; Rodríguez et al., 2018). Soft-sediment deformation was locally important. In places, the bases of these channels are mantled by breccias, which represent lag deposits. Amalgamation of sandstone indicates multiple stacked channels. Channel deposits with IHS emplaced in the inner zone of the estuarine valleys display continental meniscate backfilled structures overprinting a brackish-water trace fossil. Also, estuarine-channel deposits are commonly intercalated with mudstone layers containing a marine fauna, which provides further evidence of a basinwide sea-level rise. The stratigraphic position of FA2 resting on top of FA1 indicates a retrogradational stacking pattern, signaling marine flooding of fluvial valleys and their transitioning into transgressive estuarine systems. Therefore, channelized-estuarine deposits represent the early TST. Biostratigraphic evidence indicates that these estuarine channels were formed during the Langhian transgression (Solórzano et al., in review).

2.5.3. FA3: Tidal flat and creek complex

FA3 (Fig. 2.12 and 2.13A) represents tidal flats and tidal creeks (FC, FD, FE, FF, and FG2), swamps (FH1 and FH2), and paleosols (FG3), and is present in the middle member. The tidal flats are widely developed along the length of the estuarine system and are dissected by tidal creeks. The local presence of IHS in the tidal-creek deposits indicates minor participation of lateral accretion and limited formation of point bars (Thomas et al., 1987). The fact that IHS is relatively rare in these deposits indicates stable tidal creeks, which in turn allowed the preservation of horizontally bedded, associated tidal-flat deposits (Dashtgard et al., 2014; Rodríguez et al., 2018). Tidal-flat deposits are characteristic of modern tide-dominated macrotidal estuaries (Hamilton, 1979; Lambiase, 1980; Dalrymple et al., 1990; Dalrymple, 1992). The local presence of symmetric ripples in sand-dominated heterolithic facies suggests that intertidal areas were characterized by wave-dominated tidal flats similar to those that occur along the Korean coast (Yang et al., 2005, 2006, 2008). These deposits also display the *Skolithos* and depauperate *Cruziana* Ichnofacies, which indicate brackish-water conditions, mostly reflecting the influence of tidal currents in marginal-marine, restricted settings (Solórzano et al., 2017). In addition, high sedimentation rates

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and water turbidity, indirectly controlled by the tides, may have limited the diversity of infauna in these tidal flats (Dashtgard et al., 2014). In places, the *Glossifungites* and *Teredolites* Ichnofacies are present in tidal flat and swamp deposits, respectively, indicating erosional exhumation during ravinement. Dinoflagellates, foraminifers, calcareous nannoplankton, and bivalve shells provide further evidence of marine influence. FA3 represents part of the late TST. The tidal-flat deposits were formed during a late phase of the Langhian transgression (Solórzano et al., in review).

2.5.4. FA4: Outer-estuarine sandbar complex

FA4 (Fig. 2.12 and 2.13A) consists of outer estuarine sandbars (FC, FD, FG1), paleosols (FG3), and swamps (FH2), and is present in the uppermost interval of the middle member. The occurrence of thinner IHS strata suggests that laterally accreted, free-standing tidal bars may have been dominant in the outer zone of the Oficina valley (Rodríguez et al., 2018). Sandbars were emplaced in the estuary mouth close to the zone of maximum turbidity as indicated by the abundance of mudstone units (Jouanneau and Latouche, 1981; Dalrymple et al., 1990; Allen, 1991; Dalrymple, 1992). Estuarine sandbars were flanked by swamps and waterlogged soils. In places, these deposits display *Thalassinoides* in both firmgrounds and woodgrounds, evidencing erosional exhumation of the substrate during wave ravinement. Although at the seaward end of the estuary, these deposits record brackish-water conditions as revealed by a low diversity of trace fossils; this is consistent with the overall embayed nature of the Oficina Formation in the Orinoco Belt (Solórzano et al., 2017). FA4 represents part of the late TST. Establishment of the estuarine sandbar complex took place during the latest stage of the Langhian transgression (Solórzano et al., 2017, in review).

2.5.5. FA5: Lower delta plain of a tide-dominated delta

FA5 (Fig. 2.12 and 2.13B) consists of distributary channels (FC and FD), floodplains and interdistributary bays (FG2), and swamps (FH1), and is present in the upper member. The lower delta-plain deposits display tidal influence as indicated by the presence of IHS and mudstone drapes in the distributary channels. These channels are sparse, thin, rarely amalgamated, and are separated by widespread floodplains and interdistributary bays, suggesting extensive wetland development in the lower delta plain. As in the case of the estuarine deposits, FA5 also is affected by fluctuating salinity and periodic subaerial exposure. The presence of meniscate trace-fossils of the *Scoyenia* Ichnofacies within floodplain deposits indicates the establishment of a continental

invertebrate fauna in the lower delta-plain deposits (Rodríguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). The Orinoco Oil Belt delta complex was emplaced within a brackish-water embayment rather than in the open sea. Coeval open-marine deposits of the Oficina Formation occur in the Oritupano field, outside the Orinoco Oil Belt (Solórzano et al., 2017). The stratigraphic occurrence of FA5 resting on top of FA4 indicates a progradational stacking pattern. FA5 represents the HST.
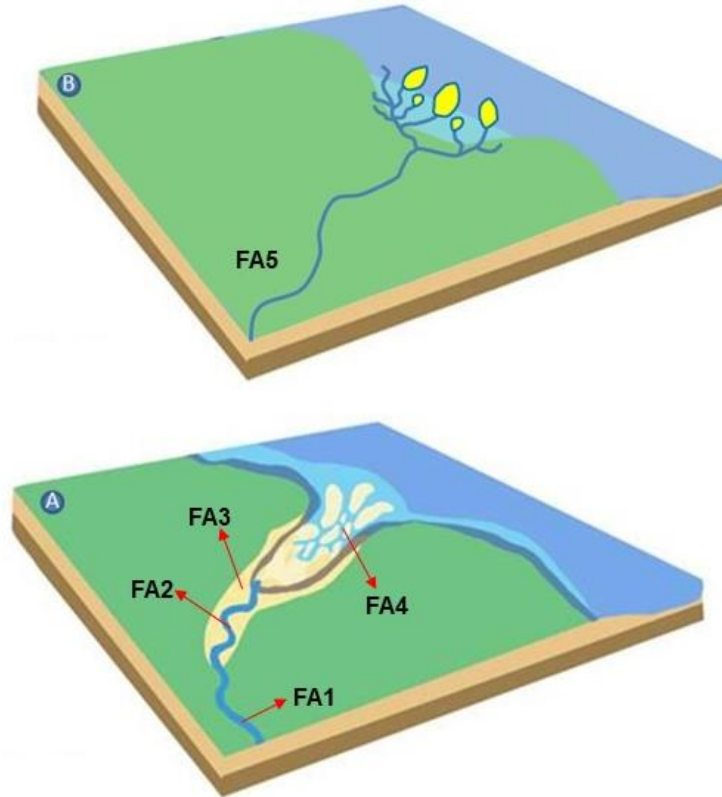
Figure 2.13. Schematic reconstruction of paleoenvironments for the Oficina Formation in the Orinoco Oil Belt. A: (fluvial and transgressive estuarine deposits). B: (highstand deltaic deposits).

2.6. Discussion

2.6.1. Regional changes in stratal architecture

Sea-level changes and regional tectonics played a significant role on sedimentation in the Orinoco Belt because they controlled erosion and infilling of the incised-valleys, as well as the history of changes in accommodation potential in the basin. Additional evidence for the tectonic control is the wedge-shaped geometry and facies architecture of sediments (Obi and Okogbue, 2004). The

Orinoco Oil Belt comprises a prism of Cenozoic sediment wedging toward the south (Latreille et al., 1983; Audemard et al., 1985; Isea et al., 1987; Parnaud et al., 1995). The Oficina Formation was deposited during the oblique collision phase between the Caribbean and South American plates (Parnaud et al., 1995), with the area being subjected to strong tectonic events that controlled sedimentation (Audemard et al., 1985; Martinius et al., 2012).

West to east stratigraphic cross-sections along the Orinoco Oil Belt show that the fluvial units extend from the Junín to Carabobo areas, being thinner toward the Ayacucho and Carabobo areas. Based on north to south stratigraphic cross-sections, the thicknesses of the fluvial deposits range from 0 to 167 m increasing towards the north and decreasing towards the south (Figs. 2.14, 2.15). In the Junín area, from north to south, the fluvial deposits decrease in thickness (41-167 m), resting on top of Cretaceous or Pre-Cretaceous strata (Fig. 2.14). In the Ayacucho and Carabobo areas, the fluvial deposits overlie the metamorphic-igneous basement, which could have controlled sedimentation in these fluvial systems by reducing accommodation potential. In fact, fluvial deposits are directly absent in some zones of the Carabobo area (e.g. C8 and C9). Therefore, the estuarine systems in these wells directly overlie the metamorphic-igneous basement. In areas of reduced accommodation space, not all the units are preserved (Hein et al, 2013). Fluvial units thin southward, eventually disappearing altogether (e.g. B4, A13) (Audemard et al., 1985). In the Ayacucho (24-68 m) and Carabobo (0-46 m) areas, the fluvial units decrease in thickness from north to south (Fig. 2.15). Fluvial deposits reach their maximum thicknesses westward in the Junín and Boyacá areas, because of increased subsidence caused by the compaction of the Pre-Cretaceous sediments, particularly north of these two areas (Audemard et al., 1985). The lower part of the Oficina Formation was mainly controlled by compressional tectonic activity (Martinius et al., 2012), and is generally restricted to paleotopographic lows on the Cretaceous or Pre-Cretaceous unconformity. The influx of sediments could have come from the nearby Guayana Shield in the south. On a regional scale, the lower member shows south-southwest to north-northeast trending fluvial channels (Solórzano et al., in review). The fluvial units represent the infill of incised-valley systems, which were formed during a relative sea-level fall.

West to east stratigraphic cross-sections along the Orinoco Oil Belt indicate that the estuarine units extend from the Junín to Carabobo areas, being thinner in the latter. Based on north to south stratigraphic cross-sections, the thicknesses of the estuarine deposits range from 39 to 288 m, increasing towards the north (Figs 2.14, 2.15). The thickness of the estuarine interval is greater
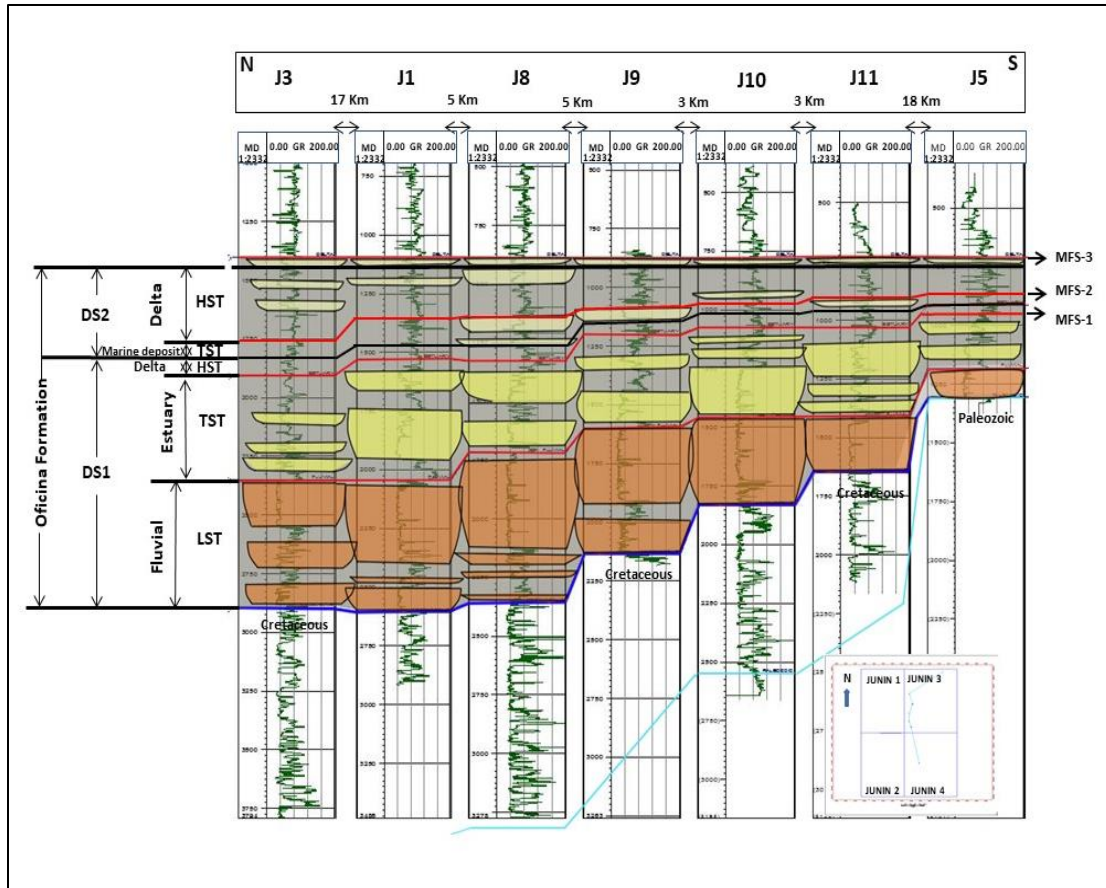
Figure 2.14. North to south stratigraphic correlation panel showing the paleoenvironmental and sequence-stratigraphic interpretation in the western part of the Orinoco Oil Belt (Junín area). Geophysical data shown in the gamma-ray log, from 0 to 200 API units.

than that of the fluvial systems in the Ayacucho and Carabobo areas, probably due to the space available to accommodate sediments, while in the Junín area the thickness of the fluvial and estuarine units is very similar. Estuarine facies are thicker in the Ayacucho (151-288 m) and Junín (54-155 m) areas than in the Carabobo (39-143 m) area. The middle member displays estuarine channels that are oriented similar to the underlying fluvial channels and that display increased marine influence towards the north-northeast (Solórzano et al., in review).

West to east stratigraphic cross-sections through the Orinoco Oil Belt demonstrate that the deltaic units extend from the Junín to Carabobo areas, being thicker towards the latter. Based on north to south stratigraphic cross-sections, the thickness of the deltaic deposits ranges from 40 m to 475 m, increasing towards the north (Figs. 2.14, 2.15). Deltaic strata are thicker in the Carabobo area (384-475 m) than in the Junín (40-134 m) and Ayacucho (140-220 m) areas, probably due to the space available to accommodate sediments. On a regional scale, the upper member shows

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distributary channels that open seaward towards the north-northeast (Solórzano et al., in review). The adjacent Oritupano Oil Field, located northeast of the Orinoco Oil Belt, hosts deposits formed in strandplain environments and in deltaic systems that prograded into the open sea rather than a restricted embayment (Solórzano et al., 2017).

2.6.2. Comparison with other tide-dominated marginal-marine environments

The fluvio-estuarine and deltaic systems of the Oficina Formation compare favorably with other tide-dominated, ancient marginal-marine strata and modern settings which display similar sedimentologic, stratigraphic and ichnologic characteristics. These include deposits of various ages formed under a wide variety of latitudinal and tectonic settings.

2.6.2.1 Carboniferous of the United States Midcontinent

Carboniferous tidal-influenced and tide-dominated marginal-marine deposits formed in Equatorial settings are widespread in the United States Midcontinent (Lanier, 1993; Lanier et al., 1993; Gibling et al., 1993; Archer et al., 1994; Kvale and Barnhill, 1994; Feldman et al., 1995; Buatois et al., 1997, 1998; Mángano and Buatois, 2004). Tidal clastics are separated by laterally persistent transgressive marine limestone units, forming classic late Paleozoic cyclothems (Heckel, 1977). In particular, exposures in Kansas and Missouri typically form northeast-southwest trending narrow outcrop belts. One of these units is the Douglas Group, which encompasses two estuarine valleys, namely the Tongaxonie and Ireland paleovalleys (Archer et al. 1994; Feldman et al., 1995). The Tonganoxie valley was incised during the latest Missourian sea level fall and filled during the earliest Virgilian transgression (Lanier, 1993; Lanier et al., 1993; Gibling et al., 1993; Archer et al., 1994; Feldman et al., 1995; Buatois et al., 1997, 1998; Mángano and Buatois, 2004). This valley is about 41 m deep, 11 km wide, and 240 km long (Feldman et al., 1995), recording southwesterly flowing rivers and ebb dominated tidal dunes, which reverted to a flood dominated tidal system during the subsequent transgression (Gibling et al., 1993). The Ireland paleovalley has not been documented with the same degree of detail, but it is thought to be similar to the Tonganoxie paleovalley (Archer et al., 1994). Tidal flat deposits are ubiquitous in these paleovalleys. As is the case of proximal deposits in the Oficina Formation, those tidal flats located close or at the fluvio-estuarine transition are characterized by an ichnofauna recording a mixed terrestrial-freshwater biota (Buatois et al., 1997, 1998; Mángano et al., 1997; Mángano and

Buatois, 2004). However, and in contrast to those from the Oficina Formation, these Carboniferous ichnofaunas consist of very shallow-tier trace fossils, dominantly arthropod trackways and grazing trails, rather than meniscate trace fossils (Diez-Canseco et al., 2015). Heterolithics representing deposition in the intertidal to subtidal zones of the middle estuary are characterized by a depauperate ichnofauna, which is regarded as typical of brackish-water settings (Archer et al., 1994; Mángano and Buatois, 2004). A similar trace-fossil assemblage is widespread in estuarine deposits of the Oficina Formation. The outer region of these paleovalleys is characterized by tabular, parallel-laminated sandstone representing deposition in upper-flow regime sand flats similar to those recorded in the Bay of Fundy of Canada (Archer et al., 1994). Whereas these high-energy deposits are unbioturbated, those corresponding to lower-energy tidal flats emplaced outside of the estuarine embayment contain abundant marine fauna and a highly diverse ichnofauna (Archer et al., 1994; Mángano and Buatois, 2004).
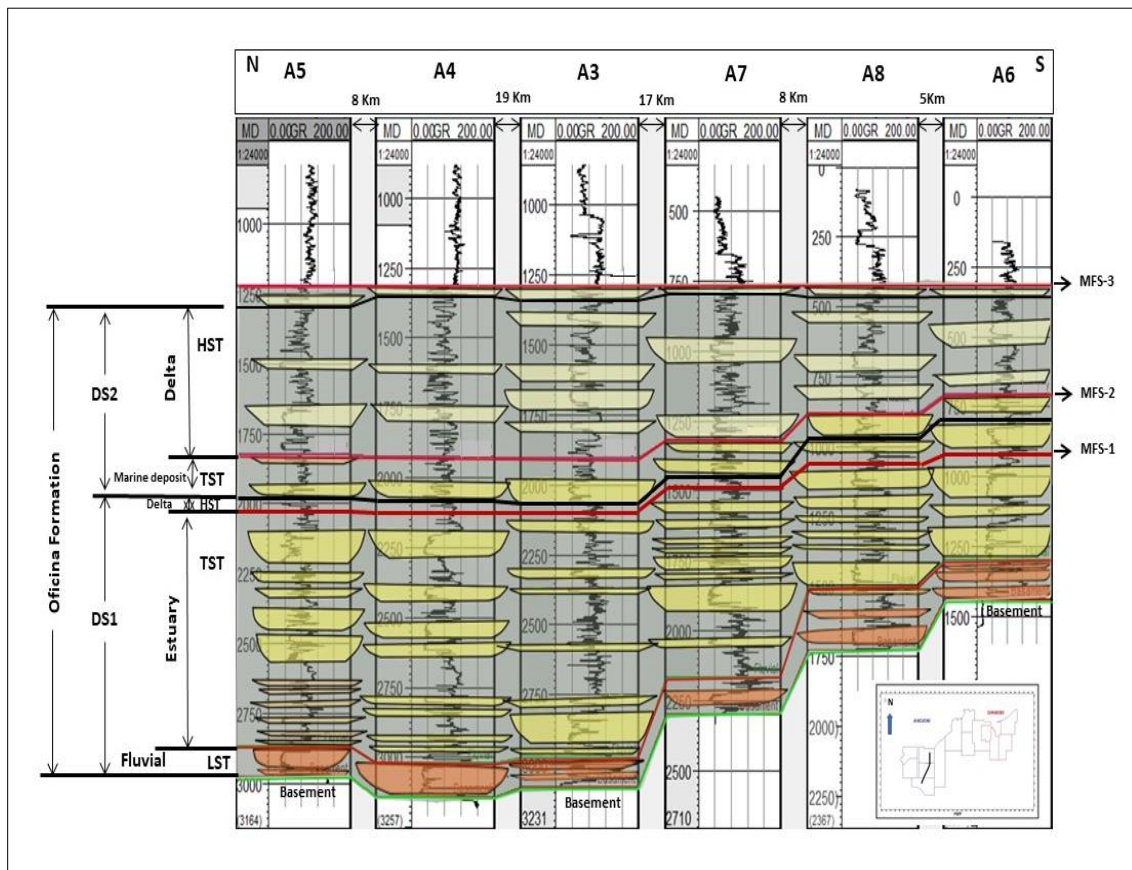
Figure 2.15. North to south stratigraphic correlation panel showing the paleoenvironmental and sequence-stratigraphic interpretation in the eastern part of the Orinoco Oil Belt (Ayacucho area). Geophysical data shown in the gamma-ray log, from 0 to 200 API units.

Finally, outer-estuarine deposits similar to those present in the Oficina Formation have been recorded in the Bandera Shale Formation of Kansas. These deposits comprise flaser- and wavy-bedded sandstone and shale and large-scale cross-stratified sandstone. Mudstone rip-up clasts and flat-topped ripples are locally present. Sinuous crested dunes are preserved at the top of large-scale cross-stratified sandstone, whereas current ripples are locally preserved on the slip face of duneforms (Brownfield et al., 1998). The Bandera Shale Formation records deposition in both tidal-flat and subtidal sandbar settings in a similar fashion to outer-estuarine deposits of the Oficina Formation. Sand was transported to the basin by rivers incised during a sea level fall and reworked by marine processes during the subsequent transgression.

2.6.2.2. Cretaceous McMurray Formation of northern Alberta, Canada

The Oficina Formation (heavy and extra heavy oil) and the Cretaceous McMurray Formation (bitumen) of northern Alberta, Canada represent two of the most important oil accumulations in the world. The two units display similarities not only from a sedimentary facies perspective, but also with respect to trace-fossil distribution and stratal stacking pattern. As with the Oficina Formation, the McMurray Formation contains lowstand fluvial deposits in the lower member, transgressive estuarine deposits in the middle member, and highstand open-bay delta and offshore deposits in the upper member (Crerar and Arnott, 2007; Musial et al., 2012; Harris et al., 2016; Gingras et al., 2016). The fluvial deposits consist of cross-stratified pebble- to very coarse-grained sandstone formed in braided channels, hosting a freshwater ichnofauna similar to that of the Oficina Formation (Musial et al., 2012). The estuarine systems comprise estuarine channels with point bars having IHS formed by lateral accretion (Musial et al., 2012; Gingras et al., 2016; Solórzano et al., 2017). The tidal-flat deposits consist of horizontal, wavy- to lenticular-bedded heterolithic facies (Gingras et al., 2016). Channel and tidal-flat deposits show variable intensities of bioturbation and display low to moderate ichnodiversity, representing the activity of an impoverished marine fauna (Gingras et al., 2016; Solórzano et al., 2017) as is the case of the Oficina Formation (Rodríguez 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Dinoflagellates are present in the middle members of the McMurray and Oficina formations, albeit occurring in lower abundance than terrestrially derived palynomorphs (Gingras et al., 2016; Solórzano et al., 2017). The upper member of the McMurray Formation comprises a wide variety of environments, such as open bay deltas, including wave- and storm-dominated prodelta to delta

front settings, and marine offshore (Gingras et al., 2016; Solórzano et al., 2017). Although the Oficina Formation in the Orinoco Oil Belt records deposition in lower delta plain settings, a wider variety of environments have been identified in the nearby Oritupano Oil Field (Solórzano et al., 2017), further underscoring similarities with the McMurray Formation.

2.6.2.3. The Eocene Ameki Group of south-eastern Nigeria

The Eocene Ameki Group of south-eastern Nigeria records deposition in a tide-dominated estuarine system covering an area of about 780 km^2. Similar to the Oficina Formation in the Orinoco Oil Belt, the Ameki Group consists of lowstand fluvial deposits in the basal part, transgressive estuarine deposits in the middle part and highstand estuarine embayment in the upper part (Ekwenye et al., 2017). The fluvial deposits are characterized by cross-bedded, pebbly, very coarse- to medium-grained sandstone forming fluvial channel-fills. These deposits are barren in ichnofauna (Ekwenye et al., 2017). Tidally-influenced fluvial channels with IHS in sandstone-dominated units indicate estuarine deposits. Mudstone breccias, mudstone drapes, herringbone, wavy lamination, flaser and lenticular bedding are present. The tide-dominated estuarine systems display tidal channels with point bars having IHS formed by lateral accretion (Ekwenye et al., 2017). Tidally-influenced fluvial-channel and tidal-channel deposits are remarkably similar to those of the Oficina Formation (Rodríguez 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Tidal-flat and tidal-creek deposits consist of parallel-laminated mudstone and bioturbated, ripple cross-laminated and cross-bedded, fine-grained sandstone. Sandbar deposits were divided into inner and outer (Ekwenye et al., 2017). Outer-estuarine tidal-sandbar deposits consist of cross-bedded, very coarse- to medium-grained sandstone. Mudstone drapes and flaser and wavy bedding are present. Inner-estuarine tidal-sandbar deposits consist of bioturbated and ferruginized sandstone overlying pebbly units. Overall, these estuarine deposits record a low-diversity brackish-water ichnofauna that illustrates the *Skolithos* and depauperate *Cruziana* Ichnofacies (Ekwenye et al., 2017), further underscoring similarities with the Oficina Formation (Rodríguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Similar to the Orinoco Oil Belt, an estuarine embayment or open estuarine has been interpreted in the upper part of Ameki Group. These deposits consist of mudstone, shale, coal, and siltstone with ostracods, gastropods, and foraminifers (Arua 1981, 1988; Ekwenye et al., 2017). Woodground *Teredolites* isp. is present in these marginal-marine deposits (Arua 1991; Ekwenye, et al. 2016, 2017).

2.6.2.4. The Eocene Aspelintoppen Formation, Arctic Norway

The Aspelintoppen Formation in the Eocene Central Basin of Spitsbergen, Norwegian Arctic consist of fluvial and tide-dominated estuarine deposits (Plink-Bjorklund, 2005), which closely resemble those of the Oficina Formation. Fluvial deposits comprise planar and trough cross-stratified coarse-grained sandstone and conglomerate, representing fluvial channels, which are formed by two and three-dimensional dunes. These channels display low sinuosity due to the coarse grain size, the low abundance of overbank deposits and relatively low paleocurrent variability. Root and wood fragments and coal layers are present as well. Ripple and parallel-laminated sandstone and mudstone record sedimentation in floodplains or suggest abandonment of channels. In contrast to the Oficina formation, fluvial channels are unbioturbated (Plink-Bjorklund, 2005). Tidally influenced fluvial deposits consist of medium- to fine-grained sandstone displaying multiple erosion surfaces and coal layer at the top of the channels. Sigmoidal cross-strata or mudstone drapes are rare. Tidal influence is signaled by landward-oriented paleocurrent direction (Plink-Bjorklund, 2005). The tidal channel fills commonly consist of fine- to very fine-grained sandstone with IHS. Root trace fossils, mudstone drapes and soft-sediment deformation structures are common. As in the case of the Orinoco Oil Belt, a brackish-water ichnofauna (e.g., *Planolites* isp., *Skolithos* isp. and *Teichichnus* isp.) has been identified (Plink-Bjorklund, 2005). Tidal sandbars comprise inclined heterolithic strata and trough-cross-stratified medium- to coarse-grained sandstone with bimodal paleocurrent directions and sigmoidal cross-strata. Sand-flat deposits interbedded with those of subtidal sandbars consist of fine- to medium-grained sandstone containing upper-flow-regime parallel lamination trough-cross stratification, and sigmoidal stratification, whereas mixed- to mud-flat and marsh deposits consist of heterolithics units of ripple-cross-laminated fine- to very fine-grained sandstone with mudstone drapes, carbonaceous mudstone and coal layer with root trace fossils. Flaser, wavy and lenticular bedding and a low diversity ichnofauna (e.g. *Planolites* isp., *Skolithos* isp., *Teichichnus* isp.) are present. As in the case of the Oficina Formation, these tidal-flat deposits are dissected by tidal creeks. In short, tidal-flat deposits of the Aspelintoppen Formation are similar to those of the Oficina Formation from both sedimentologic and ichnologic perspectives.

2.6.2.5. The Late Quaternary Gironde Estuary, France

The Late Quaternary Gironde Estuary, on the Bay of Biscay in southwestern France, is formed at

the confluence of the Dordogne and Garonne rivers and displays a maximum width of 18 km near its mouth and 3 km in its head and 80 km in length, covering an area around of 635 km² (Allen and Posamentier, 1993). It is affected by both waves and tides and comprises meandering estuarine channels with point bars (toward its head), tidal sandbars and estuarine mudstone (middle part), and sandy tidal-delta shoal in its mouth (Allen and Posamentier, 1993). An inner area that is both tidal influence and freshwater at the same time is present. Gravel and coarse-grained sand overlie the thalweg of the incised valley. The Gironde estuary comprises estuarine channels and tidal sand bars with IHS as well as estuarine mud with isolated sand lenses and ripple laminae. The latter represents tidal flats and marshes (Allen and Posamentier, 1993). Gironde estuarine mud of the middle member is overlain by a transgressive thick tidal-inlet deposit (Allen and Posamentier, 1993). The most relevant structures within the Gironde estuary are mudstone breccias, thick layers of clay and IHS. The main similarities between the Oficina Formation and the Gironde estuary are with respect to the inner part of the system, where fluvial and tidal meandering channels are dominant. However, the central and outer part of the Gironde estuary show marked wave influence, representing a departure with respect to the Orinoco Oil Belt.

2.6.2.6. Bay of Fundy estuarine complex, Canada

A probable modern analog of the tide-dominated estuarine deposits of the Oficina Formation is the Bay of Fundy estuarine complex, eastern Canada, which displays a width of 80 km at its head and 270 km in length (Desplanque and Mossman, 2001). It was formed by Cenozoic fluvial processes or Pleistocene glacial erosion, which excavated the unconsolidated underlying Triassic strata (Swift and Lyall, 1968; Roland, 1982; Dalrymple et al., 1990). The estuary consists of outer tidal sandbars dissected by channels, sand flats with shallow braided channels and a single-channel in the tidal-fluvial transition zone (Dalrymple et al., 1990). The tidally influenced sandbar deposits are constituted by cross-bedded, medium- to coarse-grained sands. These bars form bar chains attached to the shoreline at their eastern end and are separated by channels, which consists of planar to tabular or trough cross-stratified, gravel, very coarse-to medium-grained sand with IHS. Main-channel point-bar deposits display a brackish-water, low diversity and opportunistic ichnofauna, comprising incipient *Arenicolites* isp., *Diplocraterion* isp, *Siphonichnus* isp., *Skolithos* isp., and *Polykladichnus* isp. Trace makers include *Heteromastus filiformis*, *Corophium volutator*, *Macoma balthica*, *Nereis virens*, and *Cerebratulus lacteus* (Pearson and Gingras, 2006).

The sand flats within shallow braided channels consist of finer-grained sediments with parallel lamination, cross-bedding, mud drapes, and high abundance of marine biogenic structures, but restricted to local zones (Dalrymple et al., 1990). Overall, tidal-creek deposits are rarely to intensely bioturbated by *Mya arenaria*, *Corophium volutator*, *Macoma balthica*, and *Nereis* sp., which produce incipient *Skolithos* isp., *Lockeia* isp., *Arenicolites* isp., *Diplocraterion* isp., *Palaeophycus* isp., and *Thalassinoides* isp. (Dashtgard and Gringas, 2005). As such, modern examples of the *Skolithos* and *Cruziana* Ichnofacies are present in these deposits. Mixed flats, mudflats and salt marshes are present in the intertidal zone, being dissected by tidal creeks with minor proportion IHS (Dalrymple et al., 1990). The sand-dominated mixed flats present flaser and cross-lamination. Mud-dominated flats record mudstone layers, lenticular and wavy tidal bedding, soft-sediment deformation, and desiccation cracks. These deposits display a moderately diverse and abundant infauna. However, the diversity of benthic organisms decreases headward parallel to a decrease in salinity (Dalrymple et al., 1990). The *Skolithos* Ichnofacies is present in the intertidal zone as illustrated by vertical burrows of *Chiridotea coeca* (Dalrymple et al., 1990; Hauck et al., 2008). The muddy tidal-flat deposits record *Mya arenaria*, *Corophium volutator*, *Macoma balthica*, *Heteromastus filiformis* and minor proportion of *Nereis virens* and *Nereis diversicolor* (Hicklin et al. 1980; Pearson and Gingras, 2006; Dashtgard et al., 2014). These organisms produce a low-diversity and high-density trace assemblage comprising incipient diminutive *Arenicolites* isp., *Diplocraterion* isp. and *Siphonichnus* isp., and moderately large *Palaeophycus* isp., *Polykladichnus* isp. and *Teichichnus* isp. (Pearson and Gingras, 2006; Dashtgard et al., 2014). These deposits are considered characteristic of cold-temperate and possible sub-arctic mud flats (Dashtgard et al., 2014). Salt-marsh deposits comprise carbonaceous mud with desiccation cracks and root traces. These deposits record the presence of the *Glossifungites* Ichnofacies signalling the base of the tidal creeks. This ichnofacies is manifested by moderate to local intense bioturbation, represented by *Mya arenaria* and *Corophium volutator*, which produce incipient *Skolithos* isp., *Arenicolites* isp. and *Diplocraterion* isp. (Dashtgard and Gringas, 2005). The single-channel in the tidal-fluvial transition area comprises finer-grained sand with parallel lamination, cross-bedding, and mud drapes, as well as marine biogenic structures in large numbers, but in restricted zones (Dalrymple et al., 1990). Overall, this estuary displays strong tidal currents and low river discharge, which promote a well-mixed water column affecting parameters, such as salinity, water temperature and suspended-sediment concentration (Dalrymple, 1977; Knight,

1977, 1980; Amos and Long, 1980; Dalrymple et al., 1990).

2.6.2.7. The importance of eustatic changes, depositional processes, latitude and secular changes in bioturbation in tide-dominated marginal-marine settings

Ongoing research is emphasizing that climate may have been overlooked in the generation of facies models (Martini, 2014; Martinius et al., 2014). The brief review presented above indicates that the Oficina Formation in the Orinoco Oil Belt shows marked similarities with various marginal-marine units of different ages in terms of sedimentologic, ichnologic and sequence-stratigraphic features. The fact that these units have been formed under a wide variety of latitudinal settings prompts us to evaluate the role of climate on deposition in marginal-marine tide-dominated settings. Although some marginal-marine subenvironments are specific to certain latitudinal regions (e.g. mangroves in tropical areas), others are ubiquitous with respect to latitude (e.g. sandy beaches, barriers, lagoons). Differences are associated with the variable efficiency and intensity of the same physical azonal processes and locally dominant zonal processes, such as the effects of sea-ice cover in the Arctic and carbonate reef building in the tropics (Martini, 2014). Zonal features are associated with latitude, but azonal features are not. The tropical and humid character of the Oficina depositional systems is manifested in the extensive development of wetland areas in both estuaries and deltas, with formation of swamps and embayed areas, typically displaying evidence of waterlogged paleosols with pervasive root trace fossils. Overall, these characteristics resemble those of the modern Orinoco Delta, despite the differences in the degree of tidal influence in both cases, tidal dominance in the Oficina Formation and tidal influence restricted to embayed areas in the Orinoco Delta (Méndez, 2000; Buatois et al., 2012). The formation and overall physiography of coastal environments depend on bedrock, glacial advance and retreat, relative sea-level changes, and sediment redistribution by fluvial, coastal and marine processes (Hein et al., 2014). Physical processes, such as tides, waves and winds, as well as biological and chemical factors, play a significant role across climatic belts (Kelletat et al., 2013). Tidal currents are the main hydrodynamic agent in the systems analyzed in this paper, spanning lower- and higher-latitude settings. However, tidal forces tend to be weaker in higher latitudes because Coriolis effects are stronger there (Martinius et al., 2014). In any case, tidal action is revealed in all the reviewed cases by the overwhelming presence of physical sedimentary structures, such as IHS, mudstone drapes and bidirectionally oriented cross-stratification. Also, the abundance of well-defined tidal channels

crossing tidal flats, such as those recorded in the Oficina Formation, is more typical of low latitudes, being relatively rate in arctic to subarctic settings (Martini, 2014).

Transgressive conditions are usually associated with estuaries, whereas deltas are associated with regressions (Dalrymple et al., 2003, 2007, 2012). A tide-dominated estuary is a transgressive coastal setting at mouth of a river, receiving sediment from both river and sea, encompassing a wide spectrum of salinity levels (Pritchard, 1967; Dalrymple et al., 1992, 2006, 2012). A tide-dominated delta is a prograding coastal environment that receives clastic sediment from a river source, being mostly reworked by tidal currents (Hori et al., 2001; Coleman, 1981). Therefore, it is unsurprising that sea-level changes have played a key role on sedimentation of the Oficina Formation and in the other units discussed regardless of latitudinal setting. The Oficina Formation records the typical succession of fluvial incision during sea-level fall, transition from fluvial to estuarine valleys during the subsequent transgression and deltaic progradation during highstand. Notably, although tectonics were a significant factor at the time of deposition, evolution of the Oficina Formation shows a close match with the global sea-level curve of Haq and Schutter (2008; see discussion in Solórzano et al., in review). Similar depositional histories in response to relative sea-level changes are shared by other units elsewhere. In the Aspelintoppen Formation of Arctic Norway, coastal-plain aggradation took place mostly during transgressions (Plink-Bjorklund, 2005). In the Bay of Fundy, the preservation of coastal sediments is strongly influenced by transgression resulting from rapid sea-level rise over the past 6000 years (Amos et al. 1991; Shaw and Courtney 2002; Dashtgard and Gingras, 2005). Quaternary climatic and sea-level changes have controlled coastal zonality at different spatial and temporal scales (Solomon et al., 2007; Kelletat et al., 2013). Also, a common characteristic between the Oficina Formation and the other units analyzed is the presence of a depauperate marine ichnofauna reflecting brackish-water conditions in central and outer regions of the estuary and a freshwater ichnofauna in the fluvial system and the most proximal areas of the estuarine and deltaic systems. Regardless of the overall ichnologic similarities across a broad spectrum of latitudinal settings, it has been noted that the distribution of shallow-marine ichnofaunas may be controlled by climate and that three climatic zones may be recognized, namely (1) tropical and subtropical with *Ophiomorpha*, echinoid burrows as well as other ichnotaxa, (2) temperate with echinoid burrows and *Thalassinoides* and (3) arctic with only molluscan and worm structures (Goldring et al., 2004). Subsequent work extended the dominance of mollusk and worm burrows to the temperate zone (Gingras et al., 2006).

The brief comparison presented above provides some information that allows partial evaluation of this model. Incipient *Ophiomorpha* along the eastern coast of the Americas does not extend further into high latitudes, reaching as far as 34ºN and 27ºS, whereas modern examples of *Thalassinoides* may extend up to 70ºN and 50ºS (Goldring et al., 2004; Martini, 2014). Both ichnogenera are particularly common in marginal-marine deposits of the Oficina Formation. In general, crustacean burrows tend to display higher diversity in tropical shallow-marine environments of northern South America (e.g. Quiroz et al., in review). However, *Ophiomorpha* has been mentioned in the tidal sandbars of the high-latitude Eocene Aspelintoppen Formation of Arctic Norway (Plink-Bjorklund, 2005). This high-latitude occurrence of *Ophiomorpha* may simply reflect the warmer conditions of the Eocene. In contrast, arctic tidal flats display a clear dominance of worm burrows (e.g. *Nereis diveiscolor* and *Arenicola marina*) with some participation of mollusk-generated structures, such as *Macoma balthica* (Aitken et al. 1988; Weslawski and Szymelfenig, 1999; Martini, 2014). In general, arctic and subarctic infaunal associations show remarkable similarities with cold temperate tidal flats of the Bay of Fundy, except for the absence of *Corophium volutator* (Martini, 2014). Benthic activity in higher latitudes is controlled by temperature and insolation, as well as short runoff seasons and strong fluvial discharge seasonality, which impart specific stress factors on the benthos (Martinius et al., 2014). As a result, ichnodiversity levels are affected negatively by a number of factors, such as ice cover, erosion by ice pushing and lifting of sediment (Martini, 2014). Finally, secular changes in bioturbation by the continental and marginal-marine infauna have significantly impacted on sediment mixing (Buatois et al., 2005; Diez-Canseco et al., 2015). Although brackish-water ichnofaunas, which reflect the activity of highly conservative biotas, tend to be quite persistent through the Phanerozoic, subtle increases in ichnodiversity and intensity of bioturbation are apparent through geologic time in marginal-marine environments. In this regard, the Miocene illustrates the appearance of the modern brackish-water benthos (Buatois et al., 2005) and the marginal-marine ichnofaunas of the Oficina Formation favour direct comparison with modern analogues, particularly in tropical settings. In comparison, changes in the composition of freshwater ichnofaunas through the Phanerozoic have been more remarkable. This is particularly evident if the fluvio-estuarine transition of the Oficina Formation is compared with similar environments in the Paleozoic from an ichnologic perspective. The Carboniferous freshwater to terrestrial ichnofaunas from the North American mid-continent discussed above are characterized by superficial trackways and trails of the *Mermia* and *Scoyenia* Ichnofacies (Buatois

et al., 1997, 1998; Mángano and Buatois, 2004). In contrast, post-Paleozoic freshwater to terrestrial ichnofaunas display a remarkable increase in burrowing depth in fluvio-tidal transitions, as is illustrated by deposits of the Oficina Formation, which are typically intensely bioturbated by meniscate burrows of the *Scoyenia* Ichnofacies (Solórzano et al., 2017). Accordingly, secular increases in extent and depth of bioturbations have resulted in higher disturbance of the primary sedimentary fabrics. In addition, the ability of the infauna to penetrate deeper into the sediment have led to common overprint of trace-fossil suites, as illustrated in the Oficina Formation by the common occurrence of freshwater to terrestrial trace fossils cross-cutting previously emplaced brackish-water trace fossils.

2.7. Conclusions

Based on the recognition of nine sedimentary facies (FA-I) and five facies associations (FA1-5), the Oficina Formation is interpreted as recording lowstand fluvial deposits (lower member), passing upward into transgressive estuarine deposits (middle member), and highstand lower delta-plain deposits (upper member). The abundance of mudstone drapes and IHS through all the middle and upper members suggests tidal dominance. Ichnologic evidence suggests freshwater conditions in the fluvial systems, the inner part of the estuary and the delta plain, whereas brackish-water conditions dominated in the rest of the estuarine valley, including its outer region, which is consistent with the embayed physiography of the paleocoastline in the Orinoco Oil Belt. Fluvial and estuarine strata extend across the whole belt, becoming thinner toward the Ayacucho and Carabobo areas, showing south-southwest to north-northeast trending channels. Estuarine valleys display increased marine influence towards the north-northeast. Deltaic strata show a basinwide distribution, becoming thicker towards the Carabobo area and showing distributary channels that open seaward towards the north-northeast. Comparisons with other marginal-marine units under a broad spectrum of latitudinal settings stress the importance of tidal dominance and relative sea-level changes as main controls on sedimentation. However, the establishment of extensive marginal-marine wetland systems and the types of burrowing infauna that characterize the Oficina Formation may reflect the tropical nature of these coastal ecosystems.

Transition

The previous chapter 2 provides a sedimentary facies model of the Oficina Formation and comparisons with other marginal-marine units worldwide. Chapter 3 evaluates trace-fossil distribution and ichnofacies gradients along a depositional profile for the Oficina Formation from the Orinoco Oil Belt to the Oritupano Field.

I built an ichnologic model for the Oficina Formation from the Orinoco Oil Belt to the Oritupano Oil Field. For the Orinoco Oil Belt, I interpreted nine facies (FA-FI), grouped in five facies assemblages (FA1-5), three softground ichnofacies (*Scoyenia*, *Skolithos* and depauperate *Cruziana*) and two substrate-controlled ichnofacies (*Glossifungites* and *Teredolites*). For the Oritupano field, I interpreted eleven facies (FJ-FS), grouped in four facies assemblages (FA6-9), three softground ichnofacies (*Skolithos*, depauperate *Cruziana* and archetypal *Cruziana*) and two substrate-controlled ichnofacies (*Glossifungites* and *Teredolites*). The presence of softground ichnofacies allowed me to calibrate salinity-related trace-fossil models and to improve paleoenvironmental interpretations. The presence of substrate-controlled allowed me to identify transgressive surfaces of erosion. I also compared the Oficina Formation with the McMurray Formation of western Canada. Supervisors Luis A. Buatois and M. Gabriela Mángano checked trace-fossil determinations and interpretations in terms of behavior and paleoenvironmental significance and edited the manuscript. Co-author Williams Rodriguez helped with core logging.

Chapter 3

3. From freshwater to fully marine: Exploring animal-substrate interactions along a salinity gradient (Miocene Oficina Formation of Venezuela)

3.1. Abstract

Venezuela has the largest hydrocarbon reserves in the world and most of these are within the Orinoco Oil Belt. The Oficina Formation of the Orinoco Oil Belt and the Oritupano Field comprises a wide range of environments formed under variable salinity conditions. These include freshwater fluvial and fluvio-tidal transition zones, brackish-water estuarine and delta-plain segments, alternating brackish-water and near-normal marine delta-front and prodelta settings, and normal-marine wave-dominated shoreface and offshore-shelf environments. The Oficina Formation thus provides an ideal opportunity to evaluate trace-fossil distribution and ichnofacies gradients along a depositional profile and to calibrate salinity-related trace-fossil models. The Oficina Formation contains four softground ichnofacies (*Scoyenia*, depauperate *Cruziana*, *Skolithos*, and archetypal *Cruziana*) and two substrate-controlled ichnofacies (*Teredolites* and *Glossifungites*). Fluvial deposits in freshwater portions of tide-influenced, estuarine channels and distributary channels of tide-dominated deltas are locally intensely bioturbated, displaying low-diversity occurrences of the *Scoyenia* Ichnofacies. Brackish-water delta-plain and estuarine deposits display lower degrees of bioturbation and low ichnodiversity, as revealed by depauperate *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies. Wave-dominated deltaic deposits display the *Skolithos* and the depauperate *Cruziana* Ichnofacies, but the presence of some ichnotaxa (*e.g.*, *Chondrites*) suggests periods of lower salinity stress, probably during times of reduced freshwater discharge. Open-marine deposits are characterized by intense bioturbation and very high diversity, as shown by the archetypal *Cruziana* Ichnofacies in low-energy distal settings, whereas high-energy proximal settings are characterized by the *Skolithos* Ichnofacies. Faunal distribution is

strongly controlled by salinity, which makes trace-fossil evidence particularly useful for paleoenvironmental characterization of marginal-marine systems. In addition, the *Glossifungites* and *Teredolites* Ichnofacies indicate erosional exhumation of marginal-marine deposits, outlining transgressive surfaces of erosion. The Oficina Formation shows remarkable similarities in sedimentary facies and both trace-fossil and micropaleontological content with the Cretaceous McMurray Formation of western Canada.

Keywords: Orinoco Oil Belt, *Scoyenia*, *Skolithos*, *Cruziana*, *Glossifungites*, *Teredolites*

3.2. Introduction

Marginal-marine depositional systems, such as estuaries and deltas, have been subjected to increased scrutiny from an ichnologic perspective during the last three decades (*e.g.,* Pemberton et al., 1982; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; Buatois et al., 1997a, 2008, 2011, 2012; Mángano and Buatois, 2004; MacEachern et al., 2005; MacEachern and Gingras, 2007; Gingras et al., 2012, 2016; Dasgupta et al., 2016). In fact, trace fossils have become valuable tools to identify marginal-marine deposits and to delineate their subenvironments within a robust depositional and sequence-stratigraphic framework (*e.g.*, MacEachern and Pemberton, 1994). Marginal-marine environments are typified by rapid salinity changes, increased sediment discharge, high water turbidity and extreme clay flocculation, among many other controlling factors (see Buatois and Mángano, 2011, and references therein). This characteristically results in stressful environmental conditions that play a major role in controlling the response by the benthos and their interactions with the substrate, imparting detectable signals in the trace-fossil record. However, there are still few studies that document animal-substrate interactions within a single stratigraphic unit along extensive salinity gradients, from freshwater to brackish water and normal-marine salinity conditions (*e.g.*, Mángano and Buatois, 2004). Such studies are essential to calibrate stressed trace-fossil suites against those of fully marine conditions (Buatois et al., 2005).

   The Miocene Oficina Formation of the Orinoco Oil Belt and the Oritupano Field in Venezuela (Fig. 3.1A-C) comprises a wide range of depositional environments formed under variable salinity conditions. These include freshwater fluvial and fluvio-tidal transition zones, brackish water estuarine and delta-plain settings alternating brackish-water and near-normal

marine in delta-front and prodelta settings, and normal-marine shoreface and offshore-shelf environments. Therefore, this unit provides an ideal opportunity to evaluate trace-fossil distribution and ichnofacies gradients along a depositional profile. In the specific case of the Oficina Formation, refinement of paleoenvironmental reconstructions is essential because this unit hosts one of the largest hydrocarbon reservoirs in the world. The aims of this paper are to: (1) document animal-substrate interactions in different subenvironments of the Oficina Formation, (2) discuss how the pattern emerging from the analysis of this unit compares with the currently accepted models of marginal-marine depositional systems, and (3) compare our observations with those in similar deposits of the Cretaceous McMurray Formation of western Canada, whose interpretation have been subject to debate recently.
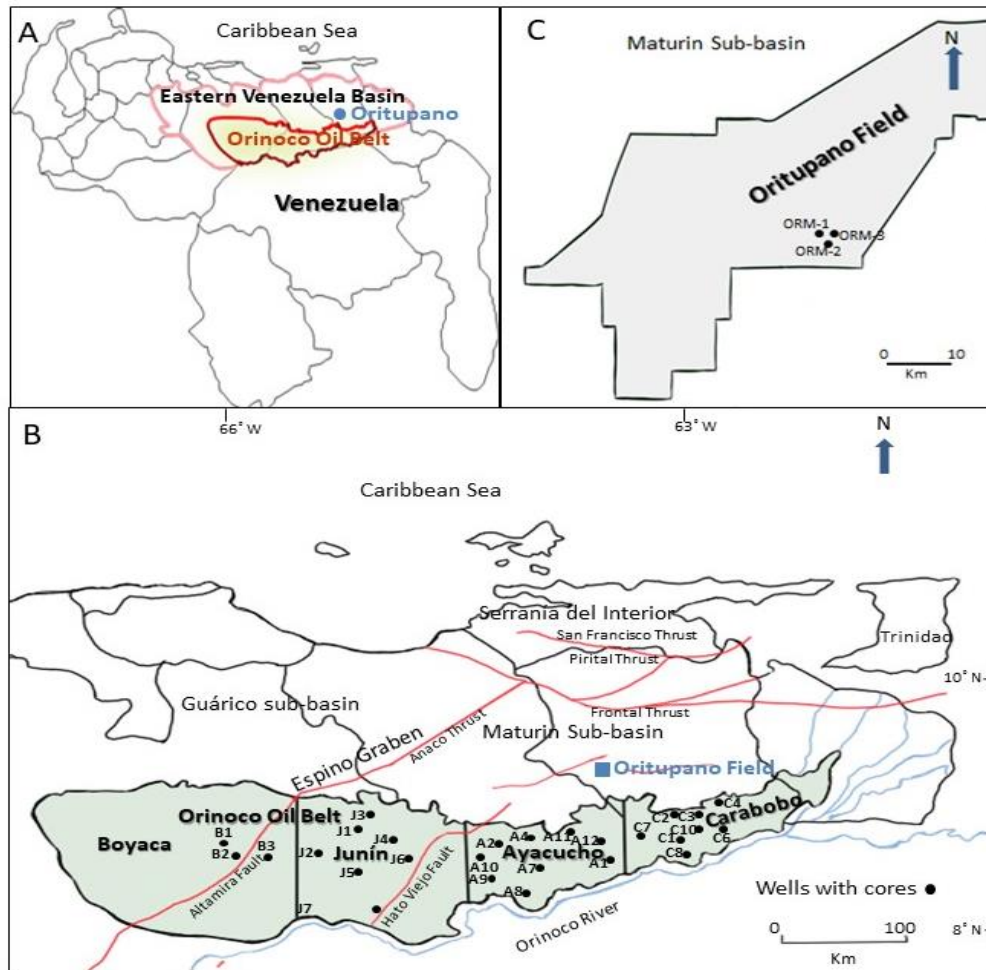
Figure 3.1. Location Map of the study areas. A) Map of Venezuela showing the location of the Eastern Venezuela Basin, outlining the Orinoco Oil Belt, and the Oritupano Field. B) Map of the Oritupano Field. C) Map of the Orinoco Oil Belt and the main associated structural features.

3.3. Geologic setting

The Eastern Venezuela Foreland Basin formed during the Neogene on the passive margin of the South American Craton and is composed of several petroleum fields; two of these are the Orinoco Oil Belt and the Oritupano area (Fig. 3.1A). This foreland basin is subdivided by the Anaco-Altamira fault system into the Maturin and Guárico sub-basins (Fig. 3.1C). The Orinoco Oil Belt spans an area of 55,315 km^2 in the southern margin of the Eastern Venezuela Basin, sub-parallel to the Orinoco River (Fig. 3.1C). The Hato Viejo fault system subdivides the Orinoco Oil Belt into two provinces, the western and eastern provinces (Latreille et al., 1983; Audemard et al., 1985). The western province is located west of the Hato Viejo fault system and consists of the Boyaca and Junín areas where the Cenozoic succession unconformably overlies Cretaceous and Paleozoic strata. The eastern province is located east of the Hato Viejo fault system, and includes the Carabobo and Ayacucho areas, where the Cenozoic succession rests on top of the Precambrian basement. The Oritupano Field is located northeast of the Orinoco Oil Belt in the Maturin sub-basin (Fig. 3.1B and 3.1C). Based on an integrated analysis of foraminifers, calcareous nannoplankton and palynomorphs, the Oficina Formation is considered of middle Miocene age (Audemard et al., 1985; Solórzano et al., 2015) and spans the Langhian Stage, and the Serravallian Stage (Fig. 3.2). Three third-order depositional sequences and three maximum flooding surfaces were identified in the Oficina Formation. These maximum flooding surfaces can be correlated throughout the Eastern Venezuela Basin (Campos et al., 1985; Giffuni et al., 2000; Flores et al., 2001) and the Orinoco Oil Belt (Latreille et al., 1983; Audemard et al., 1985; Solórzano and Farias, 2016). The main reservoir of the Orinoco Oil Belt and the Oritupano Field is in the Oficina Formation, which is characterized by alternating sandstone and mudstone with interbedded shale and coal (Rodriguez, 1981a, b; Isea, 1981; Solórzano et al., 2016; Suarez et al., 2014 a, b; Rangel et al., 2013). Most oil production is from unconsolidated sand. Previous interpretations concluded that the Oficina Formation records deposition in a fluvio-deltaic environment (Audemard et al., 1985; Latreille et al., 1983, Toro et al., 2001, Martinius et al., 2012). However, in addition to deltaic deposits, tide-dominated estuarine deposits have been identified in subsequent studies (Rodriguez, 2015), and fully marine deposits are present north of the Orinoco Oil Belt in the Oritupano Field.
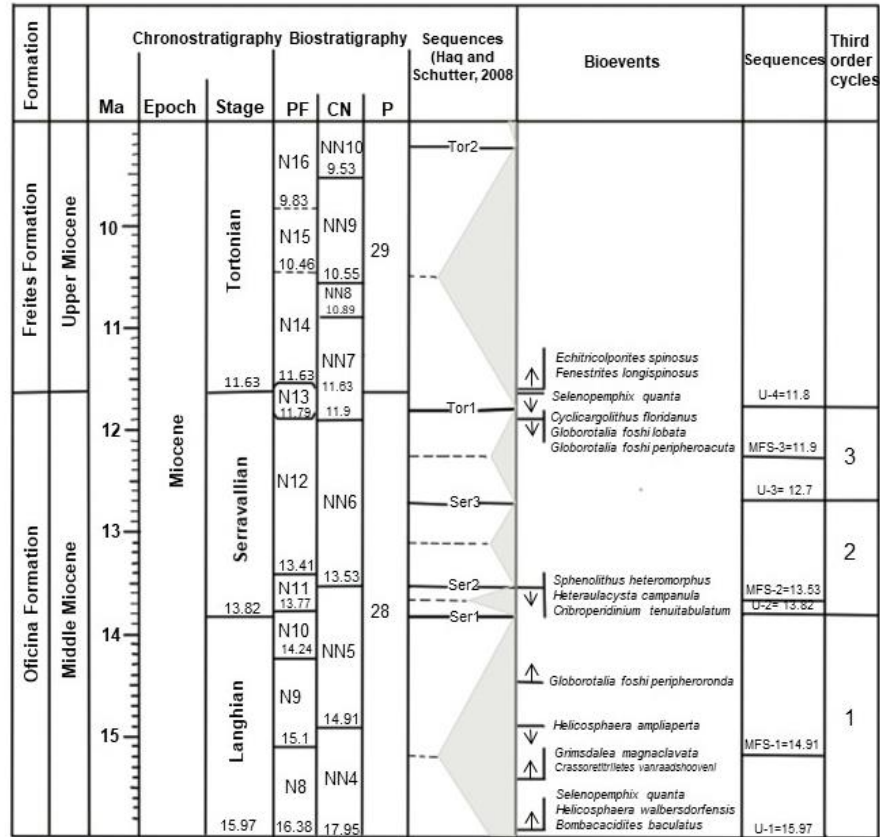
Figure 3.2. Chronostratigraphic framework for the Oficina Formation in the Orinoco Oil Belt. Modified from Solórzano et al. (2015).

The Oficina Formation was divided into three informal members: lower, middle and upper, representing fluvial, estuarine and deltaic deposits, respectively (Rodriguez, 2015). The lower member consists of massive to high-angle planar cross-stratified fine- to very coarse-grained sandstone and conglomerate. It has been interpreted as fluvial channel-fills of a lowstand systems tract. The middle member is characterized by interbedded coarse- to very fine-grained sandstone and mudstone with inclined heterolithic stratification (IHS) locally capped by coal. It has been interpreted as a tide-dominated estuarine system formed within a transgressive systems tract. The upper member is represented by fining- and thinning-upward, planar and trough cross-stratified medium- to fine-grained sandstone with mudstone drapes, as well as inclined heterolithic stratified coarse- to fine-grained sandstone units. Desiccation and syneresis cracks, siderite nodules and bands, and coal beds are also present. Coal beds tend to mark the top of the unit. The upper member has been interpreted to record highstand system tract deltaic progradation. The Oficina clastic

wedges were sourced from the cratonic shield located further south and fluvial systems show drainage towards the north-northeast. Further to the northeast and outside the Orinoco Oil Belt, in the Oritupano Field, brackish-water and open marine deposits are present, and the Oficina Formation consists of calcareous, fine- to very fine-grained sandstone and calcareous mudstone.

3.4. Materials and Methods

Conventional cores were described from the Boyaca, Junín, Ayacucho, and Carabobo areas of the Orinoco Oil Belt, and the Oritupano area to the northeast of the belt. The study includes the following wells with cores: 3 cores from the Boyaca area (B1, B2, and B3), 7 cores from the Junín area (J1, J2, J3, J4, J5, J6, and J7), 9 cores from the Ayacucho area (A4, A7, A8, A1, A2, A9, A10, A11, and A12), 8 cores from the Carabobo area (C1, C2, C6, C7, C8, C9, C3, and C10), and 3 cores from the Oritupano Field (OR1, OR2, and OR3), which together encompass 2947 m of core (Fig. 3.1C and 3.1B). Sedimentologic data were collected by detailed bed-by-bed analyses, taking into account lithology, bed thickness, bed contacts, and physical and biologic sedimentary structures. Trace-fossil data were collected and analyzed following a combined ichnofacies and ichnofabric approach, taking into account identification of ichnotaxa, ethologic groups, trophic types, population strategies, ichnodiversity, degree of bioturbation, and tiering structure. Degree of bioturbation was estimated based on the scheme of Taylor and Goldring (1993), who defined a bioturbation index (BI), ranging from 0 (no bioturbation) to 6 (complete bioturbation), after a previous scale by Reineck (1963).

3.5. The Oficina Formation ichnofauna

Sixteen ichnotaxa have been recognized in the Oficina Formation. They are described briefly below, in alphabetical order.

Asterosoma isp. is a star-shaped burrow system consisting of radial bulbous arms tapering inward towards an elevated center. In core, it typically is seen as concentric laminae of silt and clay surrounding a sand-filled inner core. *Asterosoma* has been interpreted as a specialized feeding structure of a worm-like organism linked with fully marine environments (Pemberton et al., 1992, 2001; Seilacher, 2007).

Beaconites antarcticum comprises simple, walled, meniscate, backfilled structures. It is interpreted as a feeding trace (fodinichnion) (Keighley and Pickerill, 1994). Paleozoic examples have been attributed to myriapods, particularly arthropleurids (Morrissey and Braddy, 2004; Fayers et al., 2010). Producers in post-Paleozoic occurrences include other arthropods or vermiform organisms. *Beaconites* typically occurs in nonmarine deposits (*e.g.*, Buatois and Mángano, 2004).

Bergaueria isp. consists of simple plug-shaped burrows with smooth walls. It represents either a permanent or semi-permanent dwelling burrow (domichnion) or a resting trace (cubichnion) probably produced by sea anemones (Prantl, 1945; Pemberton et al., 1988; Pemberton and Magwood, 1990). *Bergaueria* is common in fully marine conditions in either wave- or tide-dominated settings, although it also may occur in brackish-water environments, albeit with generally small size (Pemberton et al., 2001).

Chondrites isp. is a complex burrow system consisting of regularly branching feeding tunnels of uniform diameter. In core, *Chondrites* commonly appears as an array of thin elliptical dots where the vertical slice through the core truncates numerous branching tunnels. It has been suggested that *Chondrites* represents burrows produced by deposit-feeding sipunculids or chemosymbiontic organisms (Fu, 1991). *Chondrites* is typical, although not exclusive, of offshore, shelf, slope and basin-plain deposits (Buatois and Mángano, 2011)

Diplocraterion habichii is characterized by vertical, U-shaped spreiten burrows; spreiten may be retrusive, protrusive, or a combination of both. It is interpreted as dwelling burrow of suspension-feeding organisms (Fürsich, 1974), possibly polychaetes, other worm-like organisms, or amphipod crustaceans (Fürsich, 1974). *Diprocraterion* is common in sandy tidal flats, subtidal sand bodies, estuarine channels and shoreface environments (Cornish, 1986; Mángano and Buatois, 2004).

Ophiomorpha nodosa consists of branching burrow systems distinctly lined with agglutinated, pelleted sediment. The burrow lining is near-smooth on the interior and densely to strongly nodular on the exterior (Frey et al., 1978; Carmona et al., 2004). Although branching is only rarely seen in core, the pelletoidal wall is easy to distinguish. This ichnotaxon is a dwelling trace of selective detritus-feeding decapods, such as callianassids (Dworschak, 2000; Dworschak et al., 2012). Unequivocal occurrences of *Ophiomorpha* only have been reported from marine deposits (Buatois et al., 2016a). Although *Ophiomorpha* is a facies-crossing ichnotaxon,

Ophiomorpha nodosa tends to occur in shallow-marine sandstones, typically shoreface, delta-front and estuarine channel and bar deposits, as well as offshore tempestites, among other settings (Frey et al., 1978; Pemberton et al., 2001; Carmona and Buatois, 2003; Ezeh et al., 2016).

Palaeophycus tubularis consists of unbranched, distinctly lined, cylindrical, and horizontal to inclined burrows. It has been interpreted as the dwelling structures of active predators or suspension-feeding organisms, such as polychaetes (Pemberton and Frey, 1982; Gingras et al., 1999). Semiaquatic insects (orthopterans and hemipterans) and non-aquatic beetles are possible producers in continental settings (Krapovickas et al., 2009). *Palaeophycus tubularis* has been recorded in fully marine, marginal-marine and continental settings (Pemberton and Frey, 1982; Buatois and Mángano, 2004).

Palaeophycus heberti refers to sub-cylindrical, vertical, gently to strongly curved burrows with circular to elliptical cross-sections. It is interpreted as the dwelling burrow of a suspension-feeding organism similar to sabelliarid polychaetes (Pemberton et al., 1992). Structures commonly identified in core as *Terebellina* should be included in *P. heberti* (Miller, 1995). This ichnospecies is commonly found in fully marine environments (Pemberton et al., 1992, 2001).

Planolites montanus is characterized by unlined, simple, and straight to tortuous burrows with circular to elliptical cross sections. This ichnotaxon is regarded as a feeding structure (fodinichnion) of deposit feeders, probably produced by infaunal polychaetes or other worm-like organisms (Pemberton and Frey, 1982; Fillion and Pickerill, 1990; Uchman 1995; Sisulak and Dashtgaard, 2012). *Planolites* is a facies-crossing ichnotaxon that may occur in continental through deep-marine environments (Pemberton and Frey, 1982).

Phycosiphon incertum is a complex spreite structure, surrounded by a thin mantle of pale sediment; the core consists of backfilled dark material, and the spreite is made of the same pale material as the mantle. When mantle and spreite are difficult to differentiate, the transverse or longitudinal section of the lobes permits a conclusive identification of *Phycosiphon incertum* (Bromley 1996; Rodriguez-Tovar et al., 2014). However, spreite typically are not visible in core, and this ichnotaxon is identified by its dark core and pale mantle. *Phycosiphon incertum* is interpreted as the feeding structure of vermiform organisms, probably polychaetes (Goldring et al., 1991). It is present in shallow marine to bathyal environments and perhaps even at abyssal depths (Goldring et al., 1991; Fu 1991; Wetzel and Bromley 1994; Mángano et al., 2002; Wetzel, 2010; Buatois et al., 2012).

Rhizocorallium isp. is characterized by straight to sinuous, U-shaped spreiten burrows. In cores it is identified by two circular burrows joined by a horizontal band (spreite). *Rhizocorallium* is interpreted as a feeding structure produced by deposit feeders, either crustaceans or worms (Fürsich, 1974b; Rodriguez-Tovar et al., 2012; Knaust, 2013). It is a common element in shoreface and offshore environments (Pemberton et al., 1992, 2001).

Rosselia socialis consists of funnel-shaped, concentrically-fill, vertical to inclined, burrows with a narrow cylindrical shaft at the central portion. It is interpreted as a dwelling burrow produced by detritus feeders, such as terebellid polychaetes (Nara, 1995; Gingras et al., 1999). *Rosselia* is typical of shallow-marine settings, in both brackish-water and fully marine environments (Dias da Silva et al., 2014; Buatois et al., 2016b).

Skolithos linearis refers to simple, vertical to inclined, straight to curved burrows. It is interpreted as a dwelling burrow (domichnion) of suspension feeders or predators, such as phoronids or polychaetes (Alpert, 1974; Schlirf and Uchman, 2005; Sisulak and Dashtgaard, 2012). Insects or spiders can produce sculptured terminations in vertical burrows in terrestrial environments (Ahlbrandt et al., 1978; Ratcliffe and Fagerstrom, 1980; Genise, 2016). *Skolithos* is a facies-crossing ichnotaxon that may occur from continental to deep-marine environments, but is most common in high-energy shallow-marine settings (Mángano et al., 2002).

Taenidium isp. comprises unwalled, simple, horizontal, meniscate trace fosssils. It is a feeding structure (fodinichnion) produced by worm-like organisms and insects (Gregory et al., 2004; Smith et al., 2008; Krapovickas et al., 2009; Diez-Canseco et al,. 2016; Genise, 2016). This ichnotaxon is particularly common in continental environments, but is also present in marine (Buatois et al., 2001) and marginal marine settings (Diez-Canseco et al., 2015; Gingras et al., 2016).

Teichichnus rectus consists of horizontal burrows having a vertical retrusive spreite (Seilacher, 1955). In cores, it is seen as vertical tabular structures formed by tightly packed concave-up or concave-down crescentic laminae (Pemberton et al., 1992, 2001). It is interpreted as a feeding trace (fodinichnion) of a deposit feeder and may be produced by different organisms, including annelids and arthropods (Häntzschel, 1975; Fillion and Pickerill, 1990 Seilacher, 2007). Although it is a facies-crossing ichnotaxon ranging from marginal-marine to deep-sea settings, *Teichichnus* is absent in continental environments, and is therefore a good indicator of marine influence (Mángano et al., 2002).

Thalassinoides isp. consists of relatively large burrow systems comprising smooth walled, essentially cylindrical components. Branching, however, is only very rarely seen in core. It is regarded as a feeding burrow of decapod crustaceans, such as thalassinid shrimp. *Thalassinoides* may occur in a wide variety of environments, typically marginal and fully marine (Carmona et al., 2004; Buatois et al., 2016c).

3.6. Sedimentary Facies and Trace-Fossil Distribution

3.6.1. Sedimentary Facies of the Orinoco Oil Belt

Nine facies (FA-FI), grouped in five facies assemblages (FA1-5), have been identified in the Orinoco Oil Belt (Tables 3.1 and 3.2).

Table 3.1. Sedimentary Facies of the Oficina Formation in the Orinoco Oil Belt. Modified from Rodriguez, 2015.

Facies			Lithology and Texture	Dominant physical sedimentary structures	Ichnology	Bed thickness (cm)	Other characteristics	Interpretation
FA Intraclast breccia			Mudstone breccia, medium- to fine-grained sandstone and mudstone, poorly sorted	Microfaults and planar cross stratification	No trace fossils	10-50		Lag deposits, cut bank margins of meandering estuarine channels
FB Cross-Stratified very coarse-to medium-grained sandstone	FB1	Massive to Planar cross-stratified sandstone with granules	Very coarse-to medium-grained gravel-rich sandstone with dispersed granules, poorly sorted	Massive to planar cross-stratification	No trace fossils	10-50	Locally parallel-laminated mudstone, mudstone and coal clasts, generally oil impregnated, argillaceous	Braided fluvial channels
	FB2	Massive to trough cross-stratified sandstone with pebbles and mudstone clast	Coarse- to medium-grained gravel- rich sandstone, poorly sorted	Massive to trough cross-stratification	No trace fossils	20-70		

FC Cross-stratified medium- to fine-grained sandstone with mudstone drapes			Medium- to fine-grained fine sandstone, well sorted	Trough and planar cross stratification	No trace fossils	10-120	Mudstone drapes	Tidal channels, tidal flat, and tidal sandbars
FD Inclined heterolithic stratified coarse- to fine-grained sandstone and mudstone			Coarse- to fine-grained sandstone	Inclined heterolithic cross-stratification	Scarce *Rosselia socialis*, *Teichichnus rectus*, *Ophiomorpha nodosa* BI: 0-1 *Beaconites antarcticum* (BI: 4-6)	30-200	Mudstone intraclasts, mudstone drapes	Estuarine and distributary channel pointbars, tidal flat, and tidal sandbars
FE Convoluted fine- to very fine-grained sandstone and mudstone			Fine- to very fine-grained sandstone, well sorted	Convolute lamination	Scarce *Ophiomorpha nodosa* BI: 0-1	10-50		Estuarine channels and tidal flats
FF Interbedded mudstone and middle- to very fine-grained sandstone	Sandstone dominated	FF1 Parallel-laminated sandstone and mudstone	Fine- to very fine-grained sandstone, well sorted, rounded clasts; mudstone	Wavy lamination (rhythmic appearance)	*Planolites montanus*, *Teichichnus rectus*, *Rosselia socialis*, *Skolithos linearis*, *Diplocraterion habichii*, escape trace fossils BI: 0-1	1-200	Mudstone drapes and flaser bedding	Tidal sand to mixed flats
		FF2 Muddy sandstone	Fine- to very fine-grained sandstone mixed with mudstone	Sandstone is interlaminated to interbedded with light to medium grey mudstone	*Ophiomorpha nodosa* (BI:0-1), undeterminate bioturbation mottling (BI: 4-5)	1-90		Tidal sand to mixed flats
	Mudstone dominated	FF3 Parallel-laminated sandy mudstone and siltstone	Mudstone with scarce very fine sand grains, well sorted	Sand grains dispersed in mudstone- and siltstone-dominated intervals	*Bergaueria* isp., *Planolites montanus*, *Thalassinoides* isp. BI: 2-3	1-100		Tidal mud flats
		FF4 Bioturbated siltstone and mudstone	Silstone and mudstone	Massive appearance	*Teichichnus rectus*, *Thalassinoides* isp., indeterminate bioturbation mottling BI: 4-5	1-180		Tidal mud flats
		FF5 Calcareous massive mudstone with scarce limestone layers	Massive calcareous mudstone with scarce limestone layers	Massive appearance	No trace fossils	10-30	Shell remains	Tidal mud flats
	FG1		Mudstone	Massive to parallel-laminated, locally current ripples and flaser bedding	*Planolites montanus*, *Teichichnus rectus*, *Thalassinoides* isp., root trace fossils BI: 3-4	30-150	Syneresis cracks, abundant organic debris, and scarce mudstone clasts	Outer -estuary margin

FG Carbonaceous, rooted silty mudstone and thinly laminated mudstone	FG2	Mudstone and silstone	Massive to parallel-laminated, white to light gray	*Beaconites antarcticum*, *Planolites montanus*, *Taenidium* isp. BI: 4-6	30-120	Siderite nodules and bands, desiccation cracks	Floodplains, interdistributary bays and tidal flats
	FG3	Mudstone	Massive to parallel-laminated, white to light gray	Firmground *Thalassinoides* isp., *Planolites montanus*, root trace fossils BI: 1-4	50-200	Siderite nodules and bands, desiccation cracks	waterlogged paleosols
FH Coal	FH1	Coal		No trace fossils	1-60		Swamps in fluvial, estuarine and delta plain settings
	FH2	Bioturbated Coal		Woodground *Thalassinoides* isp. BI: 3-5	10-50		Swamps in estuarine system
FI Cross-Stratified very coarse-to very fine-grained sandstone	FI1	Very coarse- to medium-grained sandstone, poorly sorted	Massive sandstone	*Ophiomorpha nodosa* BI: 0-1	50-100	Sandy deposits are limited in their top or base by mudstone deposits or heterolithic zones, containing benthic foraminifera and dinoflagellates	Meandering tidal channels
	FI2	Very fine- to medium-grained sandstone with shells	Massive to planar cross-stratified	No trace fossils	10-60		Meandering tidal channels
	FI3	Very coarse-to fine-grained sandstone, poorly sorted	Massive to planar cross-stratified	No trace fossils	50-300		Meandering tidal channels

3.6.1.1. FA1: Fluvial braided channels

Facies FB1, FB2, FG2, and FH1 constitute FA1. FA1 is present in the lower part of the sedimentary succession of the Boyaca, Junín, Ayacucho, and Carabobo areas, comprising the lower member of the Oficina Formation and recording deposition within a low-sinuosity, braided fluvial system. FB1 and FB2 consist of fining-upward, massive to planar or trough cross-stratified, pebbly, very coarse- to medium-grained sandstone, locally capped by massive mudstone. These sandstone units form amalgamated packages that indicate the establishment of multi-storey, fluvial braided channels, whereas the few mudstone intervals record deposition in overbank settings. FG2 consists of massive to parallel-laminated mudstone and silstone units, and records deposition in floodplains. FH1 consists of coal layers and, records sedimentation in swamps. For the most part, FA1 lacks bioturbation. However, monospecific suites of *Taenidium* isp. occur in overbank bioturbated mudstone units that are immediately located above fluvial braided-channel deposits (Fig. 3.3A-B).

3.6.1.2. FA2: Meandering tidal channels

Facies FA, FC, FD, FE, FI1, FI2, and FI3 constitute FA2. FA2 is present in the middle part of the sedimentary succession in the Boyaca, Junín, Ayacucho, and Carabobo areas, representing the middle member of the Oficina Formation. This facies association is separated from the underlying FA1 by a transgressive surface and is interpreted as recording deposition within estuarine meandering channels. FA consists of mudstone intraclast breccia. FC and FD consist of coarse- to fine-grained sandstone and mudstone with IHS and trough and planar cross-bedded, medium-to fine-grained sandstone with mudstone drapes and are interpreted as recording deposition within estuarine meandering channels. A low-diversity assemblage of *Rosselia socialis* and *Teichichnus rectus* is present in sparsely bioturbated (BI 0-1), inclined heterolithic stratified, coarse- to fine-grained sandstone and mudstone. FE consists of sparsely bioturbated (BI 0-1), fine- to very fine-grained sandstone locally having convolute lamination and *Ophiomorpha nodosa* (Fig. 3.4A-C). In this context, both ichnofaunas indicate brackish-water conditions. Additionally, *Beaconites antarcticum* occurs in intensely bioturbated (BI 4-6), thinly interbedded, fine- to very fine-grained sandstone and siltstone units displaying IHS and current ripple cross-lamination with mudstone drapes. These deposits were formed in meandering, tide-dominated estuarine channels with point bars formed due to lateral accretion in the freshwater portion of the inner estuarine zone (Buatois, 2005; Buatois and Mángano, 2011; Martinius et al., 2012; Diez-Canseco et al., 2015). FI1-FI3 are sandstone-dominate, but intercalated within mudstone intervals containing foraminifers and dinoflagellates. FI1 consists of sparsely bioturbated (BI 0-1), massive, very coarse- to medium-grained sandstone with *Ophiomorpha nodosa*. FI2 consists of massive to planar cross-stratified, very fine- to medium-grained sandstone with shells. FI3 consists of massive to planar cross-stratified, very coarse- to fine-grained sandstone. FI1-FI3 record deposition within meandering tidal channels.
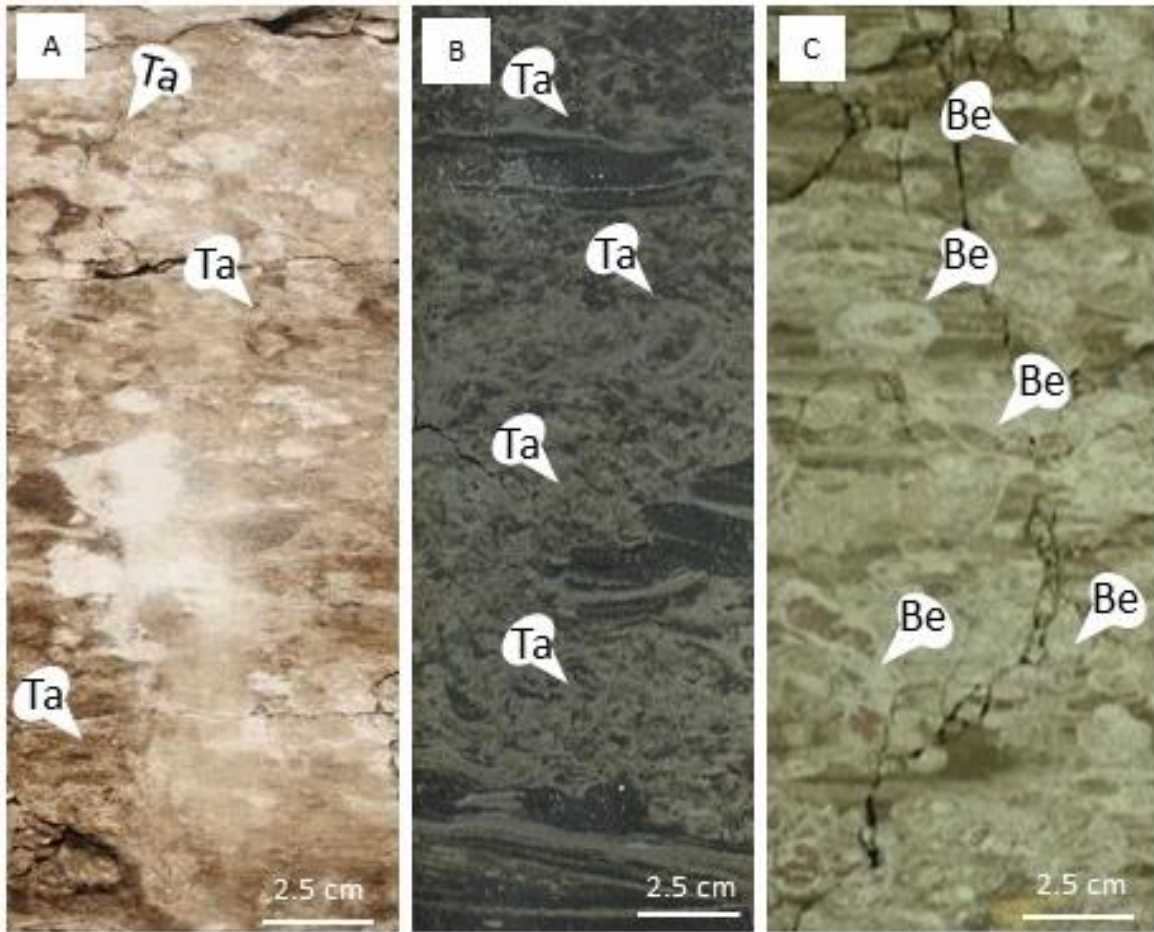
Figure 3.3. Trace-fossil distribution in freshwater deposits from the Oficina Formation in the Orinoco Oil Belt. (A) *Taenidium* isp. (Ta) from the lower member in the Junín area (Junín 3), in highly bioturbated mudstone located above fluvial braided channel units. Facies FA1, well J1, depth 723.59 m. (B) *Taenidium* isp. (Ta) from the middle member in the Junín area (Petrocedeño), in highly bioturbated mud-flat deposits. Facies FA3, well J6, depth 471.52 m. (C) *Beaconites antarcticum* (Be) from the upper member in the Junín area (Junín 3), in highly bioturbated floodplain mudstone. Facies FA5, well J3, depth 576.37 m.

3.6.1.3. FA3: Tidal flats and tidal creeks

Facies FC, FD, FE, FF1, FF2, FF3, FF4, FF5, FG2, FG3, FH1, and FH2 constitute FA3. FA3 occurs in the middle part of the sedimentary succession of the Boyaca, Junín, Ayacucho, and Carabobo areas, representing the middle member of the Oficina Formation. It consists mostly of interbedded mudstone and medium- to very fine-grained sandstone, displaying low to intense bioturbation (BI 0-6) and recording deposition in tidal flats and tidal creeks. FE and FF1-FF4 consist of interbedded very fine- to fine-grained sandstone and mudstone, displaying variable intensities of bioturbation (BI 0-5) and recording deposition in lower sand, middle mixed, and

upper mud tidal flat settings. Mudstone drapes, convolute lamination, and flaser, wavy and lenticular bedding are present. Sandstone-dominated intervals, representing sand flats, contain *Ophiomorpha nodosa*, *Skolithos linearis* (Fig. 3.4E), *Diplocraterion habichii* (Fig. 3D*), Planolites montanus*, *Teichichnus rectus*, and *Rosselia socialis* (Fig. 3.5B). In contrast, mudstone-dominated or heterolithic intervals are characterized by, *Teichichnus rectus*, *Bergaueria* isp., *Planolites montanus, Thalassinoides* isp., and indistinct bioturbation mottling recording deposition in mud flats (Fig. 3.5A, C, D, E, F, G). These tidal flats were formed in estuarine settings characterized by brackish-water conditions. In contrast, FG2 consists of intensely bioturbated (BI 4-6), massive to parallel-laminated mudstone and siltstone with *Taenidium* isp. (Fig. 3.3C-D), recording deposition in mud flats formed landward of the maximum salinity limit. These deposits contain desiccation cracks and siderite nodules and bands. FC, FD, FF5, FG3, FH1, and FH2 are subordinate components of FA3. FC and FD consist of planar and trough cross-stratified, sparsely bioturbated (BI 0-1), medium- to fine-grained sandstone with mudstone drapes and IHS, recording deposition in tidal creeks. These deposits contain *Rosselia socialis*, *Teichichnus rectus* and *Ophiomorpha nodosa*. FF5 consists of massive calcareous mudstone with scarce limestone layers and shell remains, representing transgressive deposits in the tidal flats. FG3 consists of moderately bioturbated (BI 1-4), massive to parallel-laminated mudstone with desiccation cracks and siderite nodules and bands. These deposits represent poorly developed paleosols. Firmground *Thalassinoides* isp., penetrating into the paleosols and tidal mud flats from overlying transgressive surfaces is recognized in these deposits. FH1 and FH2 consist of coal, recording deposition in swamps adjacent to tidal flats. Whereas FH1 is unburrowed, FH2 is highly bioturbated (BI 3-5), containing *Thalassinoides* isp.

3.6.1.4. FA4: Outer-estuarine sandbars

Facies FC, FD, FG1, FG3, and FH2 constitute FA4. FA4 occurs in the middle part of the sedimentary succession in the Boyaca, Junín, Ayacucho, and Carabobo areas, representing the uppermost part of the middle member of the Oficina Formation. FA4 represents deposition in an outer-estuarine sandbar complex. FC and FD consist of medium- to fine-grained sandstone and mudstone with IHS, recording deposition in outer estuarine sandbars. These deposits are thinner than those of FA2 and are unbioturbated to sparsely bioturbated (BI 0-1), containing *Rosselia socialis*, *Ophiomorpha nodosa*, and *Teichichnus rectus*.
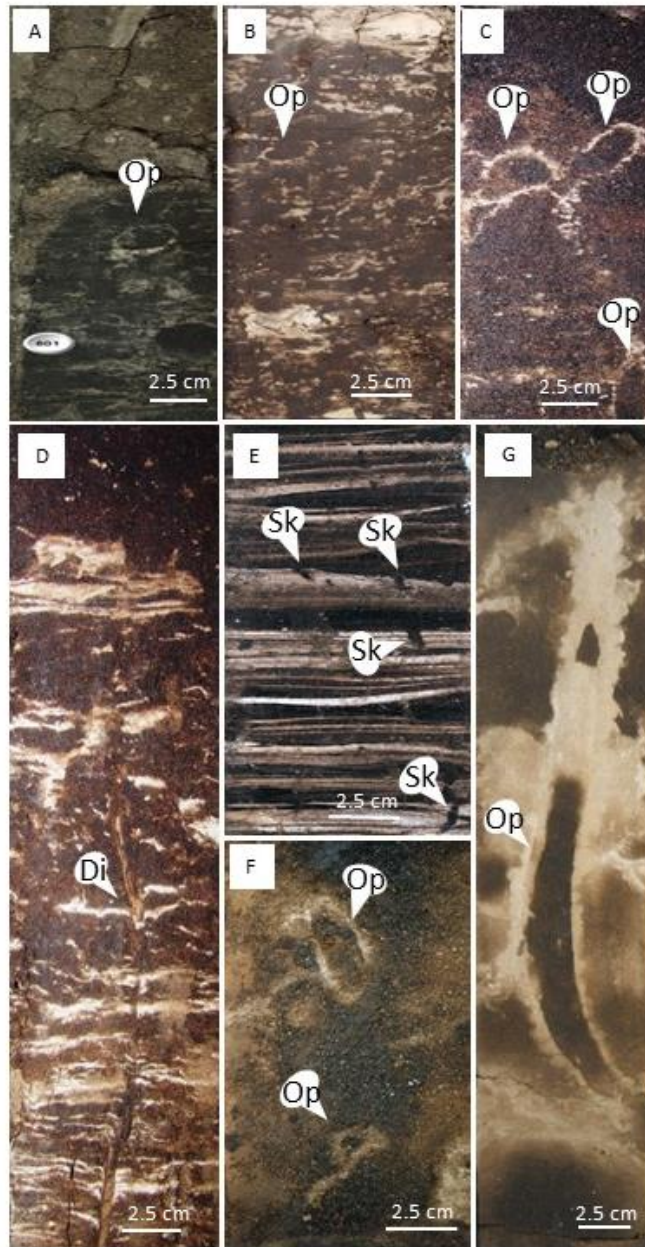
Figure 3.4. Trace-fossil distribution in marginal- to open-marine deposits of the Oficina Formation in the Orinoco Oil Belt and the Oritupano Field. (A, B, and C) *Ophiomorpha nodosa* (Op) in sparsely bioturbated, abandoned estuarine channel fills of the Orinoco Oil Belt. Facies FA2, wells C8, C9, and A2, depths 420.01 m, 960.42 m, and 686.10 m, respectively. (D) *Diplocraterion habichii* (Di) in sparsely bioturbated tidal sand- to mixed-flat deposits of the Orinoco Oil Belt (Ayacucho area). Facies FF1, well A2, depth 733.34 m. (E) *Skolithos linearis* (Sk) in bioturbated tidal sand- to mixed-flat deposits of the Orinoco Oil Belt (Junín area). Facies FF1, well J1, depth 440.13 m. (F) *Ophiomorpha nodosa* (Op) in sparsely bioturbated deltaic distributary channel fills within wave-dominated deltaic systems of the Oritupano Field. Facies FJ, well OR1, depth 1828.19 m. (G) Large, vertical *Ophiomorpha nodosa* (Op) in wave-dominated upper- to middle-shoreface deposits of the Oritupano Field, indicating normal-marine conditions. Facies FO, well OR2, depth 1706.88 m. Sandstone is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

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FG1 consists of moderately bioturbated (BI 3-4), massive to parallel-laminated carbonaceous mudstone and localized current ripples and flaser bedding, recording deposition in the outer-estuary margin. These deposits contain a low-diversity assemblage of *Teichichnus rectus*, *Thalassinoides* isp., and *Planolites montanus*. FH2 consists of highly bioturbated (BI 3-5) coal, recording deposition in swamps. *Thalassinoides* isp. is present in these deposits. FG3 consists of moderately bioturbated (BI 1-4), massive to parallel-laminated mudstone, recording immature, waterlogged paleosols. Desiccation cracks, and siderite nodules and bands are present locally. Firmground *Thalassinoides* isp. is recognized in swamps and paleosols, penetrating from overlying transgressive surfaces.

3.6.1.5. FA5: Lower delta plain of a tide-dominated delta

Facies FC, FD, FG2, and FH1 constitute FA5. FA5 is present in the upper part of the sedimentary succession in the Boyaca and Junín areas, representing the upper member of the Oficina Formation. FA5 is interpreted as recording sedimentation in a lower delta plain, reflecting progradation of a tide-dominated delta in a broad embayment. FA5 is separated from the underlying fluvio-estuarine facies assemblages by a maximum flooding surface (Solórzano et al., 2015). Sandstone units in FA5 are thinner than those in FA2 and are separated by mudstone and siltstone. The absence of FA5 in the Ayacucho and Carabobo areas is due to the fact that cores were taken only in the lower and middle parts of the sedimentary succession. FC and FD consist of fining- and thinning-upward, planar and trough cross-stratified, medium- to fine-grained sandstone with mudstone drapes, as well as inclined heterolithic stratified, coarse- to fine-grained sandstone, recording deposition in tide-influenced distributary channels. FG2 consists of massive to parallel-laminated mudstone and silstone with desiccation cracks, siderite nodules and bands, recording sedimentation in floodplains and interdistributary bays. Intensely bioturbated (BI 4-6) floodplain mudstone is characterized by the presence of *Beaconites antarcticum* (Fig. 3.3E-F). FH1 consists of coal beds, recording deposition in swamps.
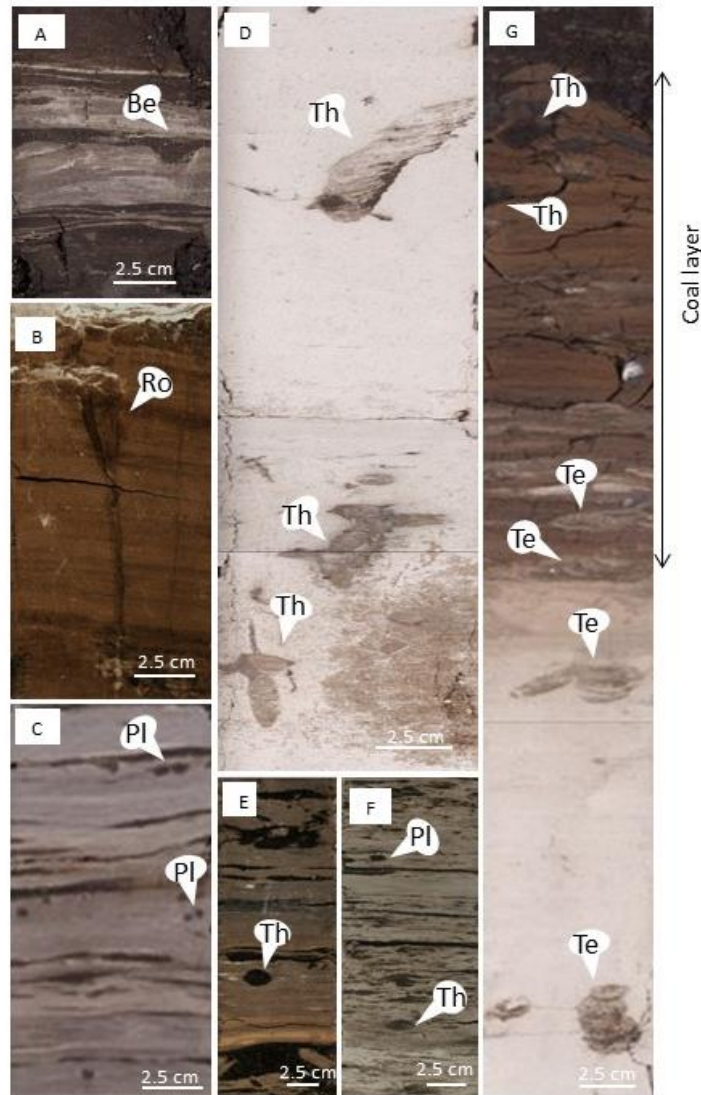
Figure 3.5. Trace-fossil distribution in marginal-marine deposits from the middle member of the Oficina Formation in the Orinoco Oil Belt. (A) *Bergaueria* isp. (Be) in sparsely bioturbated tidal mud-flat deposits in the area de Carabobo. Facies FF3, well C9, depth 984.50 m. (B) *Rosselia socialis* (Ro) in sparsely bioturbated tidal sand- to mixed-flat deposits in the Junín area. Facies FF1, well J1, depth 434 m. (C) *Planolites montanus* (Pl) in bioturbated tidal mud-flat deposits in the area de Carabobo. Facies FF3, well C9, depth 1034.18 m. (D) *Thalassinoides* isp. (Th) with rhythmic tidal infill (i.e. tubular tidalite) in tidal mud-flat deposits in the Carabobo area. Facies FF4, well C9, depth 988.16 m. (E) *Thalassinoides* isp. (Th) in tidal mud-flat deposits in the Ayacucho area. Facies FF3, well A12, depth 880.56 m. (F) *Planolites montanus* (Pl) and *Thalassinoides* isp. (Th) in tidal mud-flat deposits in the Ayacucho area. Facies FF3, well A9, depth 366.36 m. (G) *Teichichnus rectus* (Te) in tidal mud-flat deposits (Facies FF4, depth 1031.78 m) and *Thalassinoides* isp. (Th) in coal layers (Facies FH2, depth 1031.44 m). Both trace fossils from well C9 in the Carabobo area. Note that sandstone in C, E, F, and upper part of G is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

3.6.2 Sedimentary Facies of the Oritupano Field

Eleven facies (FJ-FS), grouped in four facies assemblages (FA6-9), have been recognized in the Oritupano Field (Tables 3.2 and 3.3). The sedimentary succession in the Oritupano Field represents the upper member of the Oficina Formation, which reflects highstand progradation. This interval correlates with the highstand deltaic deposits (FA5) identified in the Orinoco Oil Belt.

Table 3.2. Facies associations and interpretation in the study area.

Stratigraphic unit	Field	Facies association		Facies
Oficina Formation	Oritupano	FA9	Offshore-shelf complex	FQ, FR, and FS
		FA8	Wave-dominated shoreface	FO and FP
		FA7	Delta front and Prodelta of a wave-dominated delta	FL, FM1, FM2, and FN
		FA6	Lower delta plain of a wave-dominated delta	FJ and FK
	Orinoco Oil Belt	FA5	Lower delta plain of a tide-dominated delta	FC, FD, FG2, and FH1
		FA4	Outer estuarine sandbars	FC, FD, FG1, FG3, and FH2
		FA3	Tidal flats and tidal creeks	FF1, FF2, FF3, FF4, FF5, FC, FD, FE, FG2, FG3, FH1, and FH2
		FA2	Estuarine meandering channels	FA, FC, FD, FE, FI1, FI2, and FI3
		FA1	Fluvial braided channels	FB1, FB2, FG2, and FH1

Table 3.3. Sedimentary Facies of the Oficina Formation in the Oritupano Field.

Facies			Lithology and Texture	Dominant physical sedimentary structures	Ichnology	Thickness (m)	Other characteristics	Interpretation
FJ Cross-stratified coarse- to medium-grained sandstone			Coarse- to medium-grained sandstone, poorly sorted	Massive to planar cross-stratification	*Ophiomorpha nodosa* BI: 0-1	1.5 to 4.6	Fining-upward, erosive bases, generally oil impregnated	Distributary channel in wave-dominated delta
FK Laminated mudstone and coal			Mudstone and coal	Massive to parallel-lamination	*Planolites montanus, Teichichnus rectus, Palaeophycus tubularis, Thalassinoides isp, Palaeophycus heberti* BI: 0-1	0.3 to 1.8		Interdistributary bay in wave-dominated delta
FL Cross-stratified coarse- to medium-grained sandstone			Coarse- to medium-grained sandstone, poorly sorted	Parallel to trough planar cross-stratification	*Ophiomorpha nodosa* BI: 0-1	0.61 to 4.6	Typically coarsening-upward, generally oil impregnated	Sandy mouth bar
FM Cross-stratified fine- to very fine-grained sandstone	FM1	Trough and planar cross-stratification sandstone	Fine -to very fine-grained sandstone	Trough and planar cross-stratification	*Asterosoma* isp., *Rosselia socialis, Ophiomorpha nodosa* BI: 0-1	0.91 to 3.35		Proximal delta-front
	FM2	Parallel to wave lamination and hummocky cross stratification sandstone	Fine- to very fine-grained sandstone	Parallel to wave ripple cross-lamination and hummocky cross-stratification	*Planolites montanus, Thalassinoides* isp., *Teichichnus rectus, Palaeophycus tubularis Asterosoma* isp., *Skolithos linearis* BI: 0-1	0.91 to 3.05		Storm-dominated distal delta-front
FN Laminated calcareous mudstone with shell remains			Mudstone	Parallel lamination	*Planolites montanus, Palaeophycus heberti, Rhizocorallium* isp., *Thalassinoides* isp., *Chondrites* isp. BI: 0-1	0.30 to 3.05	Syneresis cracks and sand levels	Prodelta
FO Massive fine-grained sandstone			Fine-grained sandstone	Massive appearance	*Ophiomorpha nodosa* BI: 0-1	0.91 to 4.6		Upper to middle shoreface
FP Massive fine-grained calcareous sandstone			Fine-grained sandstone	Massive appearance	*Asterosoma* isp., *Teichichnus rectus, Planolites montanus, Palaeophycus tubularis, Thalassinoides* isp., *Palaeophycus heberti, Ophiomorpha nodosa* BI: 2-3	0.30 to 0.61		Lower shoreface

FQ Bioturbated calcareous mudstone	Highly bioturbated calcareous mudstone	Massive appearance	*Asterosoma* isp., *Planolites montanus*, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Thalassinoides* isp. BI: 2-5	1.82	*Asterosoma* isp. is the dominant ichnotaxon	Upper Offshore
FR Bioturbated calcareous mudstone	Highly bioturbated calcareous mudstone	Massive appearance	*Asterosoma* isp., *Planolites montanus*, *Palaeophycus tubularis*, *Phycosiphon incertum*, *Teichichnus rectus*, *Palaeophycus heberti*, *Rhizocorallium* isp., *Rosselia socialis* BI: 3-6	0.3	*Phycosiphon incertum* is the dominant ichnotaxon	Lower offshore
FS Massive calcareous mudstone with abundant remains of shells	Calcareous mudstone	Massive appearance	*Asterosoma* isp., *Chondrites* isp., *Planolites montanus*, *Teichichnus rectus* BI: 0-4	2.1 to 4.88		Shelf

3.6.2.1. FA6: Delta plain of a wave-dominated delta

Facies FJ and FK constitute FA6. FA6 is present in the lower part of the sedimentary succession of the Oritupano Field and records deposition in the delta plain of a wave-dominated delta. FJ consists of fining-upward, massive to planar cross-stratified, erosively based, sparsely bioturbated (BI 0-1), coarse- to medium-grained sandstone, recording deposition within deltaic distributary channels. These deposits display scarce occurrences of *Ophiomorpha nodosa* (Fig. 3.4F). Facies FK consists of sparsely bioturbated (BI 0-1), massive to parallel-laminated mudstone and coal, recording deposition in interdistributary bays. Low-diversity suites of *Planolites montanus*, *Teichichnus rectus*, *Palaeophycus tubularis*, and *Palaeophycus heberti* occur in this facies. Firmground and woodground *Thalassinoides* isp. penetrates from overlying transgressive surfaces.

3.6.2.2. FA7: Delta-front and prodelta of a wave-dominated delta

Facies FL, FM1, FM2 and FN constitute FA7. FA7 is present in the middle part of the sedimentary succession of the Oritupano Field, and records deposition in an area encompassing the delta front (Fig. 3.6A-C) and the prodelta (Fig. 3.6B) of a wave-dominated delta. FL consists of coarsening-upward, parallel to trough and planar cross-stratified, sparsely bioturbated (BI 0-1), coarse- to

medium-grained sandstone, representing deposition in sandy mouth bars. These deposits contain isolated specimens of *Ophiomorpha nodosa*. FM1 consists of trough and planar cross-stratified, sparsely bioturbated (BI 0-1), fine- to very fine-grained sandstone, representing deposition in a proximal delta front. FM1 hosts *Asterosoma* isp., *Rosselia socialis*, and *Ophiomorpha nodosa* (Fig. 3.6C). FM2 consists of parallel, wave ripple cross-laminated and hummocky cross-stratified, sparsely bioturbated (BI 0-1), fine- to very fine-grained sandstone, recording sedimentation in a storm-dominated distal delta-front. These deposits are characterized by the presence of *Planolites montanus*, *Thalassinoides* isp., *Palaeophycus tubularis*, *Teichichnus rectus, Skolithos linearis*, *Asterosoma* isp., and escape trace fossils (Fig. 3.6A). FN consists of massive to parallel-laminated, sparsely bioturbated (BI 0-1), calcareous mudstone with shell remains and syneresis cracks, interbedded with thin very fine-grained sandstone. This facies represents deposition in a prodelta. These deposits contain *Chondrites* isp., *Planolites montanus*, *Palaeophycus heberti*, *Rhizocorallium* isp., and *Thalassinoides* isp..(Fig. 3.6B).

3.6.2.3. FA8: Wave-dominated shoreface

Facies FO and FP constitute FA8. FA8 is present in the upper part of the sedimentary succession of the Oritupano Field and records deposition in a wave-dominated shoreface. FO consists of sparsely bioturbated (BI 0-1), massive, fine-grained sandstone, recording deposition in the upper to middle shoreface. Monospecific occurrences of *Ophiomorpha nodosa* are characteristic of these deposits (Fig. 3.4G). FP consists of moderately bioturbated (BI 2-3), massive, fine-grained calcareous sandstone, representing deposition in the lower shoreface. A diverse ichnofauna, comprising *Asterosoma* isp., *Teichichnus rectus*, *Planolites montanus*, *Thalassinoides* isp., *Ophiomorpha nodosa, Palaeophycus tubularis*, and *Palaeophycus heberti*, is present.

3.6.2.4. FA9: Offshore-shelf complex

Facies FQ, FR and FS constitute FA9. FA9 is present in the upper part of the sedimentary succession of the Oritupano Field and records deposition in the offshore-shelf complex (*i.e.,* below storm wave base) (Fig. 3.7A-D). FQ consists of highly bioturbated (BI 2-5), massive, calcareous mudstone with sporadic sand beds recording deposition in the upper offshore. *Asterosoma* isp. is the dominant ichnotaxon, whereas *Planolites montanus*, *Palaeophycus tubularis*, *Palaeophycus heberti*, and *Thalassinoides* isp. are common (Fig. 3.7B). FR consists of highly bioturbated (BI 3-

6), massive, calcareous mudstone, recording deposition on the lower offshore. This facies contains a diverse ichnofauna, comprising *Asterosoma* isp., *Planolites montanus*, *Phycosiphon incertum*, *Teichichnus rectus, Palaeophycus tubularis*, *Palaeophycus heberti*, *Rhizocorallium* isp., and *Rosselia socialis*. *Phycosiphon incertum* is the dominant ichnotaxon (Fig. 3.7A- C). FS consists of massive, calcareous mudstone with shell remains, displaying low to moderate bioturbation (BI 0-4) and representing deposition on the shelf (i.e., below storm wave base). *Asterosoma* isp., *Chondrites* isp., *Planolites montanus*, and *Teichichnus rectus* occur in these deposits (Fig. 3.7D).

3.6.3. Summary

In summary, FA1 represents the infill of an incised fluvial valley, whereas FA2, FA3, and FA4 record deposition within an incised estuarine valley and FA5 records progradation of tide-dominated deltas in restricted embayed shorelines that may have promoted tidal action. All these facies assemblages are widespread in the Orinoco Oil Belt. In contrast, more marine conditions are represented in the Oritupano Oil Field. In this area, FA6 and FA7 represent deposition in wave-dominated deltas adjacent to strandplains and prograding into the open sea, where wave reworking was significant. FA8 and FA9 record sedimentation in wave-dominated shorefaces and offshore-shelf complexes, respectively.

3.7. Discussion

3.7.1. Softground ichnofacies along the salinity gradient

Salinity is a crucial factor in the development of benthic organisms (Hauton, 2016; Smyth and Elliott, 2016). Maximum diversity of species occurs in fully marine conditions and secondarily in freshwater settings, while the lowest diversity of organisms is recorded in brackish-water environments (Remane and Schlieper, 1971; Pemberton and Wightman, 1992; Buatois et al., 1997b; Hauck et al., 2009; Buatois and Mángano, 2011; Diez-Canseco et al., 2015) (Fig. 3.8). Salinity is independent of physical processes and therefore its signal is difficult to detect in standard facies analysis. In contrast, faunal distribution is strongly controlled by salinity (Remane and Schlieper, 1971; MacEachern and Pemberton, 1994; Buatois et al., 1997b; Diez-Canseco et al., 2015; Ezeh et al., 2016), which makes trace-fossil evidence particularly remarkable in paleoenvironmental characterization of marginal-marine depositional systems (e.g., MacEachern

and Pemberton, 1994; Buatois et al., 1997b). Biogenic structures provide key information to reconstruct salinity conditions at the time of colonization (e.g., Dashtgard et al., 2012; Diez-Canseco et al., 2015).
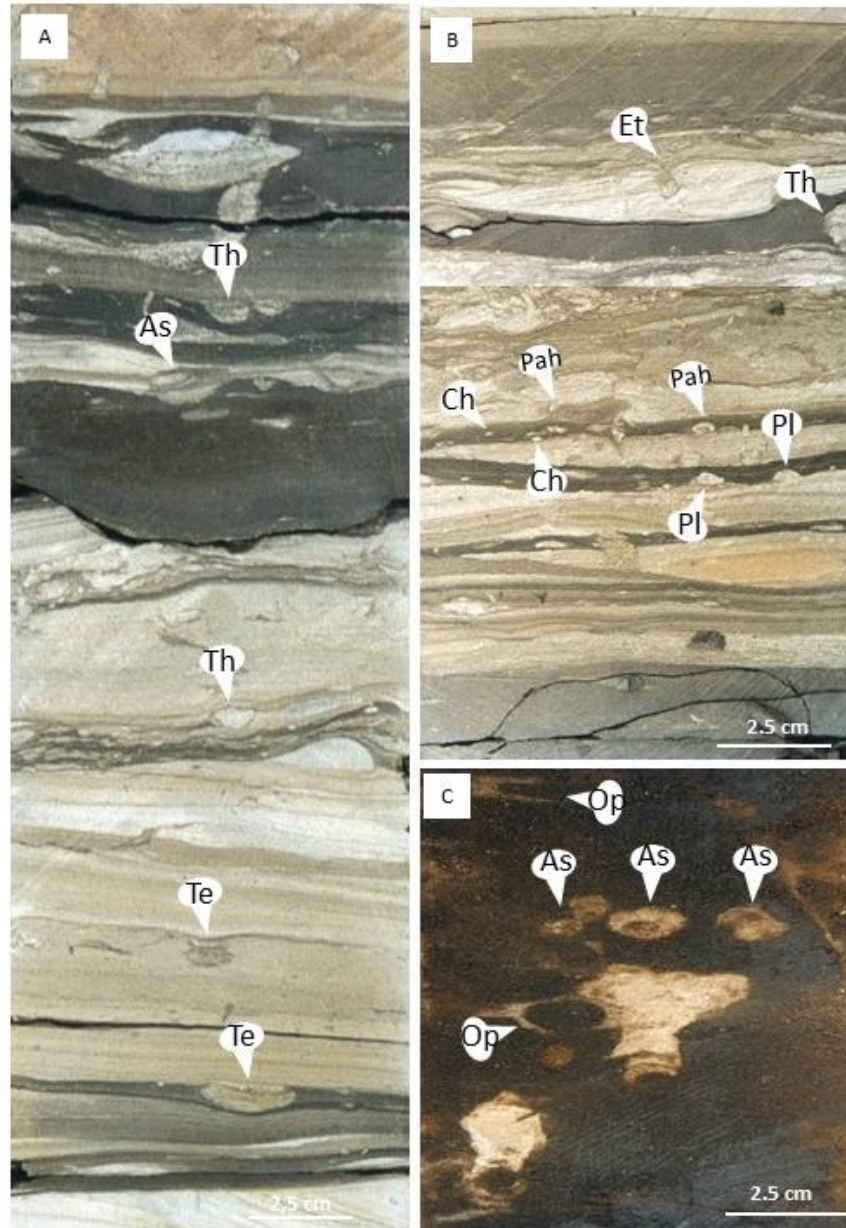
Figure 3.6. Trace-fossil distribution in delta-front and prodelta deposits (FA7) of a wave-dominated delta of the Oritupano Field. (A) *Asterosoma* isp. (As), *Thalassinoides* isp. (Th), and *Teichichnus rectus* (Te) in storm-dominated distal delta-front deposits. Facies FM2, well OR3, depth 1845.56 m. (B) *Paleophycus heberti* (Pah), *Chondrites* isp. (Ch), *Planolites montanus* (Pl), *Thalassinoides* isp. (Th), and escape trace (Et) in prodelta deposits. Facies FN, well OR1, depth 1832.45 m. (C) *Asterosoma* isp. (As) and *Ophiomorpha nodosa* (Op) in proximal delta-front deposits. Facies FM1, well OR1, depth 1823.31 m. Sandstone is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

Four softground ichnofacies have been recognized in the Oficina Formation, namely *Scoyenia*, depauperate *Cruziana*, *Skolithos*, and archetypal *Cruziana*. In the Orinoco Oil Belt, the *Scoyenia* Ichnofacies occurs in both continental and marginal-marine contexts, being present in the fluvial deposits of the lower member, the estuarine deposits of the middle member (Fig. 3.9), and the deltaic deposits of the upper member. In these environments, deposits containing the *Scoyenia* Ichnofacies display high bioturbation intensity and low diversity. The *Scoyenia* Ichnofacies is characterized by an association of low diversity, mostly monospecific occurrences of meniscate trace fossils (e.g., *Scoyenia*, *Beaconites*, and *Taenidium*) and arthropod trackways (Frey et al., 1984; Buatois and Mángano, 2004; Krapovickas et al., 2009; Diez-Canseco et al., 2015, 2016). This ichnofacies is typical of continental environments, in places being associated with intensely bioturbated deposits (Frey et al., 1984; Frey and Pemberton, 1984; 1987; Buatois and Mángano, 1995, 2002, 2004; Krapovickas et al., 2009). However, it is also present in the freshwater portion of inner estuarine and deltaic areas (Buatois et al., 1997b; Mángano and Buatois, 2004; Diez-Canseco et al., 2015, 2016; Rodriguez, 2015). Presence of the *Scoyenia* Ichnofacies in the Oficina Formation supports its widespread occurrences in freshwater deposits formed in a wide variety of depositional settings.

In addition to its typical occurrence in abandoned channel-fills and overbank fines in a fluvial context, the *Scoyenia* Ichnofacies also is present in marginal-marine deposits of deltaic and estuarine environments in the Orinoco Oil Belt. In marginal-marine contexts, this ichnofacies indicates a fluvial-tidal transition zone located in the inner part of the deltaic and estuarine environments, which represent a setting placed between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997b, 1998; Dalrymple and Choi, 2007; Buatois and Mángano, 2011; Rodriguez, 2015; Diez-Canseco et al., 2015, 2016; Shchepetkina et al., 2016). Ichnofaunas from the fluvial-tidal transition zone may be represented by an impoverished marine and freshwater ichnofacies. The fluvial-tidal transition zone of the deltaic and estuarine settings displays salinity fluctuations from brackish-water to freshwater conditions (Diez-Canseco et al., 2015; Gingras et al., 2016). Ichnodiversity along the tidal-fluvial transition decreases with decreasing saltwater intrusion, indicating that this ichnologic parameter can be used to predict salinity conditions during colonization (Buatois et al., 1997b; Dashtgard et al., 2012). The fluvio-tidal transition is dominated by freshwater to oligohaline (0–2 ppt) and the fluvial reach is freshwater (0 ppt) (Shchepetkina et al., 2016). Also, the fluvio-tidal transition zone has been

reported with values of salinity from 0 to 0.5 ppm (Remane and Schlieper, 1971; Buatois and Mángano, 2011, Diez-Canseco et al., 2015). In the inner part of the deltaic and estuarine systems of the Orinoco Oil Belt, freshwater conditions coexisted with tidal influence. As a result, typical freshwater trace-fossil suites are present in deposits showing evidence of tidal deposition, representing what has been referred to as "the paradox of continental ichnofaunas in tidal rhythmites" (Buatois et al., 1997b). Because of this, it has been advocated that freshwater ichnofacies should be incorporated as fundamental elements of estuarine and deltaic ichnofacies models (Buatois and Mángano, 2011; Diez-Canseco et al., 2015).
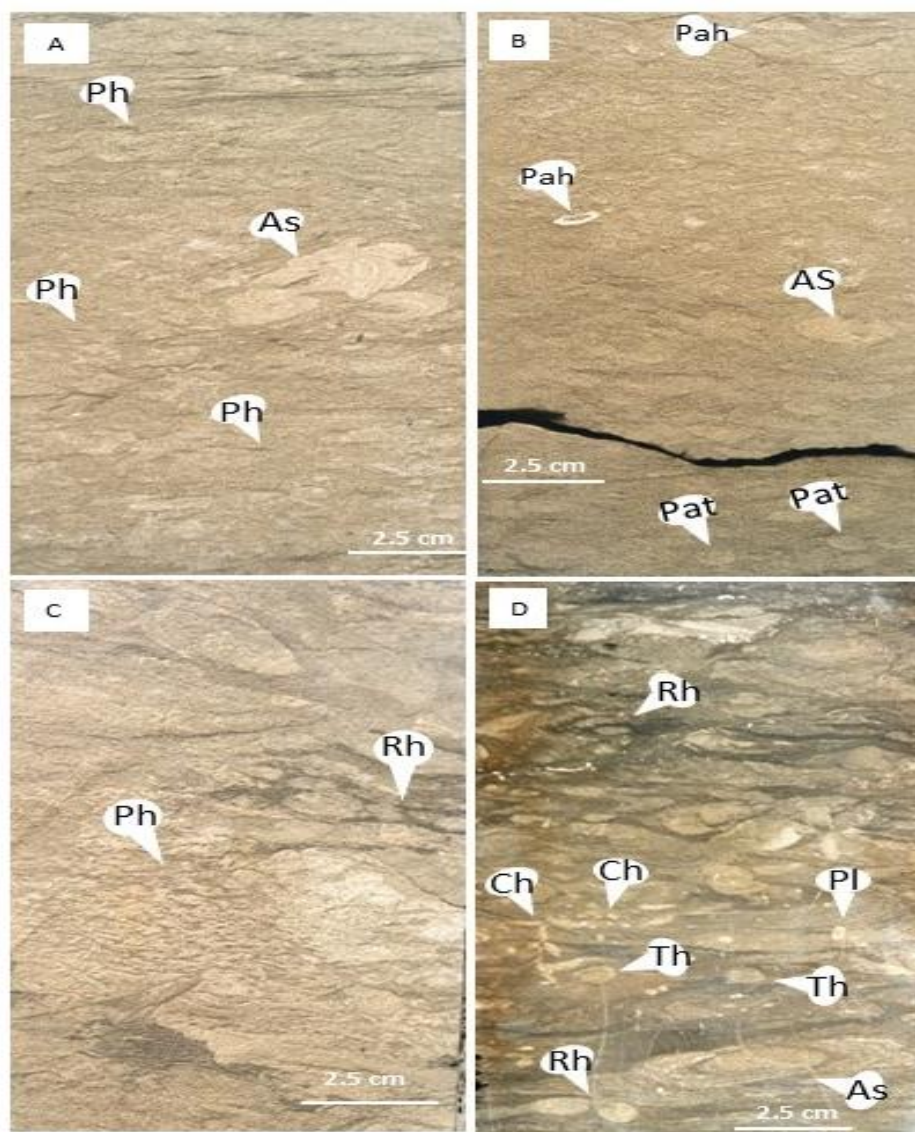
Figure 3.7. Trace-fossil distribution in offshore-shelf deposits (FA9) from the Oficina Formation in the Oritupano Field. (A) *Phycosiphon incertum* (Ph) and *Asterosoma* isp. (As) in lower-offshore deposits. Facies FR, well OR2, depth 1696.82 m. (B) *Asterosoma* isp. (AS), *Palaeophycus tubularis* (Pat), and *Palaeophycus heberti* (Pah) in upper-offshore deposits. Facies FQ, well OR2, depth 1701.39 m. (C) *Rhizocorallium* isp. (Rh) and *Phycosiphon incertum* (Ph) in lower-offshore deposits. Facies FR, well OR2, depth 1702.30 m. (D) *Rhizocorallium* isp. (Rh), *Chondrites* isp. (Ch), *Thalassinoides* isp. (Th), *Asterosoma* isp. (As), and *Planolites montanus* (Pl) in shelf deposits. Facies FS, well OR1, depth 1821.18 m.
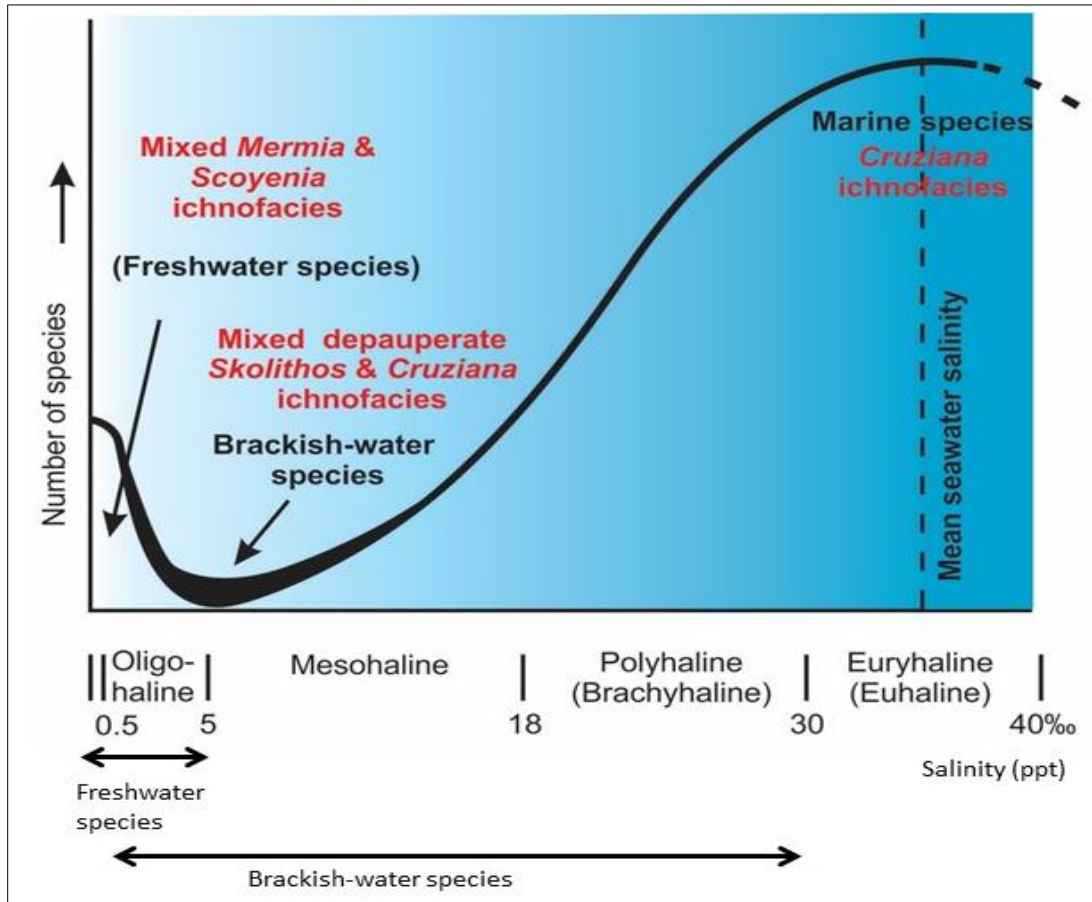
Figure 3.8. Relationships among salinity, ichnodiversity, and ichnofacies. After Buatois and Mángano (2011; modified from Remane and Schlieper, 1971; Pemberton and Wightman, 1992).

In the Oficina Formation inner estuarine zones, freshwater to terrestrial trace-fossil suites are overprinted on brackish-water suites. This results in the superimposition of elements of the *Scoyenia* Ichnofacies cross-cutting elements of the depauperate *Cruziana* Ichnofacies and probably reflects colonization during subsequent freshwater conditions or directly during subaerial exposure. This example is interpreted as the record of temporal fluctuations between brackish-water and freshwater to terrestrial conditions (Buatois and Mángano, 2011; Diez-Canseco et al.,

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2015). Whereas some elements of the marine infauna can adapt to brackish-water environments, the freshwater benthos do not survive under brackish-water and, therefore, their trace fossil assemblages do not intergrade with brackish-water suites (Pemberton and Wightman, 1992; Buatois et al., 1997b; Mángano and Buatois, 2004). Freshwater organisms disappear rapidly with a slight increase in the salinity, whereas the marine benthos experience a more gradual decrease in number under brackish-water conditions (Remane and Schlieper, 1971; Pemberton and Wightman 1992; Buatois and Mángano, 2011; Diez-Canseco et al., 2015; Gingras et al., 2016).

The depauperate *Cruziana* and *Skolithos* Ichnofacies also are present in the transgressive tide-dominated estuarine deposits of the middle member in the Orinoco Oil Belt formed under brackish-water conditions (Fig. 3.9). Extensive ichnologic evidence supports the notion that low diversity occurrences of the depauperate *Cruziana* Ichnofacies are linked with brackish-water conditions in the marginal-marine depositional systems (Pemberton et al., 1982; Wightman et al., 1987, Buatois and Mángano, 2011; Gingras et al., 2016) with values of salinity from 0.5‰ to 30‰) (Remane and Schlieper, 1971; Buatois and Mángano, 2011; Diez-Canseco et al., 2015). These settings encompass a wide variety of subenvironments, including intertidal zones of restricted coasts, shallow lagoons, estuaries, bays and delta plains. All these areas are characterized by steep salinity gradients that are accompanied by rapid and extreme changes in others factors, such as temperature, subaerial exposure, turbulence, oxygen content, and water turbidity. These fluctuations result in physiologically stressful conditions for numerous organisms, resulting in low ichnodiversity, small body sizes, high mortality rates, rapid reproduction capacity, short life cycles, and early sexual maturity (Remane and Schlieper, 1971; Pemberton and Wightman, 1992; Buatois and Mángano, 2011; Sisulak and Dashtgard, 2012; Gingras et al., 2016). Brackish-water portions of estuarine systems are characterized by lower degrees of bioturbation (as well as less uniform distribution of bioturbation) and lower ichnodiversity than their fully marine counterparts.

The reduced diversity in these brackish-water ecosystems could be associated with seasonal cyclicity and tidal currents. In estuarine systems, marine polychaetes are typically passively transported by tides from adjacent marine and marginal-marine sites because their larvae do not swim (Gingras et al., 2016). The abundance of worm-generated structures in the estuarine deposits of the Oficina Formation seems to support this scenario. In addition, inclined heterolithic stratified successions (i.e., interbedded sandstone and mudstone beds), which are abundant throughout the estuarine succession in the Orinoco Oil Belt, have been regarded as indicators of

seasonal cyclicity (Hubbard et al., 2011, Sisulak and Dashtgard, 2012). According to this interpretation, the saltwater wedge is introduced upstream during periods of low river discharge, resulting in stratified flow and the establishment of brackish-water conditions (i.e., oligohaline to mesohaline).
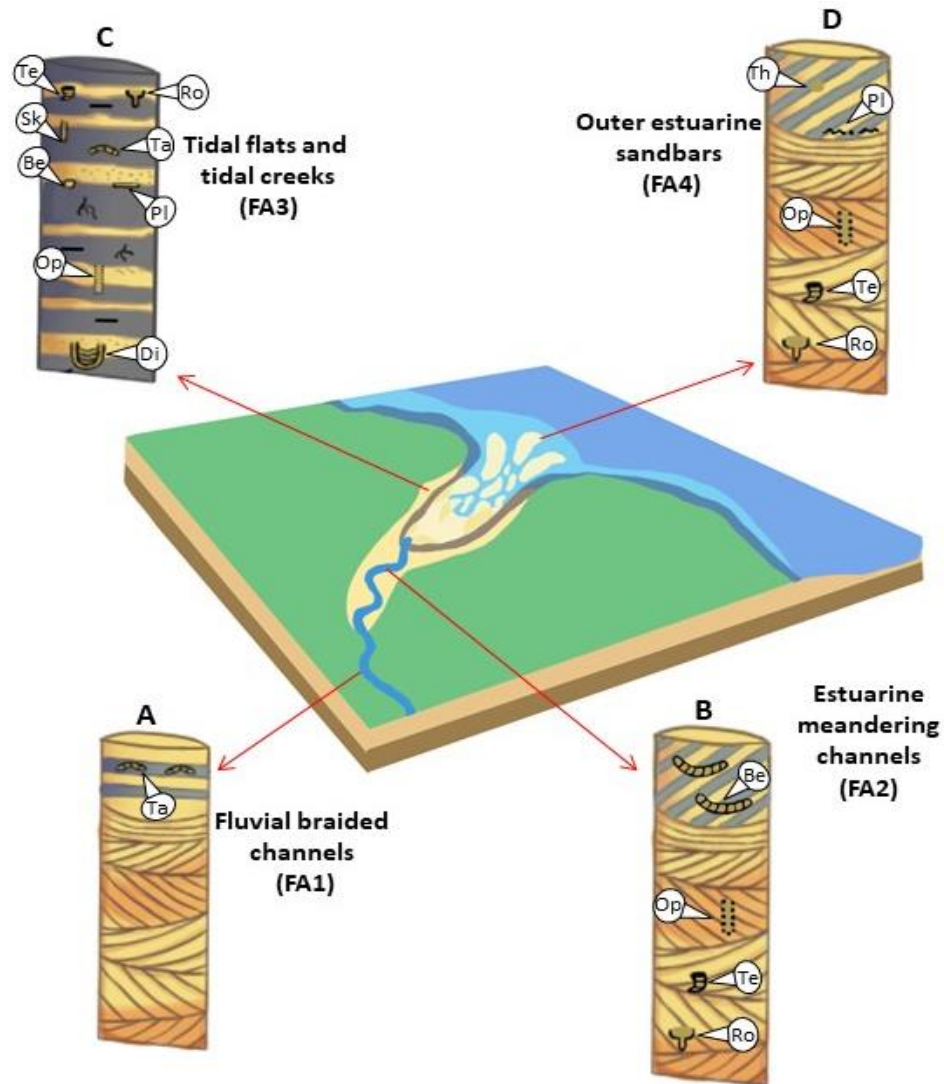
Figure 3.9. Schematic reconstruction of trace-fossil distribution under lowstand and transgressive conditions in fluvio-estuarine deposits of the embayment in the Orinoco Oil Belt. (A) Fluvial channel deposits are rarely bioturbated, displaying *Taenidium* isp. (Ta). (B) Estuarine-channel deposits are sparsely bioturbated by *Ophiomorpha nodosa* (Op), *Teichichnus rectus* (Te), and *Rosselia socialis* (Ro). *Beaconites antarcticum* (Be) in highly bioturbated estuarine-channel deposits with IHS represent the freshwater portion of the inner-estuarine zone. (C) Tidal-flat and tidal creek deposits displaying variable intensities of bioturbation and low diversity are indicated by *Skolithos linearis* (Sk), *Ophiomorpha nodosa* (Op), *Diplocraterion habichii* (Di), *Rosselia socialis* (Ro), *Teichichnus rectus* (Te) *Bergaueria* isp. (Be), and *Planolites montanus* (Pl). (D) Outer-estuarine sandbar deposits displaying variable intensities of bioturbation and low diversity contain *Rosselia socialis* (Ro), *Teichichnus rectus* (Te), *Planolites montanus* (Pl), *Ophiomorpha nodosa* (Op), and *Thalassinoides* isp. (Th).

These conditions promote the establishment of impoverished marine trace-fossil suites typical of salinity-stressed environments (Hubbard et al., 2011; Sisulak and Dashtgard, 2012; Gingras et al., 2016). Estuarine areas typically experience tidal influence as indicated by the abundance of sigmoidal bedding, draped foresets, reactivation surfaces, and bidirectionally oriented cross-stratification, whereas the presence of dinoflagellates indicates marine influence (Gingras et al., 2016). The brackish-water ichnofauna of the Oficina estuarine systems in the Orinoco Oil Belt is associated with dinoflagellates and tidally generated physical structures. Dinoflagellates (*e.g.*, *Selenopemphix quanta*, *Sumatrodinium hispidum*, *Cribroperidinium tenuitabulatum*, *Heteraulacysta campanula* and *Selenopemphix nephroides*) have been reported in the middle and upper members of the Oficina Formation in the Orinoco Oil Belt (Solórzano et al., 2015). Evidence of tidal action includes extensive IHS, mudstone drapes, bidirectionally oriented cross-lamination, and tubular tidalites.

The tide-influenced deltaic deposits (upper member) that overlie the tide-dominated estuarine interval in the Orinoco Oil Belt represent highstand progradation (Fig. 3.10). In addition to their occurrence in fluvial and estuarine deposits, the *Scoyenia* Ichnofacies also is present in floodplain mudstone of deltaic deposits, as indicated by the presence of monospecific suites of *Beaconites antarcticum* in deposits displaying intense bioturbation. Therefore, the *Scoyenia* Ichnofacies records deposition in the inner part of the deltaic systems between the maximum salinity and the maximum tidal limit (Buatois et al., 1997b, 1998; Dalrymple and Choi, 2007; Buatois and Mángano, 2011; Rodriguez, 2015; Diez-Canseco et al., 2015, 2016). Freshwater species display high abundance in areas where salinity in less than 5 ppm (Remane and Schlieper, 1971; Buatois and Mángano, 2011; Diez-Canseco et al., 2015). Mudstone drapes and IHS, which are characteristic of tide-dominated settings (Pemberton et al., 1982; Thomas et al., 1987; Ranger and Pemberton, 1992; Lettley et al., 2009; Gingras et al., 2016), are present in some distributary-channel deposits recording the presence of tidal currents. These deltaic distributary-channel deposits are barren of ichnofauna. The lack of bioturbation may be due to (1) rapid migration of 2D and 3 dunes; (2) low sand/mud ratio, and (3) extreme brackish-water conditions. Interbedded fine-grained interdistributary-bay deposits are also unbioturbated. The absence of bioturbation may have resulted from extreme brackish-water conditions, which is expected for deltas that are thought to have prograded into a brackish-water embayment rather than the open sea.
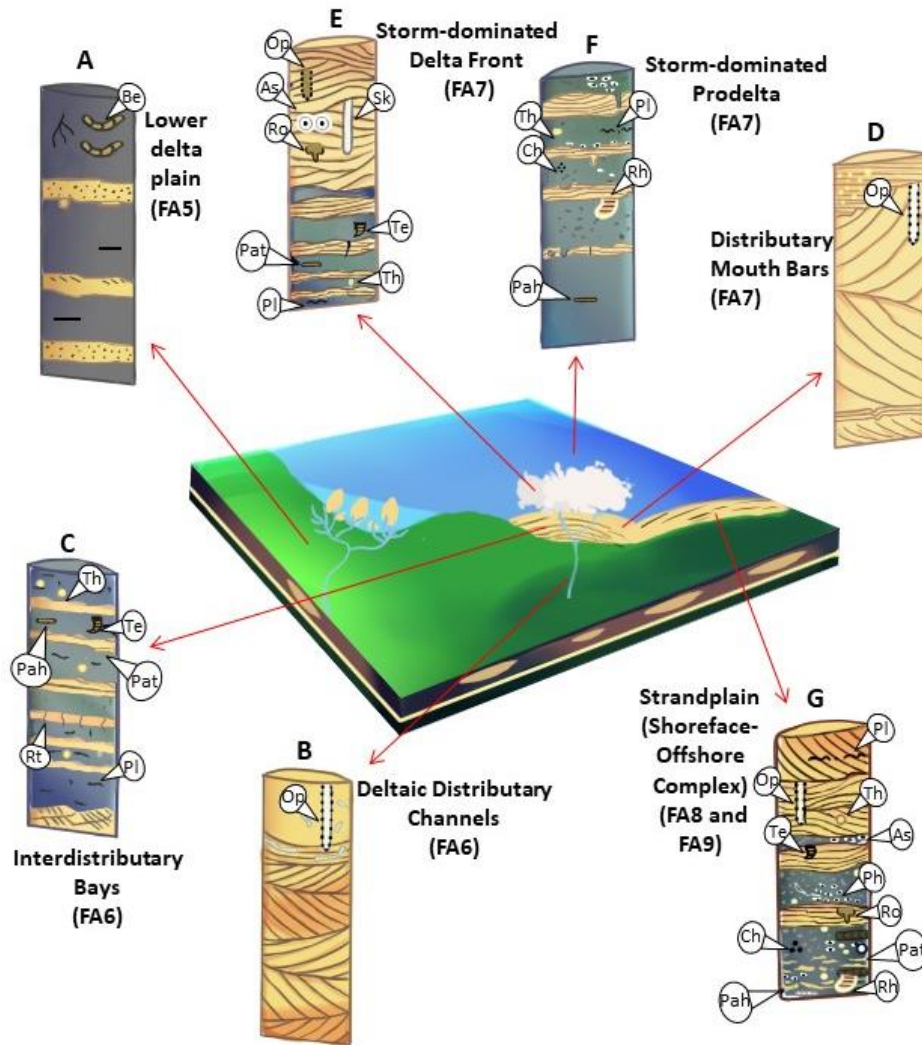
Figure 3.10. Schematic reconstruction of trace-fossil distribution under regressive conditions in a tide-dominated delta formed in an embayment (Orinoco Oil Belt), and wave-dominated delta and shoreface-offshore complex facing the open sea (Oritupano Oil Field). (A) Lower delta-plain deposits contain *Beaconites antarcticum* (Be) in highly bioturbated floodplain mudstone located in the freshwater portion of the inner deltaic zone. (B) Deltaic distributary-channel deposits are sparsely bioturbated by *Ophiomorpha nodosa* (Op). (C) Interdistributary-bay deposits display low-diversity suites and low bioturbation of *Planolites montanus* (Pl), *Teichichnus rectus* (Te), *Thalassinoides* isp. (Th), *Palaeophycus tubularis* (Pat), and *Palaeophycus heberti* (Pah). (D) Sandy distributary mouth-bar deposits record isolated specimens of *Ophiomorpha nodosa* (Op). (E) Sparsely bioturbated storm-dominated delta-front deposits contain *Ophiomorpha nodosa* (Op), *Teichichnus rectus* (Te), *Thalassinoides* isp. (Th), *Asterosoma* (As), *Rosselia socialis* (Ro), *Planolites montanus* (Pl), *Palaeophycus tubularis* (Pat), and *Skolithos linearis* (Sk). (F) Sparsely bioturbated storm-dominated prodelta deposits contain *Planolites montanus* (Pl), *Palaeophycus heberti* (Pah), *Rhizocorallium* isp. (Rh), *Thalassinoides* isp. (Th), and *Chondrites* isp. (Ch). (G) Strandplain (shoreface-offshore complex) deposits contain high-diversity suites and variable intensities of bioturbation, including *Ophiomorpha nodosa* (Op), *Teichichnus rectus* (Te), *Thalassinoides* isp. (Th), *Asterosoma* isp. (As), *Rosselia socialis* (Ro), *Planolites montanus* (Pl), *Palaeophycus tubularis* (Pat), *Palaeophycus heberti* (Pah), *Phycosiphon incertum* (Ph), *Rhizocorallium* isp. (Rh), and *Chondrites* isp. (Ch).

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Rapid salinity fluctuations also are supported by the presence of syneresis crack and siderite nodules and bands, all of which are common in brackish-water settings (Plumber and Gostin, 1981; MacEachern and Pemberton, 1994; Buatois et al., 2012). Additionally, the occurrence of dinoflagellates provides further evidence of marine influence (Solórzano et al., 2015). In addition to their presence in the estuarine deposits, the depauperate *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies are present in the wave-dominated deltaic deposits of the Oritupano Field, which reflect highstand progradation (Fig. 3.10). The interdistributary bay deposits host low-diversity trace-fossil suites, with low intensities of bioturbation, indicative of lower-energy conditions in protected bays (Buatois and Mángano, 2011). The scarce occurrences of *Ophiomorpha nodosa* in deltaic distributary channels, exemplifying the S*kolithos* Ichnofacies, indicate pauses in sedimentation or channel abandonment (Buatois and Mángano, 2011). *Ophiomorpha nodosa* in these distributary-channel deposits allows distinction from freshwater fluvial channels (Buatois et al., 2008).

The regressive, wave-dominated deltaic environment of the Oritupano Field also display stressed expressions of marine suites (*i.e.*, depauperate *Cruziana* Ichnofacies) typically associated with periods of increased fluvial discharge. These suites tend to alternate with assemblages having ichnotaxa (*e.g.*, *Chondrites* isp.) that are suggestive of times of reduced salinity stress and near-normal marine salinity conditions, particularly in delta-front and prodelta environments (Pemberton et al., 2001; MacEachern et al., 2005; Buatois and Mángano, 2011; Buatois et al., 2012). The presence of brackish-water ichnofauna is due to increased fluvial discharge from distributary deltaic channels; periodic salinity fluctuations due to river freshets play a major role in trace-fossil distribution (MacEachern et al., 2005; Buatois et al., 2008). In addition to changes in the composition of the ichnofauna, alternation of normal-marine salinity with times of dilution of marine salinity are evidenced by the intercalation of highly bioturbated beds with high ichnodiversity and sparsely bioturbated intervals with low ichnodiversity. The sparse bioturbation may suggest rapid sedimentation, elevated freshwater discharge or sporadic dysaerobic conditions (Buatois et al., 2012). Intensely bioturbated deposits with more typical marine ichnotaxa only are present in the Oritupano Field, reflecting a highstand progradation. The deltaic system identified in the Orinoco Oil Belt also prograded, but into a brackish-water embayment that never attained normal-marine conditions.

In addition, the wave-dominated regressive deposits of the upper member in the Oritupano

Field display the presence of the archetypal *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies in shoreface to offshore and shelf deposits formed along adjacent strandplains (Fig. 3.10). Therefore, the Oritupano Field illustrates open-marine facies that are not represented in the Orinoco Oil Belt, helping to calibrate the ichnodiversity levels associated with fully marine conditions. It has been noted that the maximum diversity of species occurs in fully marine conditions due to the activity of a euryhaline fauna under mean seawater salinity (30-40‰) (Remane and Schlieper, 1971; Pemberton and Wightman, 1992; Buatois and Mángano, 2011; Diez-Canseco et al., 2015). The archetypal *Cruziana* Ichnofacies occurs in wave-dominated lower shoreface and offshore-shelf complexes, whereas the *Skolithos* Ichnofacies is restricted to the upper through lower shoreface. The presence of larger and more vertical *Ophiomorpha nodosa* in upper- and middle-shoreface deposits suggests that the sediments were deposited by relatively slow aggradation under moderately high hydraulic conditions. The low diversity of burrows may indicate a stressful environment, probably due to the high-energy conditions and migration of dunes and longshore bars (Buatois and Mángano, 2011). Moderately bioturbated lower-shoreface deposits are attributed to the sporadic emplacement of sand beds during storms. These storm beds were rapidly colonized by opportunistic, suspension-feeding organisms prior to their re-colonization and thorough reworking by the resident fair-weather infauna. Overall, the absence or scarcity of mudstone partings or layers in the upper- to middle-shoreface deposits supports high energy due to waves and currents in proximal nearshore settings and indicates deposition above fair-weather wave base and continuous water agitation (Sømme et al., 2008; Buatois et al., 2012). In contrast, the faunal assemblage present in the lower-shoreface deposits is interpreted to reflect low to moderate energy conditions.

The archetypal *Cruziana* Ichnofacies is present in offshore-shelf complexes where mudstone commonly displays total bioturbation. These deposits represent suspended sediment fall-out in low-energy settings and record deposition below fair-weather wave base (offshore) and below storm wave base (shelf) (MacEachern and Pemberton, 1992; Sømme et al., 2008; Buatois et al., 2012; Ezeh et al., 2016). The Oficina upper-offshore deposits consist of highly bioturbated calcareous mudstone units with very rare sandstone beds. The upper-offshore received significant amounts of sand from the adjacent lower shoreface, resulting in deposition of sandy muds and silts. The high degree of bioturbation and high diversity of the trace fossil assemblage that constitute the archetypal *Cruziana* Ichnofacies in the offshore deposits, as well as the presence of

intercalated mudstone and sandstone layers, suggest environments with long periods of reduced sedimentation, located between storm and below fair-weather wave base (MacEachern and Pemberton, 1992; Buatois and Mángano, 2011). The Oficina lower-offshore deposits grade basinward into the shelf. These deposits receive more silt than sand with clay, producing silty mudstone facies and are not affected by storms. The shelf zone records sedimentation below the limit of storm wave action and displays very low energy and sand-starved conditions (Buatois and Mángano, 2011). Ichnodiversity and trace-fossil abundance are higher in the lower offshore than in the shelf.

3.7.2. Ichnofacies and Sequence Stratigraphy

The *Teredolites* and *Glossifungites* Ichnofacies have been recorded in both the Orinoco Oil Belt and the Oritupano Field. These ichnofacies are useful to delineate discontinuities of sequence-stratigraphic significance, such as transgressive surfaces of erosion (TSE), regressive surfaces of marine erosion (RSME) and co-planar surfaces (flooding surface/sequence boundary) (MacEachern et al., 1992; Pemberton et al., 2004; Buatois and Mángano, 2011). Some of the most common occurrences of these substrate-controlled ichnofacies are at transgressive surfaces of erosion, also known as ravinement surfaces, formed by tides and waves during the landward shift of the shoreline (MacEachern et al., 1992; Cattaneo and Steel, 2003; Catuneanu, 2006; Buatois et al., 2008; Buatois and Mángano, 2011). Tidal-ravinement surfaces are common in estuarine deposits (Allen and Posamentier, 1993; Catuneanu, 2006; Yang et al., 2009). Also, substrate-controlled ichnofacies may be formed in connection to autogenic processes, such as erosion along the base of estuarine, distributary and tidal channels, and cut-bank margins of tidal channels and creeks (see Buatois and Mángano, 2011 and MacEachern et al., 2012 for a discussion of examples). In particular, autogenic tidal scouring is common in various subenvironments within tide-dominated systems (Willis, 2005). Differentiating allogenic (*i.e.* due to relative changes in sea level) and autogenic surfaces delineated by substrate-controlled ichnofacies can be complicated. In the present case, the combination of stratal stacking pattern reflecting changes in water depth and regional mapping of the surfaces strongly suggests an allogenic origin.

The *Glossifungites* and *Teredolites* Ichnofacies are present in the transgressive tide-dominated estuarine deposits of the Orinoco Oil Belt and in the regressive wave-dominated deltaic deposits of the Oritupano Field, in both situations delineating transgressive surfaces of erosion.

These surfaces develop substrate-controlled ichnofacies because the exhumed surfaces originate within a marine or marginal marine environment, favoring colonization by organisms before deposition of the overlying sediment (MacEachern et al., 1992). The middle member estuarine deposits of the Orinoco Oil Belt comprise a transgressive system tract displaying a retrogradational stratal stacking pattern (Rodriguez, 2015). In these deposits, the *Glossifungites* Ichnofacies (Fig. 3.11A-C) is manifested by low to intense bioturbation and low diversity, represented by dwelling traces of suspension-feeding organisms (*i.e.*, firmground *Thalassinoides* isp.) that penetrate into the paleosols (Fig. 3.11A-B) and tidal flat muds (Fig. 3.11C) from overlying transgressive surfaces. Overlying transgressive strata are typically characterized by abundant shell debris (transgressive lags) (Fig. 3.11B) delineating the base of meandering estuarine-channel deposits with IHS (Fig. 3.11C). The *Glossifungites* Ichnofacies is developed in firm but unlithified substrates (MacEachern et al., 1992; Pemberton et al., 2004; Buatois and Mángano, 2011). Although it may be present in a wide variety of sequence-stratigraphic contexts, the *Glossifungites* Ichnofacies develops preferentially in transgressive settings (Gingras et al., 2004). In this context, the shell beds and the *Glossifungites* Ichnofacies may reflect high-frequency sea-level dynamics (from fourth to sixth order), representing TSE of different orders formed within a transgressive complex (Rodriguez-Tovar et al., 2007).

In contrast, in the upper member of the Oficina Formation in the Oritupano Field, the *Glossifungites* Ichnofacies is present in wave-dominated deltaic deposits forming progradational stacking patterns, delineating transgressive surfaces of erosion but within a highstand systems tract. These surfaces indicate parasequence boundaries, formed under high-energy conditions during short-term transgressions that punctuated an overall normal regressive scenario. Therefore, they do not indicate systems tract boundaries (Catuneanu, 2006). In these deposits, the *Glossifungites* Ichnofacies is indicated by firmground *Thalassinoides* isp. that penetrate into highly bioturbated interdistributary-bay deposits (Fig. 3.11D); firmground burrows are filled with coarse-grained sand and shell remains from the overlying transgressive deposits.

The *Teredolites* Ichnofacies consists of borings emplaced in marginal-marine woodgrounds, typically associated with swamps and bays. The ichnogenus *Teredolites* is the archetypal ichnotaxon in fossil woodgrounds, but other trace fossils including *Thalassinoides* also may be present (Buatois et al., 2002; Gingras et al., 2004). Biogenic structures are passively filled with sediments with the overlying sediment.
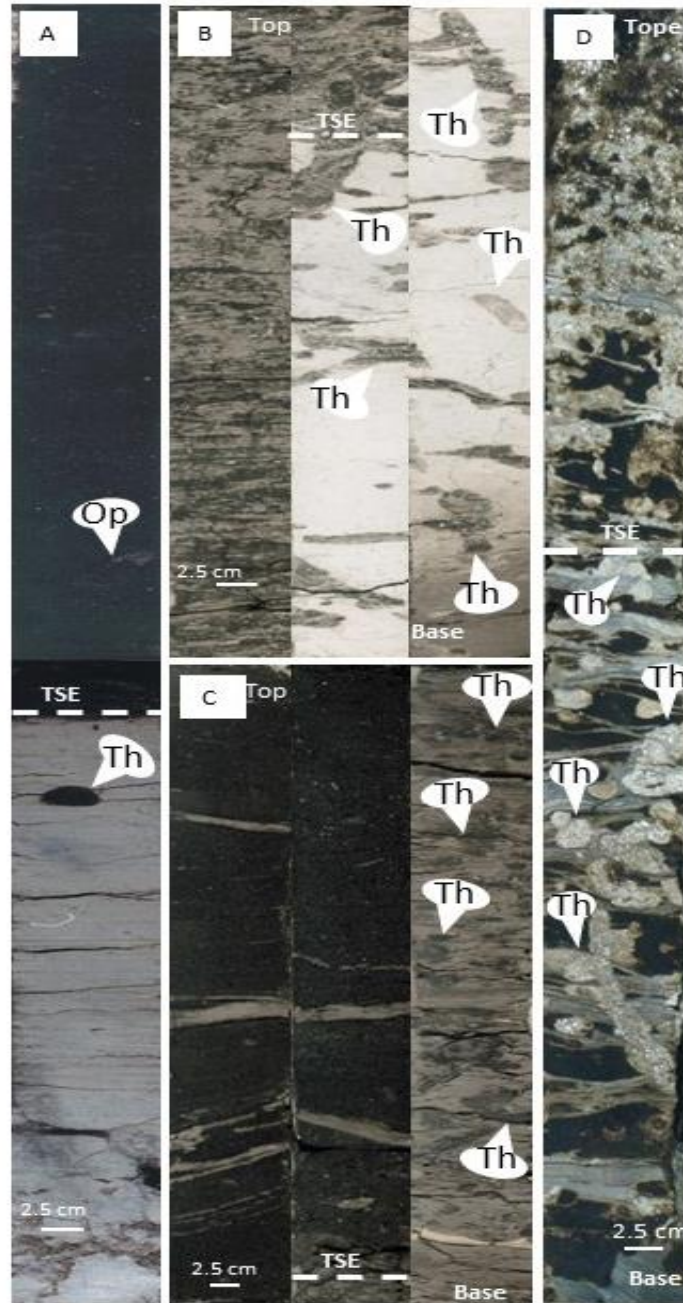
Figure 3.11. *Glossifungites* Ichnofacies in cores from the Oficina Formation in the Orinoco Oil Belt and the Oritupano Field delineating transgressive surfaces of erosion. (A) *Thalassinoides* isp. (Th) penetrating into a paleosol from an overlying transgressive surface that delineates the base of meandering estuarine channel deposits. Facies FG3, well A4, depth 779.67 m, middle member, Ayacucho area. (B) *Thalassinoides* isp. (Th) penetrating into the paleosol (FG3) deposits from an overlying transgressive surface. Facies FF3, well A8, depth 376.73 m, middle member, Ayacucho area. (C) *Thalassinoides* isp. (Th) penetrating into the tidal mud-flat deposits from an overlying transgressive surface that marks the base of meandering estuarine-channel deposits with IHS. Facies FF3, well A8, depth 347.77 m, middle member, Ayacucho area. (D) *Thalassinoides* isp. (Th) penetrating into the interdistributary-bay deposits from an overlying transgressive surface. Facies FK, well OR3, depth 1839.16 m, upper member, Oritupano Field. Note that in A, C, and D sandstone is impregnated with hydrocarbon resulting in dark color, while mudstone is light color.

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The *Teredolites* Ichnofacies occurs in resistant xylic substrates that may be preserved as coal or lignite in the stratigraphic record (Pemberton et al., 2001). This ichnofacies is associated with omission surfaces formed in a wide variety of paralic settings, such as bays, estuaries, lagoons, and deltas (Bromley et al., 1984; Pemberton et al., 1992; MacEachern et al., 2007). The *Teredolites* Ichnofacies occurs in brackish-water to fully marine environments, and the involved tracemakers apparently cannot tolerate freshwater (Buatois and Mángano, 2011). The *Teredolites* Ichnofacies is delineated by very high density of woodground *Thalassinoides* isp. penetrating coal layers in both the estuarine deposits of the middle member in the Orinoco Belt and the deltaic deposits of the upper member in the Oritupano Field (Fig. 3.12A-C). The burrows are filled with coarse-grained sands and shell remains from overlying transgressive lags. In the estuarine deposits of the Orinoco Belt, the *Teredolites* Ichnofacies occurs in swamp deposits (Fig. 3.12A-B), whereas in the Oritupano Field, it developed in interdistributary bay facies (Fig. 3.12C).
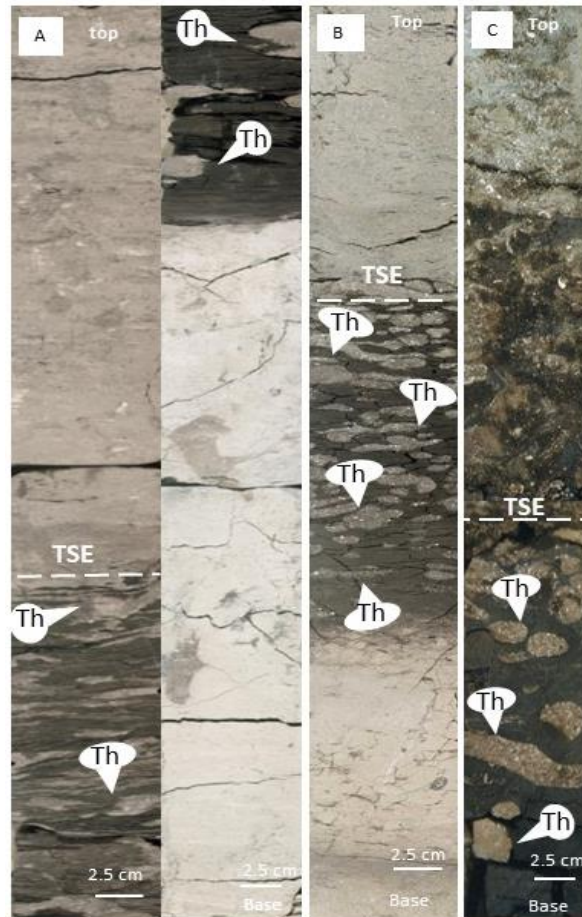
Figure 3.12. *Teredolites* Ichnofacies in cores from the Oficina Formation in the Orinoco Oil Belt and the Oritupano Field delineating transgressive surfaces of erosion. (A) *Thalassinoides* isp. (Th) penetrating into a coal layer of swamp deposits (FH2) from an overlying transgressive surface. Facies FA4, well A10, depth 415.74 m, middle member, Ayacucho area. (B) *Thalassinoides* isp. (Th) penetrating into coal layers in the swamp deposits (FH2) from an overlying transgressive surface. Facies FA4, well A8, depth 326.44 m, middle member, Ayacucho area. (C) *Thalassinoides* isp. (Th) penetrating into coal layers in the interdistributary-bay deposits from an overlying transgressive surface in the Oritupano field. Facies FK, well OR3, depth 1838.24 m, upper member, Oritupano Field.

3.7.3. Comparison of the Miocene Oficina Formation with the Cretaceous McMurray Formation of western Canada

The Miocene Oficina Formation and the Cretaceous McMurray Formation of northern Alberta, Canada represent two of the most important oil accumulations in the world. These two units are remarkably similar with respect to sedimentology, stratigraphy, ichnology and palynology (Table 3.4). Recently, the origin of the middle member of the McMurray Formation has been subject to intense debate (cf. Blum, 2017; Gingras and Leckie, 2017).

Similar to the Oficina Formation, the McMurray Formation has been subdivided into three members. The lower member is dominated by lowstand fluvial deposits, the middle member is characterized by transgressive estuarine point-bar deposits, and the upper member consists of highstand coastal marine deposits (Crerar and Arnott, 2007; Musial et al., 2012). The fluvial deposits of the McMurray Formation consist of cross-stratified pebbly to very coarse-grained sandstone formed in braided channels. These channel-fill deposits are locally interbedded with overbank mudstone or siltstone units that contain continental ichnofossils (Musial et al., 2012). A freshwater ichnofauna has been recognized recently, consisting of *Taenidium bowni* (*Naktodemasis bowni* in original study, but see Krapovickas et al., 2009, Diez-Canseco et al., 2016 and Buatois et al., 2016a for a discussion on the ichnotaxonomic status of *Naktodemasis*), *Planolites* isp., and *Taenidium* isp. (Musial et al., 2012). Fluvial deposits of the Oficina Formation are characterized by cross-stratified, pebbly, very coarse- to medium-grained sandstone representing braided channels (Rodriguez, 2015). In these fluvial deposits, bioturbation is normally absent, but *Taenidium* isp. occurs in overbank mudstone units above channel-fill deposits.

Table 3.4. Comparison between the Oficina and McMurray formations. No micropaleontological information is available for the Oritupano Field. Information on the McMurray Formation based on Gingras et al. (2016).

Unit	Setting			Characteristic	Oficina Formation (Miocene, Venezuela)	McMurray Formation (Cretaceous, Canada)
Lower	Fluvial			Sedimentology	Massive to planar trough cross-stratified pebble to medium-grained fluvial braided channels.	Cross-stratified pebble to very coarse-grained fluvial braided channels.
				Ichnology	Terrestrial bioturbation is normally absent. However, *Taenidium* isp. present in overbank setting.	Continental bioturbation is normally absent. However, *Taenidium bowni* and *Planolites* isp. occur in IHS-bearing units.
				Palynology	Terrestrial palynomorphs: *Bombacacidites baculatus*, *Psilatricolporites pachydermatus*, *Bombacacidites Zuatensis*, *Bombacacidites brevis*, *Spirosyncolpites spiralis*, *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni.*	Not applicable
Middle	Tide-dominated estuarine	Estuarine channels and sandbars		Sedimentology	Estuarine channels and sandbars characterized by trough and planar cross-stratified sandstone with mudstone drapes. Estuarine channel-fills with IHS and convolute lamination.	Estuarine channels and in-channel bar deposits characterized by trough and planar cross-stratified and current rippled sandstone. Estuarine channels with IHS in sandstone- and mudstone-dominated units.
				Ichnology	Estuarine channels in the brackish-water portion: depauperate *Cruziana* Ichnofacies (*Rosselia socialis*, *Teichichnus rectus*) and *Skolithos* Ichnofacies (*Ophiomorpha nodosa*), BI: 0-1, firmground of *Thalassinoides* isp.. Estuarine channels in the freshwater portion: *Beaconites antarcticum*, BI 4-6, recording deposition between the maximum salinity limit and the maximum tidal limit.	Estuary channels and in-channel bar deposits: *Planolites* isp., *Cylindrichnus* isp., *Palaeophycus* isp., *Skolithos* isp., *Arenicolites* isp., fugichnia, *Conichnus* isp.. BI 0–2. Estuarine channels with IHS in sandstone-dominated units: *Palaeophycus* isp., *Rosselia* isp., *Arenicolites* isp., *Bergaueria* isp., *Thalassinoides* isp., *Lockeia* isp., *Ophiomorpha* isp., *Planolites* isp., *Cylindrichnus* isp., *Gyrolithes* isp., fugichnia, BI 0–5. Estuarine channels with IHS in mudstone-dominated units: *Rosselia* isp., *Rhizocorallium* isp., *Chondrites* isp.. BI 0–3. Firmground of *Thalassinoides* isp., *Skolithos* isp., and *Palaeophycus* isp..
				Palynology	Not applicable	Dinocysts: *Nyktericysta* spp., *Vesperopsis* spp.

			Sedimentology	Tidal flats-tidal creek deposits consist of interbedded mudstone and sandstone.	Tidal flat deposits consist of horizontal, wavy to lenticular bedded heterolithic facies.
		Tidal-flat	Ichnology	Tidal flats-tidal creeks: *Cruziana* Ichnofacies (*Planolites montanus*, *Teichichnus rectus*, *Rosselia socialis*, *Bergaueria* isp.) and *Skolithos* Ichnofacies (*Skolithos linearis*, *Diplocraterion habichii*, *Ophiomorpha nodos*a), BI 0-1. Firmground of *Thalassinoides* isp.	Tidal flats: *Planolites* isp., *Teichichnus* isp., *Cylindrichnus* isp., *Palaeophycus* isp., *Skolithos* isp., *Lockeia* isp., *Arenicolites* isp., *Conichnus* isp., *Ophiomorpha* isp., *Schaubcylindrichnus freyi*, *fugichnia*. Moderate diversity and impoverished. BI 3–5.
			Palynology	Dinoflagellates: *Selenopemphix quanta*, *Sumatrodinium hispidum*, *Cribroperidinium tenuitabulatum*, *Heteraulacysta campanula*, *Selenopemphix nephroides.* Terrestrial palynomorphs: *Bombacacidites baculatus*, *Bombacacidites brevis*, *Psilatricolporites pachydermatus*, *Bombacacidites Zuatensis*, *Spirosyncolpites spiralis*, *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni.*	Not applicable
			Foraminifers	Benthic foraminifers: *Miliammina* sp., *Ammobaculites salsus*, *Elphidium poeyanum*, *Boliminella elegantissima*, *Bolivinids*, *Uvigerina isidroensis*, *Dorothia nutalli*, *Arenoparrela* sp., *Hanzawaia carstensi*, *Cibicidoides* sp., *Ammonia beccarii*, *Amphistegina lessonii*, and *Pseudononion pizarrensis.* Planktonic foraminifers: *Globorotalia foshi peripheroacuta*, *Globorotalia foshi peripheroronda*	Not applicable
Upper	Tide-dominated delta		Sedimentology	Lower delta plain: characterized by mudstone and planar and trough cross-stratified sandstone with mudstone drapes and IHS.	Not applicable
			Ichnology	Lower delta plain: *Scoyenia* Ichnofacies (*Beaconites antarcticum*), BI: 4-6.	Not applicable

		Palynology	Dinoflagellates: *Selenopemphix quanta*, *Sumatrodinium hispidum*, *Cribroperidinium tenuitabulatum*, *Heteraulacysta campanula*, *Selenopemphix nephroides*. Terrestrial palynomorphs: *Bombacacidites baculatus*, *Bombacacidites brevis*, *Psilatricolporites pachydermatus*, *Bombacacidites Zuatensis*, *Spirosyncolpites spiralis*, *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni*.	Not applicable
		Foraminifers	Benthic foraminifers: *Miliammina* sp., *Ammobaculites salsus*, *Elphidium poeyanum*, *Boliminella elegantissima*, *Bolivinids*, *Uvigerina isidroensis*, *Dorothia nutalli*, *Arenoparrela* sp., *Hanzawaia carstensi*, *Cibicidoides* sp., *Ammonia beccarii*, *Amphistegina lessonii*, and *Pseudononion pizarrensis*. Planktonic foraminifers: *Globorotalia foshi peripheroacuta*, *Globorotalia foshi lobata*	Not applicable
Wave-dominated delta	channel, bay and sandy mouth bar	Sedimentology	Wave- dominated delta. Distributary channels: massive to planar cross-stratified sandstone. Interdistributary bays: laminated mudstone and coal. Sandy mouth bars: parallel stratified and trough and planar cross-stratified sandstone.	Not applicable
		Ichnology	Distributary channels: *Skolithos* Ichnofacies *(Ophiomorpha nodosa)*, BI 0-1. Interdistributary bays: *Cruziana* Ichnofacies *(Planolites montanus, Teichichnus rectus*, *Palaeophycus tubularis*, *Thalassinoides* isp., and *Palaeophycus heberti)*, BI 0-1. Sandy mouth bars: *Ophiomorpha nodosa*, BI 0-1.	Not applicable

	Delta-front to Prodelta	Sedimentology	Delta front: hummocky, trough and planar cross-stratified sandstone. Prodelta: Parallel-laminated calcareous mudstone with shell remains.	Open bay delta: wave- and storm-dominated prodelta to delta front. Heterolithic successions of HCS and oscillation rippled sandstone and parallel-laminated dark mudstone.
		Ichnology	Delta front: *Skolithos* and *Cruziana* Ichnofacies (*Asterosoma* isp., *Rosselia socialis*, *Planolites montanus*, *Thalassinoides* isp., *Teichichnus rectus*, *Palaeophycus tubularis*, *Palaeophycus heberti*, *Ophiomorpha nodosa*, *Skolithos linearis*), BI: 0-1. Prodelta: depauperate *Cruziana* Ichnofacies (*Planolites montanus*, *Paleophycus heberti*, *Rhizocorallium* isp., *Thalassinoides* isp., *Chondrites* isp.), BI: 0-1.	Prodelta to delta front: *Planolites* isp., *Palaeophycus* isp., *Skolithos* isp., *Cylindrichnus* isp., *Teichichnus* isp., fugichnia, *Chondrites* isp., *Gyrolithes* isp., *Arenicolites* isp., *Rhizocorallium* isp., *Asterosoma* isp., *Conichnus* isp., and *Bergaueria* isp.. BI 2–4.
	Wave-dominated shoreface	Sedimentology	Wave-dominated shoreface. Middle and upper shoreface deposits consist of scarcely bioturbated massive sandstone. Lower shoreface deposits consist of moderately bioturbated massive sandstone.	Not applicable
		Ichnology	Upper and middle shoreface: *Skolithos* Ichnofacies (robust *Ophiomorpha nodosa*), BI: 0-1. Lower shoreface: Archetypal *Cruziana* Ichnofacies (*Asterosoma* isp., *Teichichnus rectus*, *Planolites montanus*, *Palaeophycus tubularis*, *Thalassinoides* isp., *Palaeophycus heberti*, *Ophiomorpha nodosa*), high ichnodiversity. BI 2-3.	Not applicable
	Offshore-shelf complex	Sedimentology	Offshore-shelf complex: bioturbated calcareous mudstone.	Marine offshore: bioturbated silty and sandy mudstone.
		Ichnology	Offshore: archetypal *Cruziana* Ichnofacies (*Asterosoma*, *Planolites montanus*, *Palaeophycus tubularis*, *Phycosiphon incertum*, *Teichichnus rectus*, *Palaeophycus heberti*, *Rhizocorallium* isp., *Thalassinoides* isp., *Rosselia socialis)*, high ichnodiversity, BI 2-6. Shelf: Archetypal *Cruziana* (*Asterosoma* isp., *Chondrites* isp., *Planolites montanus*, *Teichichnus rectus*), BI: 0-4.	Marine offshore: Archetypal *Cruziana* Ichnofacies (*Planolites* isp., *Chondrites* isp., and *Teichichnus* isp., *Palaeophycus isp.*, *Skolithos* isp., *Phycosiphon* isp., *Rhizocorallium* isp.), BI 4–5.

Taenidium bowni, Taenidium isp., *Cylindrichnus*, and *Siphonichnus* have been recorded in channel-fills with IHS of the lower member of the McMurray Formation displaying both brackish-water and freshwater ichnofacies (Harris et al., 2016). Similar example has been documented herein for the Oficina Formation with *Beaconites antarcticum* overprint *Teichichnus rectus* in channel-fill intervals (Buatois and Mángano, 2011; Diez-Canseco et al., 2015). In both formations, the *Scoyenia* and *Cruziana* Ichnofacies delineate the fluvial-tidal transition area located in inner estuarine zones, between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997b, 1998; Dalrymple and Choi, 2007; Buatois and Mángano, 2011; Rodriguez, 2015; Diez-Canseco et al., 2015, 2016).

The middle members of both the Oficina and McMurray formations have been interpreted to represent tide-dominated estuarine systems. Both formations record estuarine channels with point bars having IHS formed by lateral accretion. In the Oficina Formation, these channel-fill deposits record a depauperate marine ichnofauna with low ichnodiversity and degree of bioturbation. In the McMurray Formation, channel deposits show an impoverished marine fauna displaying variable intensities of bioturbation and recording low to moderate ichnodiversity. The tidal-flat deposits of the Oficina Formation display similar low ichnodiversity and an impoverished marine ichnofauna. Although moderate diversity levels are attained in the tidal-flat deposits of the McMurray Formation, ichnofaunas therein can be regarded as examples of the depauperate *Cruziana* Ichnofacies, as is the case of the Oficina Formation. Dinoflagellates also are common in the middle members of both the McMurray and Oficina formations, albeit occurring in lower abundance than terrestrially derived palynomorphs. Additionally, the Oficina Formation contains foraminifers (I.G.I.S and BioSTRAT, 2006; Suarez et al., 2014b; Solórzano et al., 2015). Dinocysts also have been reported in the middle member of the McMurray Formations (Gingras et al., 2016). The diversity of the dinoflagellates in the Oficina Formation is greater than in the McMurray Formation. Overall, the low diversity of trace fossils and marine plankton is consistent with brackish-water conditions (Hubbard et al., 2011; Sisulak and Dashtgard, 2012; Gingras et al., 2016). A saltwater wedge introduced upstream during periods of low river discharge resulted in stratified flow and the establishment of brackish water conditions (Hubbard et al., 2011, Sisulak and Dashtgard, 2012). Abundance of continental palynomorphs may dilute the presence of dinoflagellates in marginal-marine settings (Czarnecki et al., 2014; Gingras et al., 2016). High river discharge facilitates the movement of the saltwater wedge downstream, allowing for greater

concentrations of terrestrially derived pollen and spores (Hubbard et al., 2011, Sisulak and Dashtgard, 2012). In any case, palynologic and ichnologic information provides incontrovertible evidence of marine influence. The upper member of the Oficina Formation is more complex than the upper member of the McMurray Formation because the former comprises a wide range of depositional environments, encompassing delta-plain to delta-front, prodelta, shoreface and offshore-shelf deposits. However, the deltaic intervals in both units are similar with regard to sedimentology and ichnology. The upper member of the McMurray Formation records deposition in an open bay delta, including wave- and storm-dominated prodelta to delta front environments. The archetypal *Cruziana* Ichnofacies is present in these deposits with high ichnodiversity and bioturbation, displaying normal marine conditions. Similar prodelta to delta-front deposits also are present in the Oficina Formation, as represented by wave-dominated deltaic systems. Brackish-water and near-normal marine salinity conditions alternate in the delta-front and prodelta environments. The presence of complex feeding traces indicative of fully marine conditions in these deposits indicates the recurrent return to near-normal marine salinity conditions (Pemberton et al., 2001; MacEachern et al., 2005; Buatois and Mángano, 2011; Buatois et al., 2012). Shoreface and offshore-shelf environments are present in the upper member of the Oficina Formation. The archetypal *Cruziana* Ichnofacies occurs in these deposits, displaying high ichnodiversity and intensity of bioturbation, indicating normal-marine salinity conditions. Offshore deposits also are recorded in the McMurray Formation as indicated by the presence of high-diversity suites of the archetypal *Cruziana* Ichnofacies. It has been suggested that the middle member of the McMurray Formation, traditionally interpreted as brackish-water and estuarine (*e.g.*, Pemberton et al., 1982; Ranger and Pemberton, 1992; Gingras et al., 2016; Gingras and Leckie, 2017), may represent deposition in freshwater fluvial environments (Fustic et al., 2012; Blum et al., 2016; Blum, 2017). Our current study yields insights into this current controversy by showing that the brackish-water estuarine deposits in the Oficina Formation display an ichnofauna that is strikingly similar to that of the middle interval of the McMurray Formation. In addition, the middle member of these two units contain marine dinoflagellates, further reinforcing the brackish-water interpretation.

3.8. Conclusions

The Miocene Oficina Formation provides an ideal opportunity to evaluate trace-fossil distribution

and ichnofacies because it comprises a wide range of depositional environments formed under variable salinity conditions. These include freshwater fluvial and fluvio-tidal transition zones, brackish-water estuarine and delta-plain segments, alternating brackish-water and near-normal marine delta-front and prodelta settings, and normal-marine salinity shoreface, offshore and shelf settings. Six ichnofacies have been recognized in the Oficina Formation; *Scoyenia*, depauperate *Cruziana*, *Skolithos*, archetypal *Cruziana*, *Teredolites*, and *Glossifungites*. The former four are softground ichnofacies that occur along a salinity gradient, whereas the latter two represent substrate-controlled ichnofacies that occur at discontinuity surfaces. The faunal distribution in the Oficina Formation is strongly controlled by salinity and physical sedimentological processes. Therefore, biogenic structures provide key information to reconstruct salinity conditions. The Orinoco Oil Belt contains freshwater and brackish-water ichnofauna. Fluvial freshwater deposits of tide-influenced estuarine, distributary channel-fills and tide-dominated delta settings are locally intensely bioturbated and are reflected by very low-diversity occurrences of the *Scoyenia* Ichnofacies. Tidal currents and brackish-water conditions within estuarine environments allowed the establishment of opportunistic and impoverished marine ichnofacies (*i.e.*, *Skolithos* and depauperate *Cruziana* Ichnofacies) characterized by low bioturbation and ichnodiversity. The Oritupano Field illustrates open-marine facies that are not represented in the Orinoco Oil Belt, therefore helping to calibrate the ichnodiversity levels associated with fully marine conditions. Deltaic distributary channels and interdistributary bays record brackish-water conditions with the presence of *Skolithos* and depauperate *Cruziana* Ichnofacies, displaying low bioturbation and ichnodiversity. Delta-front and prodelta deposits contain ichnotaxa more typical of normal marine environments (*e.g.*, *Chondrites*) in intervals that alternate with beds containing stressed marine trace-fossil suites (*i.e.*, depauperate *Cruziana* Ichnofacies). Shoreface, offshore and shelf deposits are characterized by intense bioturbation and overall very high diversity, and are represented by the *Skolithos* and archetypal *Cruziana* Ichnofacies, further supporting normal-marine salinity conditions in this part of the basin. The *Glossifungites* and *Teredolites* Ichnofacies are characterized by firmground and woodground *Thalassinoides* isp., respectively, and represent transgressive surfaces of erosion (parasequence boundaries), in the tide-dominated estuarine and wave-dominated deltaic environments.

Transition

Chapter 3 provides a detailed documentation of the trace-fossil distribution and ichnofacies gradients along a depositional profile for the whole Oficina Formation. The next chapter (Chapter 4) includes the third-order sequence-stratigraphic model, based on the integration of sedimentologic, stratigraphic, ichnologic, and biostratigraphic datasets.

I built a third-order sequence-stratigraphic model for the Oficina Formation in the Orinoco Oil Belt, based on the integration of sedimentologic, stratigraphic, ichnologic, and biostratigraphic information. Therefore, I interpreted the palynomorphs, planktonic foraminifers and calcareous nannoplankton biozones, the maximum flooding surfaces (MFS-1, MFS-2 and MFS-3), the sequence boundaries (U-1, U-2, U-3, and U-4), the depositional environments (fluvial, estuary and delta) and the systems tract (LST, TST and HST). Subsequently, I integrated these datasets, which allowed me to define two third-order depositional sequences (DS1-2). DS1 is bounded by U-1 and U-2 and includes MFS-1. DS1 consists of lowstand fluvial valleys, transgressive estuarine valleys and thin highstand deltaic deposits. DS2 is bounded by U-2 and U-3 and includes MFS-2. DS2 comprises thin transgressive deposits and thick highstand deltaic deposits. Supervisors Luis A. Buatois and M. Gabriela Mángano checked sequence-stratigraphic interpretations and edited the manuscript. Co-author Williams Rodriguez helped with core logging. Co-author A. Farias assisted with identification of microfossils.

Chapter 4

4. Sequence stratigraphic framework of the Miocene Oficina Formation, Orinoco Oil Belt of Venezuela: Integrating multiple datasets for the recognition of third-order depositional sequences

Solórzano, E.J., Buatois, L.A., Farias, A., Rodríguez, W.J., Mángano M.G., Sequence stratigraphic framework of the Miocene Oficina Formation, Orinoco Oil Belt of Venezuela: Integrating multiple datasets for the recognition of third-order depositional sequences, AAPG Bulletin. In review.

4.1. Abstract

The middle Miocene Oficina Formation (15.97-12.7 Ma) in the Orinoco Oil Belt comprises a single 2nd-order sequence, which is divided into two third-order sequences (DS1-2), based on the integration of sedimentologic, stratigraphic, ichnologic and biostratigraphic datasets using well logs and core. DS1 is bounded by sequence boundaries U-1 (15.97 Ma) and U-2 (13.82 Ma) and includes maximum flooding surface MFS-1 (14.91 Ma). It consists of thick lowstand systems tract (LST) and transgressive systems tract (TST) strata, and a thin highstand systems tract (HST) package. DS1 is associated with incised-valley systems formed during a relative sea-level fall. These valleys consist of fluvial braided channels, swamps, paleosols, floodplains and the *Scoyenia* Ichnofacies. The fluvial valleys were replaced by estuaries during the Langhian transgression. The estuarine valley-fill displays a retrogradational stacking pattern, comprising meandering estuarine channels, tidal flats, estuarine sandbars, paleosols, and swamps. The *Glossifungites*, *Teredolites*, *Scoyenia*, *Skolithos*, and depauperate *Cruziana* Ichnofacies have been identified. Based on regional mapping of the *Glossifungites* Ichnofacies, DS1 was subdivided into three fourth-order sequences. DS2 is bounded by U-2 (13.82 Ma) and U-3 (12.7 Ma) and includes MFS-2 (13.53 Ma). It consists of a thin TST and a thick HST. It was essentially developed during the Serravallian sea-level highstand, and is constituted by lower delta plain deposits, displaying a progradational stacking pattern. These deposits consist of distributary channels, interdistributary bays, floodplains, and the *Scoyenia* Ichnofacies. Third-order sequences closely match with the middle Miocene third-order global eustatic curve and define the facies architecture at reservoir scale.

4.2. Introduction

During the last decade, the extensive heavy and extra heavy oil sand deposits of the middle Miocene Oficina Formation in the Orinoco Oil Belt (Fig. 4.1) became an increasingly important target for the oil industry. Venezuela has the world's largest oil reserve in place, with the oil sands in the Orinoco Oil Belt hosting 1,020 MMM barrels of which 218 MMM of barrels of in-place oil can be produced with the current technology (Magna Reserva Project, 2012).

A detailed biostratigraphic analysis allowed setting up a chronostratigraphic framework for the Oficina Formation. Calcareous nannoplankton, planktonic foraminifers, and palynomorphs have become important tools for establishing a paleoenvironmental and sequence-stratigraphic framework (Solórzano et al., 2015). In addition, recent work has allowed definition of second-order depositional sequences (Martinius et al., 2012; Rodriguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Third-order sequences also have been recognized in the Oficina Formation for the Petrocedeño area (Martinius et al., 2012), which provide a better understanding of reservoir distribution and are associated with relative sea-level changes, systems tract and sedimentary environments. The middle Miocene eustatic changes (Haq and Schutter, 2008) played an essential role in the definition of third-order cycles for the Oficina Formation. The Oficina Formation was deposited during the oblique collision phase between the Caribbean and South American plates (Parnaud et al., 1995), with the area being subjected to strong tectonic events that controlled sedimentation (Audemard et al., 1985; Martinius et al., 2012).

The Oficina Formation comprises a wide range of depositional environments, from fluvial to tide-dominated estuarine and delta plain settings, which are represented in the lower, middle, and upper members, respectively (Rodriguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Proper understanding of the variability of sedimentary facies in these depositional environments is important for both exploration strategies and reservoir characterization. For example, channel migration played an important role in the distribution of sand bodies, resulting in complex facies and stratigraphic architecture. The main goal of this paper is to propose a third-order sequence-stratigraphic framework for the Oficina Formation in the Orinoco Oil Belt by the integration of sedimentologic, stratigraphic, ichnologic and biostratigraphic datasets using well logs and core.

Figure 4.1. Map of the Orinoco Oil Belt and the main associated structural features.

4.3. Geologic setting

Deposition within the Eastern Venezuela Basin can be divided into four main phases: (1) a Paleozoic pre-rift phase, (2) a rift-and-drift phase during Jurassic and earliest Cretaceous time, (3) a Cretaceous-Paleogene passive margin period, and (4) a Paleogene-Quaternary oblique collision phase (transpression) between the Caribbean and South American plates, during which the foreland basin and the Serranía del Interior were formed (Eva et al., 1989; Parnaud et al., 1995; Talwani, 2002) (Fig. 4.2). The first phase is represented by Cambrian sand and shale deposition, as shown by the Hato Viejo and Carrizal formations, respectively (Fig. 4.2). During the second phase, red sediments, affected by basaltic sills (La Quinta Formation) accumulated in the Espino graben during the Jurassic. The passive margin phase consists of three major transgressive episodes (Fig. 4.2). The first of these transgressive episodes took place during the Cretaceous and is represented by the Barremian Barranquin Formation, the Albian-Aptian El Cantil and Canoa formations, the Cenomanian-Campanian Querecual, San Antonio, and Tigre formations, and the

Maastrichtian San Juan Formation. The main hydrocarbon source rocks were deposited during this phase. The second transgressive episode is represented by the Paleocene Vidoño Formation and the Eocene Caratas Formation. The third transgressive episode of the passive margin phase took place during the early Oligocene with the accumulation of the lower interval of the Merecure Formation. Finally, the collision phase was diachronic, spanning the early-middle Eocene in the west to the late Oligocene-middle Miocene in the east, and continues to present day. This phase is represented by the upper interval of the Merecure Formation (late Oligocene), early-middle Miocene Oficina Formation, early-middle Miocene Carapita Formation, late-middle Miocene Freites Formation, late Miocene La Pica Formation, and Plio-Pleistocene Mesa and Las Piedras formations.

Figure 4.2. North to south stratigraphic correlation chart along the Eastern Venezuela Basin showing general chronostratigraphy and tectonic phases (modified from Parnaud et al., 1995).

The Eastern Venezuela Foreland Basin formed on the passive margin of the South American Craton during the Neogene. This basin comprises a prism of Cenozoic sediment wedging toward the south (Parnaud et al., 1995; Di Croce et al., 1999) indicating that tectonic control played a significant role on sedimentation and the history of changes in accommodation potential in the basin (Fig 4.3).
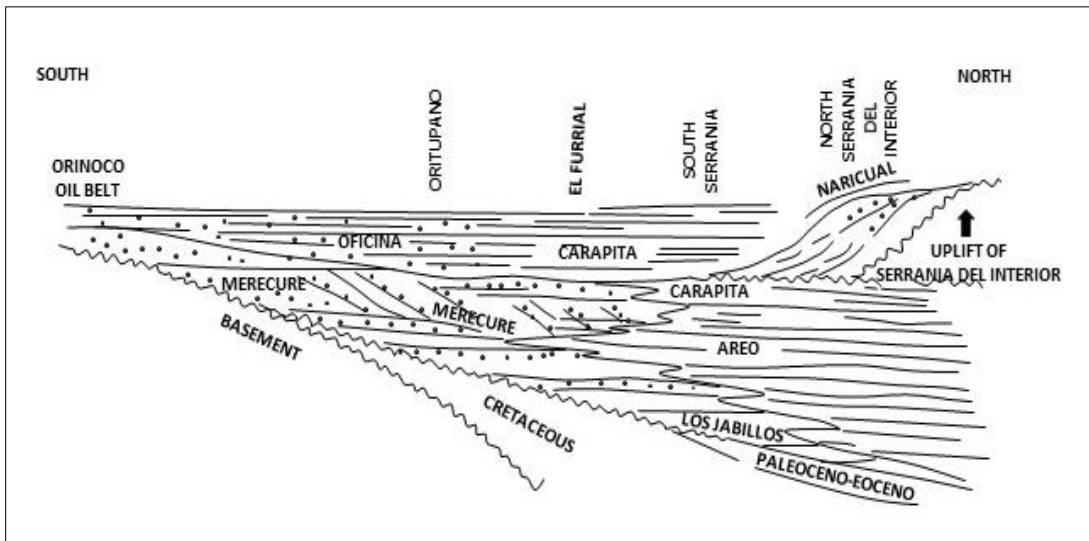
Figure 4.3. North to south schematic cross-section of the Eastern Venezuela Basin displaying Cenozoic sediments wedging toward the Orinoco Oil Belt, which indicates tectonic control due to the wedge-shaped geometry of sediments (modified from Parnaud et al., 1995).

The Eastern Venezuela Basin is composed of several petroleum provinces, and one of them is represented by the oil fields of the Orinoco Oil Belt (Parnaud et al., 1995), which spans an area of 55,315 km^2 in the southern margin of the Eastern Venezuela Basin, sub-parallel to the Orinoco River (Fig. 4.1). The Hato Viejo fault system subdivides the Orinoco Oil Belt into two provinces, the western and eastern provinces (Latreille et al., 1983; Audemard et al., 1985) (Fig. 4.4). The western province is located west of the Hato Viejo fault system and consists of the Boyacá and Junín areas. In the Junín area, the Oficina Formation overlies the Tigre and Canoa formations (late Maastrichtian), the Carrizal and Hato Viejo formations (Cambrian), and the igneous-metamorphic basement. In the Boyacá area, the Oficina Formation (Miocene) overlies the Roblecito Formation (Oligocene), the La Pascua Formation (Oligocene), the Tigre-Canoa formations (Cretaceous), the La Quinta Formation (Jurassic), and the igneous-metamorphic basement (Fig. 4.4). The eastern province is located east of the Hato Viejo fault system, and includes the Carabobo and Ayacucho areas, where the Oficina Formation rests on top of the Precambrian basement (Fig. 4.4).

Additionally, the eastern province was divided into central and eastern domains by the Magna Reserva Project (2012). The central domain includes the southeastern part of the Junín area and the northwestern part of the Ayacucho area. The eastern domain comprises the southeastern part of the Ayacucho area and the entire Carabobo area. In this study, the Pre-Cretaceous top consists of Paleozoic and basement rocks. The Paleozoic unconformity is truncated southeast of the Junín area onto basement in Junín 10 and Junín 6 blocks (Solórzano et al., 2009). The Cretaceous unconformity (a combination of nondeposition and erosion) is truncated towards the south of the Junín area onto Paleozoic unconformity and is well developed in the northern area (Solórzano et al., 2009).

The Orinoco Oil Belt hosts the middle Miocene Oficina Formation (Audemard et al., 1983; Solórzano et al., 2015, 2017). This unit is divided into (a) a lower member, overlying Cretaceous or Pre-Cretaceous rocks (basement or Paleozoic) and of fluvial origin, (b) a middle member characterized by tide-dominated brackish-water estuarine deposits formed within a transgressive systems tract resting directly on top of the lower Oficina and (c) an upper member recording tide-dominated deltaic sedimentation representing a highstand progradation into a brackish-water embayment (Rodriguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018).
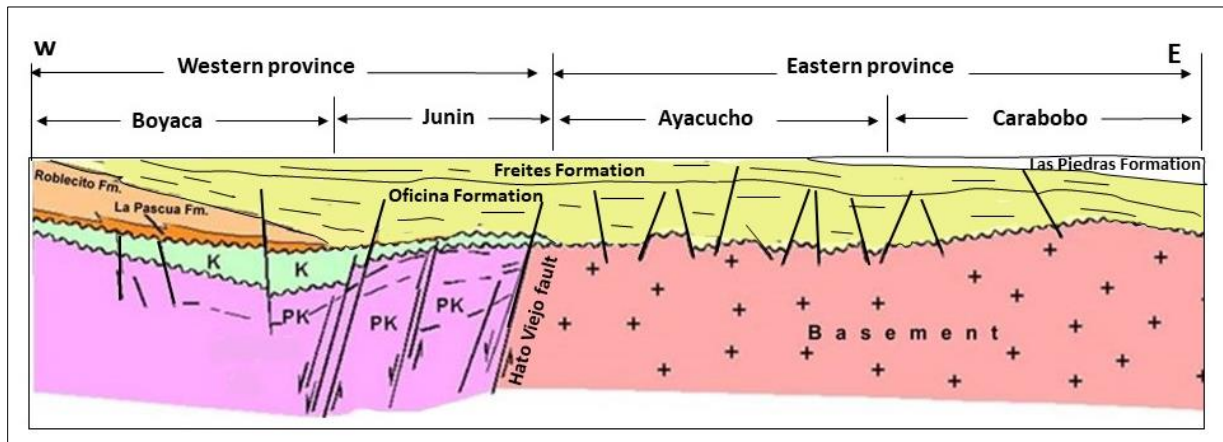
Figure 4.4. West to east structural section showing Cenozoic stratigraphy across the Orinoco Oil Belt (modified from Audemard et al., 1985).

4.4. Materials and Methods

The chronostratigraphic framework for the Orinoco Oil Belt was developed using calcareous nannoplankton, palynomorphs, and foraminifers from previous studies (Audemard et al., 1985; Solórzano et al., 2015; Solórzano and Farias, 2017). Approximately 3000 samples from 96 wells, mostly side wall core and core, have been revised and reinterpreted. The ages of the strata were assigned based on the interpretation and integration of the biozones following key references, such as Martini (1971) for nannoplankton, Muller et al. (1987) and Williams and Bujak (1985) for palynomorphs, and Blow (1969, 1979) for foraminifers. The stratigraphic ranges were updated following more recent references (see Solórzano et al., 2015; Solórzano and Farias, 2017). Integration of the biozones was calibrated with the time scale of Ogg et al. (2008). The bioevents were interpreted based on the First Appearance Datum [FAD] and Last Appearance Datum [LAD] of the species. Twenty seven cored wells from the Oficina Formation in the Orinoco Oil Belt were described (B1, B2, B3 Boyacá area, J1, J2, J3, J4, J5, J6, J7 Junín area A4, A7, A8, A1, A2, A9, A10, A11, A12 Ayacucho areas, C1, C2, C3, C6, C7, C8, C9, C10 Carabobo area), totalizing 2744 m of core. Core-based facies were characterized identifying lithology, textural characteristics, bed and bedset thickness, stratification, physical sedimentary structures, bed boundaries, bioturbation index, trace-fossil distribution, and ichnological suites (Fig. 4.5-4.6). In addition, logs (resistivity, density, neutron and gamma ray) from a total of 300 wells were analyzed and correlated (Fig. 4.7).
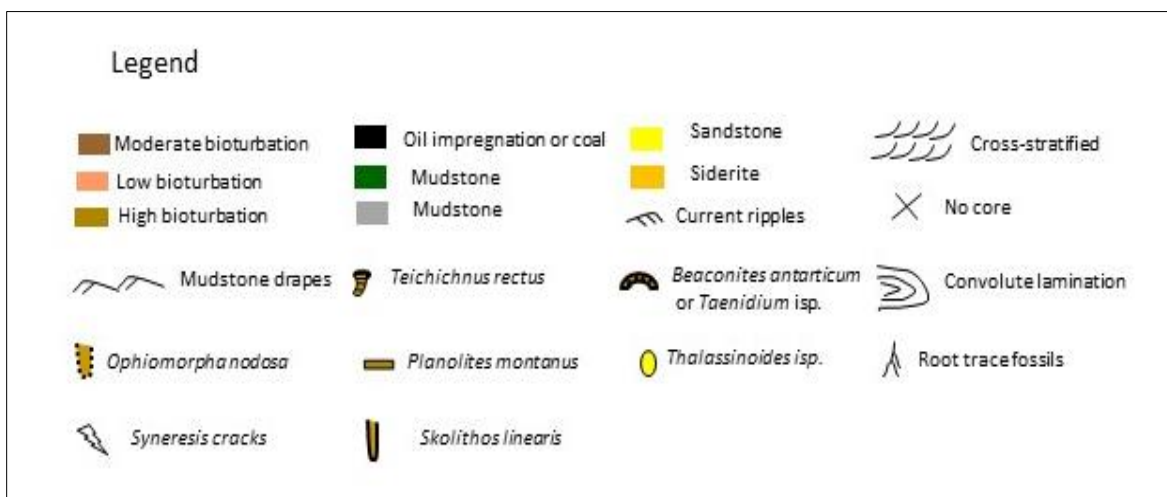
Figure 4.5. Lithology, sedimentary structures and trace fossil legend for well J1.
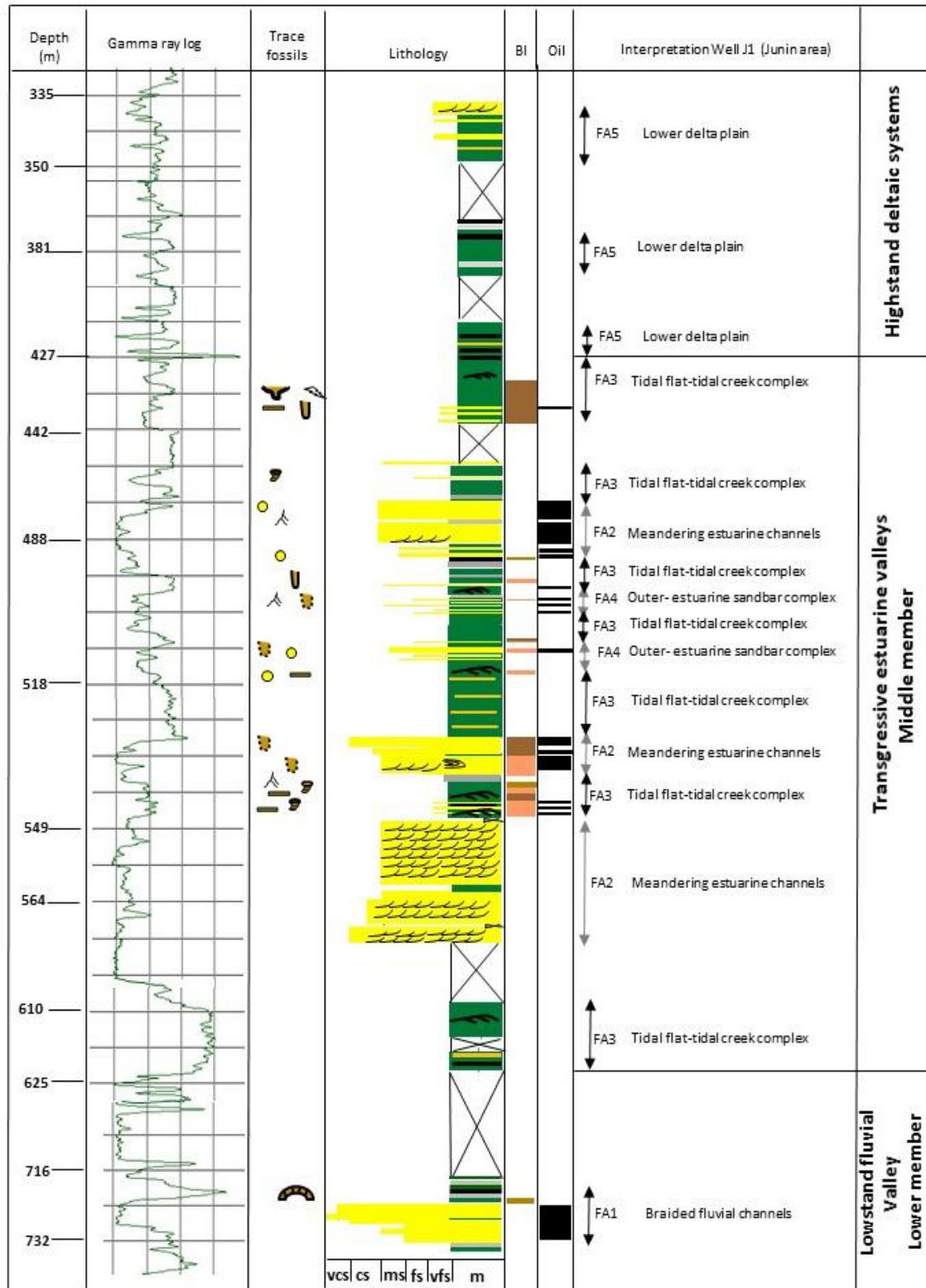
Figure 4.6. Sedimentological and ichnological log for well J1.
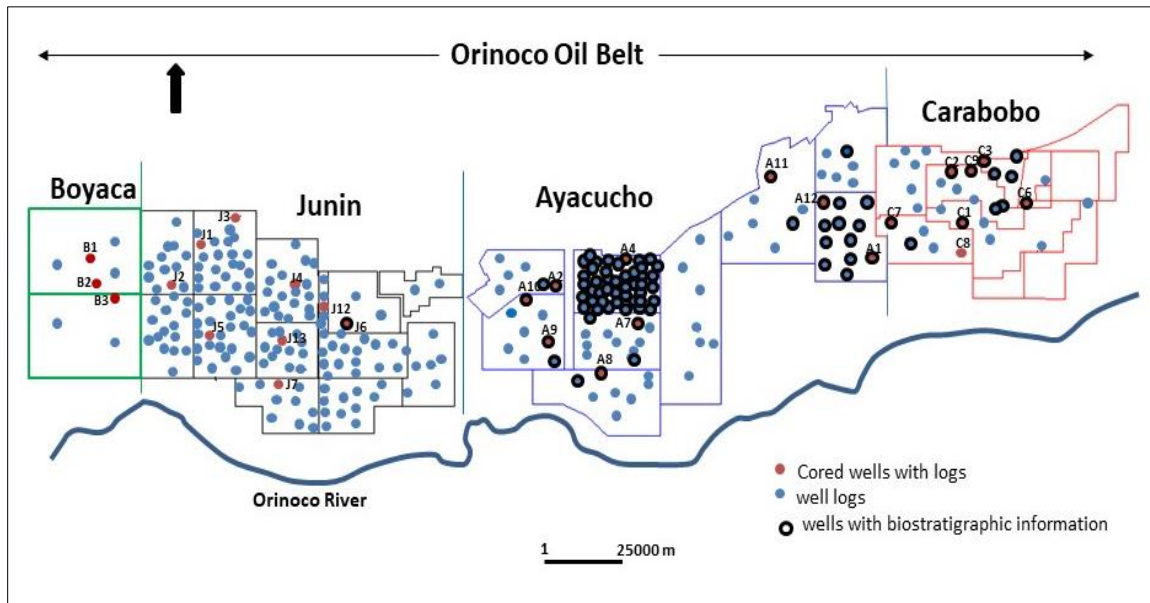
Figure 4.7. Map of the Orinoco Oil Belt showing the location of wells and biostratigraphic information.

4.5. Paleoenvironmental framework: Integration of sedimentologic and ichnologic datasets

The paleoenvironmental framework for Oficina Formation in the Orinoco Oil Belt is based on the integration of sedimentologic, ichnologic and biostratigraphic datasets using well logs and core. Sedimentologic observations have been integrated with detailed ichnologic information which has been presented and discussed elsewhere (Solórzano et al., 2017).

4.5.1. Fluvial systems

The Oficina fluvial systems along the Orinoco Oil Belt are represented by braided-fluvial channels, floodplains, swamps, and paleosols, which are grouped in FA1 (Figs. 4.6, 4.8A, B and 4.13A, Table 4.1). These deposits occur in the lower member, where they form the lower package of DS1, representing the lowstand systems tract (LST). The fluvial braided channel-fills are represented by stacked sandstone successions of multiple depositional units or storeys. Scarce mudstone and siltstone layers record sedimentation in floodplain settings, indicating fluvial channels of low sinuosity. These channels are characterized by two and three-dimensional dunes that migrated along the bottoms of river channels (Miall, 2010; Brekke et al., 2017). Grain size suggests high energy conditions. These channels have been previously described in the lower Oficina Formation

in the Orinoco Oil Belt (e.g., Audemard et al., 1983; Isea et al., 1987; Toro et al., 2002; Solórzano et al., 2009; Martinius et al., 2012; Rodriguez, 2015; Solórzano et al., 2017). Similar channels have been documented in the lower McMurray Formation (e.g., Crerar et al., 2007; Hubbard et al., 2011; Musial et al., 2012; Hein et al., 2013; Gingras et al., 2016; Brekke et al., 2017). The coal layers in the lower member are associated with sedimentation in swamps. The drying-upward coal layers are interpreted as swamps and are associated to variations in the groundwater table in regressive systems, delineating the base or the top of parasequences (Wadsworth et al., 2003, 2010). The *Scoyenia* Ichnofacies is present in overbank deposits overlying the channel-fills, indicating freshwater conditions (Solórzano et al., 2017). Generally, the lower member is restricted to paleotopographical lows, representing the infill of incised fluvial valleys.
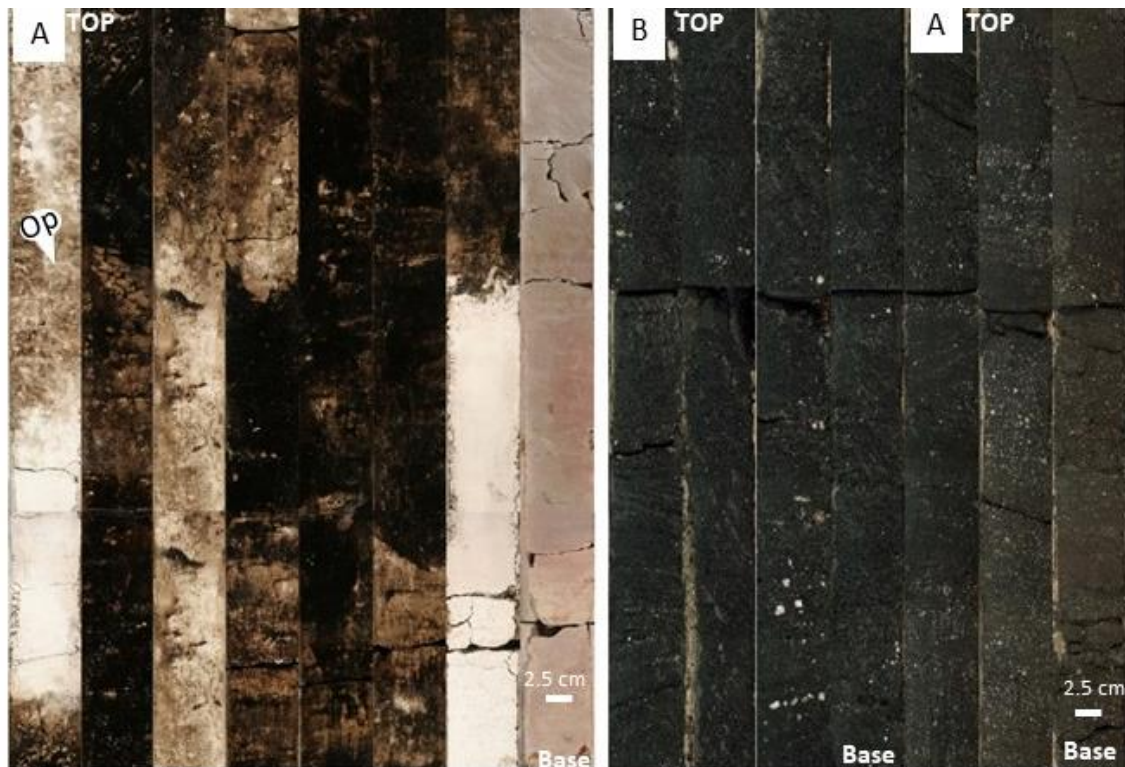
Figure 4.8. Fluvial deposits in the Oficina Formation of the Orinoco Oil Belt. (A) Fluvial braided channel deposits with interbedded paleosols and floodplain deposits containing *Taenidium* isp. (Ta), reflecting the presence of the *Scoyenia* Ichnofacies, which indicates freshwater conditions. Well J1, depth 723.59-731.52 m. (B) and (C) Pebbly, very coarse- to medium-grained sandstone formed in fluvial braided channels; grain size suggests high energy conditions. Well A8, depths 502-505.3 m and 512.97-515.42 m Sandstone is impregnated with hydrocarbon resulting in dark color, whereas paleosols are lighter-colored and floodplain deposits are brown.

4.5.2. Estuarine systems

The Oficina estuarine systems across the Orinoco Oil Belt are represented by deposits formed in meandering channels, tidal flats, tidal creeks, outer estuarine sandbars, and swamps, as well as paleosols. These deposits (Table 4.1) are grouped in FA2 (Figs 4.6, 4.9, 4.13B), FA3 (Figs 4.6, 4.10A-I, 4.13C), and FA4 (Fig. 4.6, 4.11, 4.13D). Estuarine deposits are restricted to the middle member where they occur mostly in DS1. The presence of the cross-stratal sets in the channel infills suggests that the flow energy within estuarine channels was characterized by the migration of two and three-dimensional dunes during periods of high river discharge when the maximum tidal limit migrated seaward. In many instances, the bases of these channels are mantled by breccias displaying subrounded to angular mudstone clasts within an oil saturated medium- to fine-grained sandstone matrix. These breccias have been documented in laterally accreting tidal point bars of tidal settings elsewhere (Gingras et al., 2017; Brekke et al., 2017).

Table 4.1. Sedimentary facies, facies association, trace-fossil distribution and their relationship with the third-order sequences. Sedimentologic observations have been integrated with detailed ichnologic information which has been presented and discussed elsewhere (Solórzano et al., 2017).

3er-order sequences	Member	Environments	Sedimentary Facies	Facies Association	Trace-fossil distribution and Ichnofacies
DS2	upper	Lower delta plains of tide-dominated deltas and thin transgressive deposits reflecting delta abandonment	Coarse- to fine-grained sandstone, silstone, mudstone, coal, IHS, mudstone drapes, planar and trough cross-stratification, siderite, and syneresis cracks (FC, FD, FG2, and FH1).	FA5 (Lower delta plain): floodplains, distributary channels, interdistributary bays, and swamps	*Beaconites antarcticum* and *Planolites montanus* (*Scoyenia* Ichnofacies)
DS1	lower and middle	Fluvial to tide-dominated estuaries and subordinate deltaic deposits	Estuaries/deltas: Mudstone breccia, coarse- to very fine-grained sandstone planar and trough cross-stratification, mudstone drapes, IHS, convolute lamination, interbedded sandstone and mudstone, flaser, wavy and lenticular bedding, limestone and calcareous mudstone, siderite, syneresis cracks, and shell remains (FA, FC, FD, FE, FI, FF, FG, and FH)	Estuaries/Deltas: FA4 (Outer estuarine sandbars): Sandbar, swamps, and paleosols. FA3 (tidal flats, tidal creeks): tidal flats, swamps, and paleosols. FA2 (estuarine meandering channels):	Estuaries/Deltas: *Ophiomorpha nodosa*, *Skolithos linearis*, *Diplocraterion habichii* (*Skolithos* Ichnofacies), *Rosselia socialis*, *Planolites montanus*, *Teichichnus rectus*, *Thalassinoides* isp (depauperate *Cruziana* Ichnofacies), *Beaconites antarcticum* (*Scoyenia* Ichnofacies), firmground *Thalassinoides* isp. (*Glossifungites* Ichnofacies), and woodground *Thalassinoides* isp (*Teredolites* Ichnofacies), and escape trace fossils

			Fluvial: Pebbly, very coarse- to medium-grained sandstone, coal, mudstone, silstone, massive to planar or trough cross-stratification (FB1, FB2, FG2, and FH1)	Estuarine channels. Fluvial: FA1(Braided fluvial channels): fluvial channels, floodplains, swamps, and paleosols	Fluvial: *Taenidium* isp. (*Scoyenia* Ichnofacies)

The presence of *Ophiomorpha nodosa* in some channel fills indicate that these channels were filled, at least in part, during a relative sea-level rise (Fig. 4.9), which is consistent with the occurrence of shell-bearing marine mudstone overlying channel fills (Solórzano et al., 2017). The presence of inclined heterolithic stratification at the base or top of the estuarine channels indicates point-bar deposits (Fig. 4.9). The bulk of the channel fills is formed by inclined heterolithic stratification (IHS) resulting from lateral accretion of point bars in meandering channels (Thomas et al., 1987; Hovikoski et al., 2008; Gingras et al., 2016). IHS is common in tide-dominated estuarine systems (Crerar et al., 2007; Hovikoski et al., 2008; Buatois and Mángano, 2011; Choi et al., 2013; Rodriguez, 2015; Gingras et al., 2016, 2017; Solórzano et al., 2017). IHS consists of inclined and interbedded sandstone and mudstone layers. Sandstone beds are associated with periods of high river discharge and mudstone intervals with low discharge and flood currents. These deposits contain a low diversity of brackish-water trace fossils (Solórzano et al., 2017; Rodríguez et al., 2018). Bioturbated IHS has been documented in many estuarine point-bar deposits (e.g. Stewart and MacCallum, 1978; Pemberton et al., 1982; Smith, 1988; Smith, 1989; Ranger and Pemberton, 1997; Wightman and Pemberton, 1997; Musial et al., 2012; Choi et al., 2013; Diez-Canseco et al., 2015, 2016; Gingras et al., 2016, 2017). IHS is considered a good indicator of seasonal cyclicity (Hovikoski et. al., 2008; Hubbard et al., 2011; Sisulak and Dashtgard, 2012; Choi et al., 2013; Gingras et al., 2002) and tidal currents (Choi et al., 2004; Hovikoski et. al., 2008; Gingras et al., 2016, 2017). The Oficina estuarine channel fills also display mudstone drapes and convolute lamination. The mudstone drapes are formed during a brief slack-water period on the tide-dominated point bars (Choi et al., 2004; Hovikoski et al., 2008; Rodriguez, 2015; Gingras et al., 2016). The convolute lamination formed as result of loading, rapid sedimentation or slumping (Hubbard et al., 2011).

Some estuarine channels overlie paleosols, which consist of light-colored mudstone with scarce root trace fossils. These paleosols are in places bioturbated (*Thalassinoides* isp.), indicating

the presence of the *Glossifungites* Ichnofacies and revealing erosional truncation during transgressions (Solórzano et al., 2017). Also, these channels are intercalated with coal layers that are interpreted as swamps. These swamp deposits also contain *Thalassinoides* isp., but within the context of the *Teredolites* Ichnofacies (Solórzano et al., 2017).
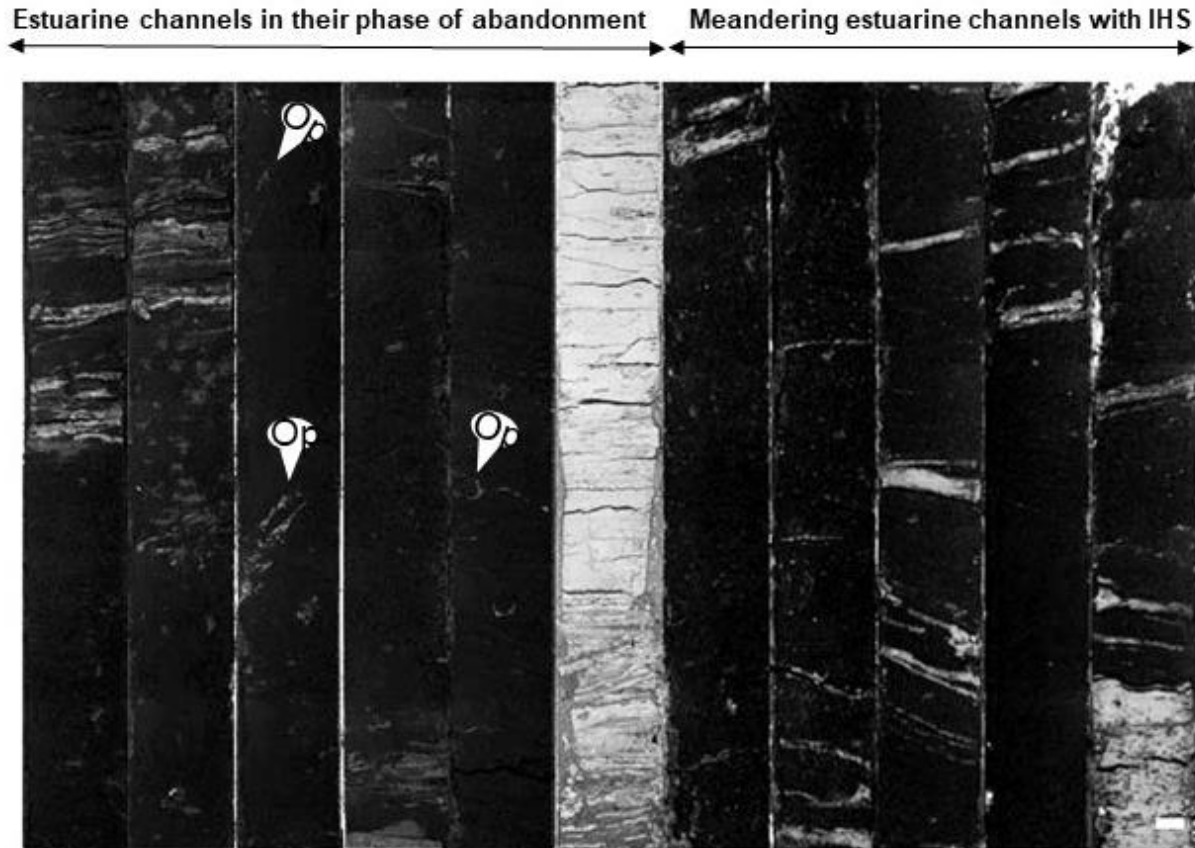
Figure 4.9. Estuarine deposits in the Oficina Formation of the Orinoco Oil Belt displaying meandering estuarine channels with inclined heterolithic stratification (IHS) and *Ophiomorpha nodosa* (Op), which indicates that these channels were marine influenced during their abandonment. IHS represents tide-dominated estuarine channels formed by lateral accretion of point bars deposits. Well A8, depth (313.02-346.25 m). Sandstone is impregnated with hydrocarbon resulting in dark color, whereas mudstone is light color.

The Oficina tidal-flat deposits (Fig. 4.10A-I) consist of bioturbated interbedded mudstone and sandstone. Flaser, wavy and lenticular bedding are common in, although not exclusive of, tidal-flats environments (Weimer et al., 1981; Reineck and Wunderlich, 1968; Hovikoski et al., 2008; Sisulak and Dashtgard, 2012; Gingras et al., 2016, 2017). Siderite nodules and bands, such as those present in the Oficina Formation, are particularly abundant in environments affected by

fluctuating salinity (Plummer and Gostin, 1981; MacEachern et al., 2005; Hovikoski et al., 2008; Buatois et al., 2012, Martinius et al., 2012). The wetting-upward coal layers are interpreted as formed in swamps and also are associated to variations in the groundwater table in transgressive systems, typically forming either the base or the top of parasequences (Wadsworth et al., 2003, 2010). *Thalassinoides* isp. forming tubular tidalites displaying infill with inclined laminae are also present in Oficina Formation, further supporting tidal influence (Gingras et al., 2012, 2015; Wetzel et al., 2014; Solórzano et al., 2017). Burrows are large and display an open aperture that facilities the entrance of sediment by tides. Tubular tidalites have been observed in a variety of marginal marine deposits, such as subtidal point-bar, intertidal-flat, or tidal-channel-thalweg (Gingras et al., 2015).

Outer estuarine sandbars (Fig. 4.11) also consist of thinner IHS strata and sandstone with mudstone drapes, also representing tidally generated deposits within Oficina estuarine valleys. These bars are formed by the migration of two and three-dimensional dunes reflecting high energy environments (Brekke et al., 2017). Low energy sedimentation is indicated by suspension fallout that alternates with bed-load transport and deposition. These bars were deposited in the estuary mouth close to the zone of maximum turbidity as indicated by the abundance of mudstone units. Overall, the maximum turbidity zone is near the saltwater wedge, but the elevated turbidity zone and high suspended-sediment concentration are present from the fluvial-tidal transition zone to beyond the mouth of the estuary (Uncles et al., 2006; Dalrymple et al., 2012). Syneresis cracks are present in estuarine sandbar systems of the Oficina Formation as well, strongly suggesting that these settings were affected by fluctuating salinity (Plummer and Gostin, 1981; Hovikoski et al., 2008; Buatois et al., 2012, Martinius et al., 2012). Estuarine sandbars were flanked by swamps and waterlogged soils. Swamp deposits and paleosols are bioturbated, as indicated by *Thalassinoides* isp., representing the *Teredolites* and *Glossifungites* Ichnofacies, respectively (Solórzano et al., 2017). The outer estuarine sandbars were formed during a transgression, forming the uppermost part of the middle member of the Oficina Formation. The *Teredolites* and *Glossifungites* Ichnofacies delineate transgressive surfaces of erosion within these estuarine systems (Solórzano et al., 2017). In the inner zone of the Oficina estuarine settings, the presence of the *Scoyenia* Ichnofacies records deposition between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997b, 1998; Dalrymple and Choi, 2007; Buatois and Mángano, 2011; Rodriguez, 2015; Diez-Canseco et al., 2015, 2016; Shchepetkina et al., 2016; Solórzano et al., 2017) that

indicate a fluvial-tidal transition area. This area displays salinity fluctuations from brackish-water to freshwater conditions (Diez-Canseco et al., 2015; Gingras et al., 2016; Solórzano et al., 2017). Therefore, the *Scoyenia* Ichnofacies may be overprinting the trace-fossil suite representative of the depauperate *Cruziana* Ichnofacies. The *Skolithos* and depauperate *Cruziana* Ichnofacies also are present in the Oficina transgressive estuarine valley deposits formed under brackish-water conditions (Solórzano et al., 2017). These deposits display low to moderate bioturbation intensity and low diversity. The latter one could be linked with seasonal cyclicity and tidal currents present in these brackish-water environments. Seasonality promotes the development of brackish-water conditions and an impoverished ichnofauna because the saltwater wedge pushes landward during periods of low river discharge creating a stratified flow (Hubbard et al., 2011; Sisulak and Dashtgard, 2012; Gingras et al., 2016; Solórzano et al., 2017).

In summary, the estuarine deposits preserved in the middle member of the Oficina Formation are formed within transgressive systems tracts (TST) displaying a retrogradational stacking pattern. In DS1, the estuarine interval is separated from the underlying fluvial interval by a transgressive surface (TS) that is mantled by abundant shells and pebbles or is indicated by the occurrence of marine ichnofacies, foraminifers, nanofossils and dinoflagellates. The presence of limestone and calcareous mudstone layers and shell remains (Fig. 4.10H, I) are more common in the Ayacucho and Carabobo areas than in the Boyacá and Junín areas, further indicating marine influence and the transition to more marine settings towards the northeast. The Oficina estuarine facies record deposition within an incised estuarine valley.

The sandstone units of the middle Oficina in the Orinoco Oil Belt have been traditionally considered to record deposition in a fluvio-deltaic environment (Audemard et al., 1985; Latreille et al., 1983, Toro et al., 2001, Martinius et al., 2012). However, this interpretation is not consistent with the retrogradational stacking pattern recorded in the middle member, which indicates the transgressive nature of these deposits (Rodriguez, 2015; Solórzano et al., 2017; Rodríguez et al., 2018). Transgressive conditions are usually associated with estuaries, whereas deltas are associated with regressions (Dalrymple et al., 2003, 2007).
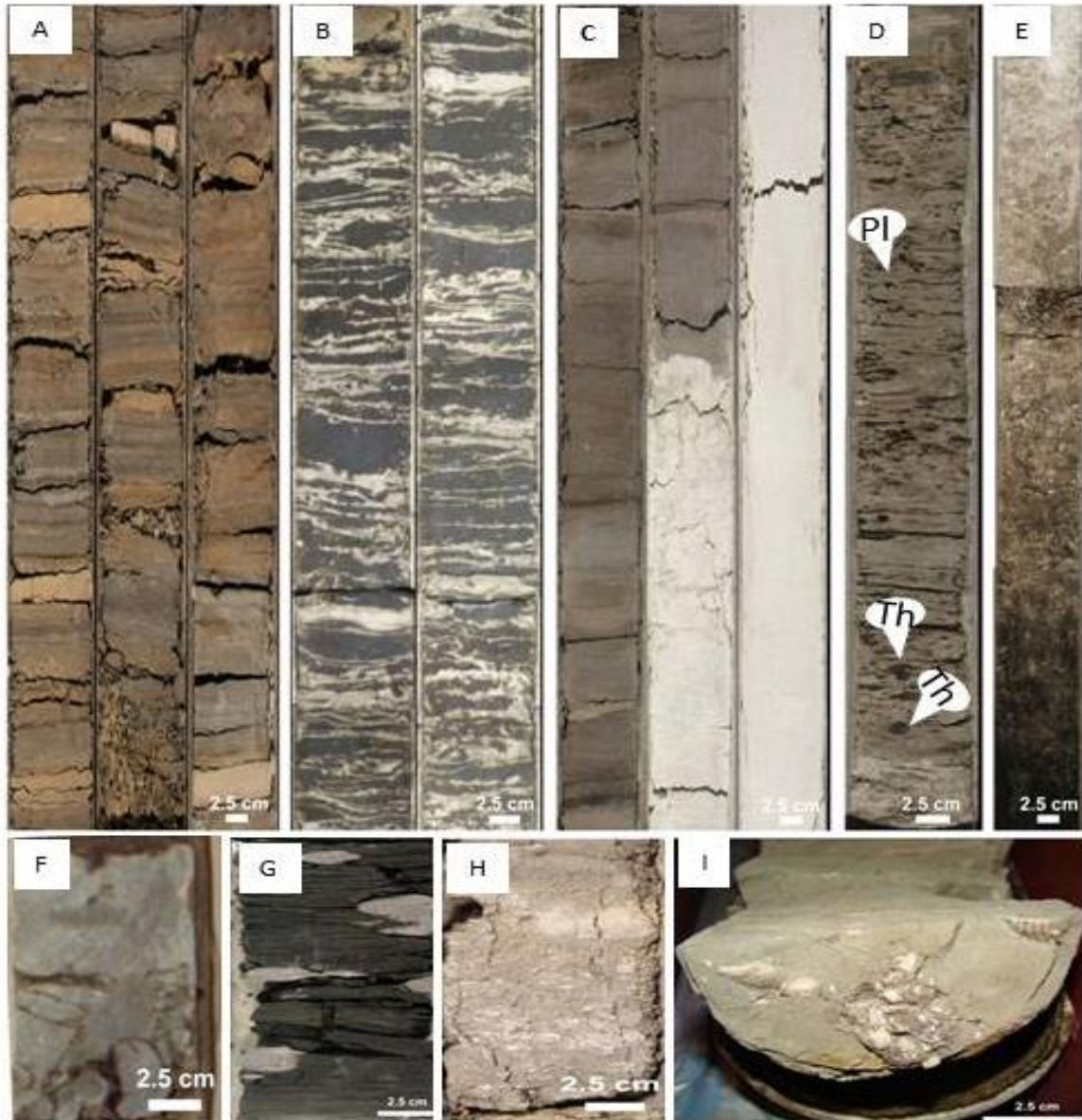
Figure 4.10. Tidal flat and tidal creek deposits. (A) Mud flat deposits with siderite bands suggesting environments affected by fluctuating salinity. Well J1, depth 519.37 m. (B) Interbedded mudstone and sandstone in tidal sand- to mixed-flat deposits from tide-dominated estuarine settings. Well A11, depth 786.68 m. (C) Waterlogged paleosols in mud flat deposits, reflecting the development of wetland zones in estuarine environments. Well J1, depth 381.30 m. (D) *Planolites montanus* (Pl) and *Thalassinoides* isp. (Th) in mud-flat deposits, reflecting the presence of the depauperate *Cruziana* Ichnofacies, which indicates brackish-water conditions, associated with tidal currents. Well A9, depth 365.76 m. (E) Indistinct bioturbation mottling in mud-flat deposits. Well A9, depth 448.36 m. (F) Limestone layers providing evidence of marine influence. Well C1, depth 556.56 m. (G) *Thalassinoides* isp. (Th) in coal layer (swamp deposits), reflecting the presence of the *Teredolites* Ichnofacies, which indicates erosional exhumation during ravinement. Well A10, depth 416 m. (H) and (I) massive calcareous mudstone with shell remains providing further evidence of marine influence. Well C9, depth 925.07 m. Sandstone is impregnated with hydrocarbon resulting in dark color, whereas mudstone is light color.

Figure 4.11. Outer-estuarine sandbar deposits within the estuarine embayment. Well A12, depth 828.14-832.41 m.

4.5.3. Deltaic systems

In the Orinoco Oil Belt, the lower delta plain of the tide-influenced deltaic systems is represented by floodplains, distributary channels, interdistributary bays, and swamp deposits, which are grouped in FA5 (Figs 4.6, 4.12, Table 4.1). These deposits record highstand progradation, essentially evidenced in the upper member of the Oficina Formation where they form the bulk of DS2. However, thin deltaic deposits also occur in the uppermost interval of DS1, forming a thin HST.

In DS2, transgressive deposits form a thin TST interval reflecting delta abandonment, which rest directly on top of the underlying highstand systems tract (HST) deposits, therefore mantling a FS/SB. The Oficina deltas of the Orinoco Oil Belt prograded in a brackish-water embayment rather than in the open sea, as is the case of coeval deltaic deposits in the Oritupano

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Field, located further to the northeast, which display a significant wave influence (Solórzano et al., 2017). Deltaic distributary channel fills are sparse, thin and are separated by floodplain and interdistributary bay deposits (Fig. 4.13D). These channels record migration of 2D and 3D dunes and were separated by extensive floodplains. The deltaic systems of the upper member are strongly controlled by tides displaying inclined heterolithic stratification and mudstone drapes. As previously discussed, these structures are characteristics of tide-dominated environments (Pemberton et al., 1982; Thomas et al., 1987; Ranger and Pemberton, 1992; Lettley et al., 2009; Gingras et al., 2016). Although more commonly recorded in estuarine settings, IHS may be produced in deltaic systems as well (Choi et al., 2004; Martinius et al., 2012; Rodriguez, 2015; Solórzano et al., 2017). As in the case of the estuarine deposits, syneresis cracks and siderite nodules and bands, indicate environments affected by fluctuating salinity and periodic subaerial exposure (Plummer and Gostin, 1981; Hovikoski et al., 2008; Buatois et al., 2012, Martinius et al., 2012). The coal layers in the upper member are associated with sedimentation in swamps, being linked with high water tables. In places, the floodplain deposits record the presence of the *Scoyenia* Ichnofacies, as indicated by *Beaconites antarcticum*, which indicate the establishment of a continental invertebrate fauna in these environments (Solórzano et al., 2017). This ichnofacies records deposition between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997, 1998; Dalrymple and Choi, 2007; Buatois and Mángano, 2011; Rodriguez, 2015; Diez-Canseco et al., 2015, 2016; Shchepetkina et al., 2016; Solórzano et al., 2017).

Figure 4.12. Lower delta plain deposits of tide-dominated deltas representing distributary channels with floodplains and swamps. Well J1, depth 337.71 m.

4.6 Biostratigraphy

Calcareous nannoplankton, palynomorphs, and planktonic foraminifers were used to develop the chronostratigraphic framework for the Oficina Formation in the Orinoco Oil Belt. The detailed biostratigraphic information and the chronostratigraphic correlations have been presented and discussed elsewhere (Audemard et al., 1985; Solórzano et al., 2015; Solórzano and Farias, 2017).

4.6.1. Interpretation of age

Terrestrial palynomorphs and dinoflagellates are the most diverse and abundant in the study area (Fig. 4.14, Table 4.2). A middle Miocene age is suggested for the Oficina Formation due to the presence of palynoevents of the *Crassoretitriletes vanraadshooveni* Zone of Muller et al. (1987) (Zone 28), as indicated by the first occurrences of *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni*, *Bombacacidites baculatus* and the dinoflagellate *Selenopemphix quanta*. The former two also have been recorded in Petrocedeño Field in the Junín area (Martinius et al., 2012, 2013). Middle Miocene elements, namely *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni* and *Selenopemphix quanta*, occur in the overlying Freites Formation. However, the Freites Formation also records the first occurrences of several late Miocene elements, such as *Bombacacidites ciriloensis*, *Echitricolporites spinosus*, *Fenestrites spinosus*, *Fenestrites longispinosus*, *Psilatricolporites caribbiensis*, and *Cyatheacidites annulatus* (late Miocene). Accordingly, a middle to late Miocene age is estimated for the Freites Formation.

Calcareous nannoplankton (Fig. 4.8, Table 4.2) defines three zones, NN6, NN5, and NN4, all indicative of a middle Miocene age. NN6 is marked by the LAD of *Cyclicargolithus floridanus* (11.9 Ma). NN5 is signaled by the LAD of *Sphenolithus heteromorphus* (13.53 Ma). NN4 records the LAD of the zonal marker *Helicosphaera ampliaperta* (14.91 Ma) and the FAD of *Helicosphaera walbersdorfensis* (15.97 Ma).

The planktonic foraminifers (Fig. 4.14, Table 4.2), such as *Globorotalia foshi peripheroacuta* and *Globorotalia foshi lobata*, suggest the presence of the foraminifer zone N12, whereas the *Globorotalia foshi peripheroronda* bioevent indicates the presence of the foraminifer zone N9. In addition, Audemard et al. (1985) reported the presence of *Globorotalia foshi foshi*

(N10) and *Gs. ruber* (N12). In short, planktonic foraminifers also suggest a middle Miocene age. Integration of this dataset with the Time Scale of Ogg et al. (2008) allows distinguishing the two middle Miocene stages; Langhian and Serravallian stages (Fig. 4.15). The Langhian Stage is defined by the calcareous nannoplankton zones NN4 and NN5, and the foraminifer zones N9 and N10, whereas the Serravallian Stage is indicated by the calcareous nannoplankton zone NN6 and the foraminifer zone N12. In summary, the Oficina Formation is of middle Miocene age, spanning from 15.97 to 12.7 Ma.
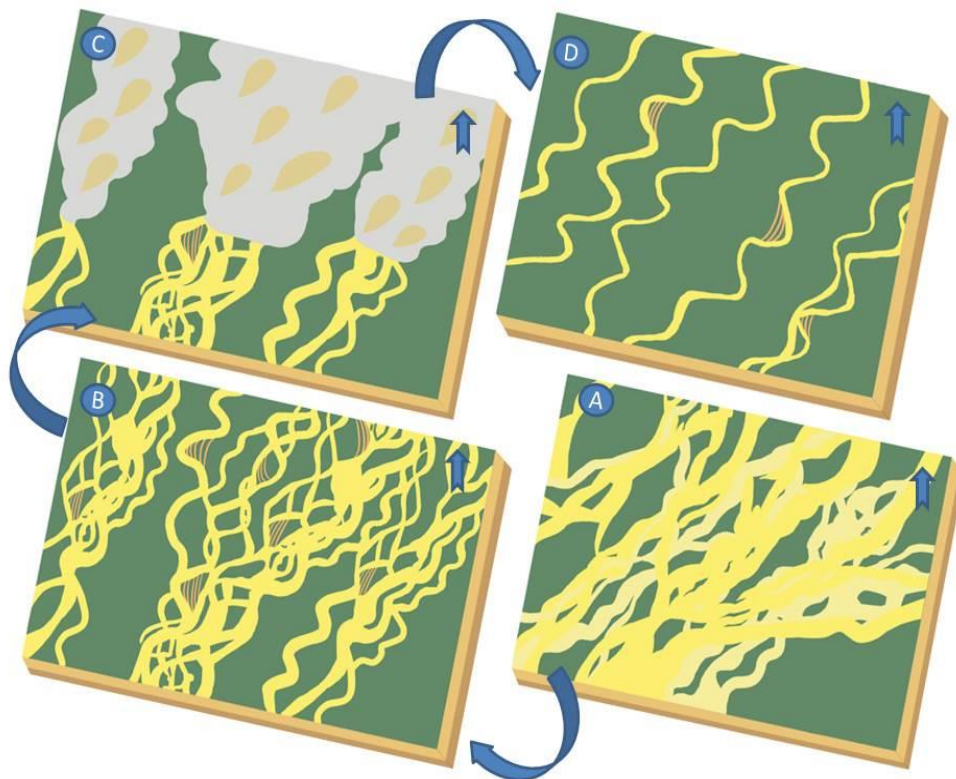
Figure 4.13. Facies model of the Oficina Formation. (A) Fluvial braided channels and floodplains in the lower member. (B) Meandering estuarine channels, tidal flats, and point bars in the middle member. (C) Outer estuarine sandbars at the mouth of the estuary in the middle member. (D) Lower delta plain deposits with distributary channels and floodplains in the upper member.

4.6.2. Sequence stratigraphic analysis

Two maximum flooding surfaces (MFS-1 and MFS-2) were recognized in the Oficina Formation and one maximum flooding surface (MFS-3) was identified in the lower part of the Freites Formation (Fig. 4.16). These surfaces show good matching with those proposed globally by Haq

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and Schutter (2008).

The tops of NN4, NN5 and NN6 were regarded as maximum flooding surfaces MFS-1, MFS-2 and MFS-3, respectively (Figs 4.15, 4.16). The top of NN4 (MFS-1), determined by the nannofossil Helicosphaera ampliaperta, is correlated with the maximum flooding surface below Ser1 (Figs 4.15, 4.16). MFS-1 also has been reported outside the Orinoco Oil Belt, in the Anaco area of the Eastern Venezuela basin by Campos et al. (1985) and Flores et al. (2001) based on the presence of *Praorbulina glomerosa* (Fig. 4.16). The top of NN5 (MFS-2), characterized by the presence of the nannofossil Sphenolithus heteromorphus and the foraminifer *Globorotalia foshi peripheroronda* and *Globorotalia foshi foshi*, is correlated with the maximum flooding surface that separates Ser 1 and Ser 2 (Figs 4.15, 4.16). MFS-2 also has been reported in the Anaco area of the Eastern Venezuela basin by Campos et al. (1985), based on the presence of *Globorotalia foshi foshi* (Fig. 4.16). MFS-2 also has been reported in the Maturin sub-basin of the Eastern Venezuela basin by Di Croce et al. (1999). The top of NN6 (MFS-3), determined by the presence of the nannofossil *Cyclicargolithus floridanus* and the foraminifers *Globorotalia foshi peripheroacuta*, *Globorotalia foshi lobata*, and *Gs. ruber*, is correlated with the maximum flooding surface located between Tor1 and Ser3 (Figs 4.15, 4.16).

According to well log information, four sequence boundaries were interpreted, and these are U-1, U-2, U-3, and U-4. U-1 is linked with the lower part of the Langhian stage (15.97 Ma) (Fig. 4.15). U-2 can be associated with Ser 1 and U-3 with Ser 3, which indicates the top of the Oficina Formation (Fig. 4.15). U-4 could be correlated with Tor 1 and occurs within the Freites Formation (Fig. 4.15).

Therefore, two third-order sequences have been interpreted for the Oficina Formation and these are depositional sequences 1-2 (DS1-2) and one depositional sequence 3 (DS3) was identified for the Freites Formation. DS1 is defined by sequence boundaries U-1 (15.97 Ma) and U-2 (13.82 Ma) and includes the maximum flooding surface MFS-1 (14.91 Ma) (Fig. 4.15). DS2 is bounded by sequence boundaries U-2 and U-3 (12.7 Ma), including maximum flooding surface MFS-2 (13.53 Ma) (Fig. 4.15). DS2 also has been reported in the Maturin sub-basin of the Eastern Venezuela basin by Di Croce et al. (1999). DS 3 is defined between sequence boundaries U-3 and U-4 (11.8 Ma) and includes the maximum flooding surface MFS-3 (11.9 Ma) (Fig. 4.15). In summary, these sequences (DS1-3) match with the middle Miocene third-order global eustatic curve of Haq and Schutter (2008).
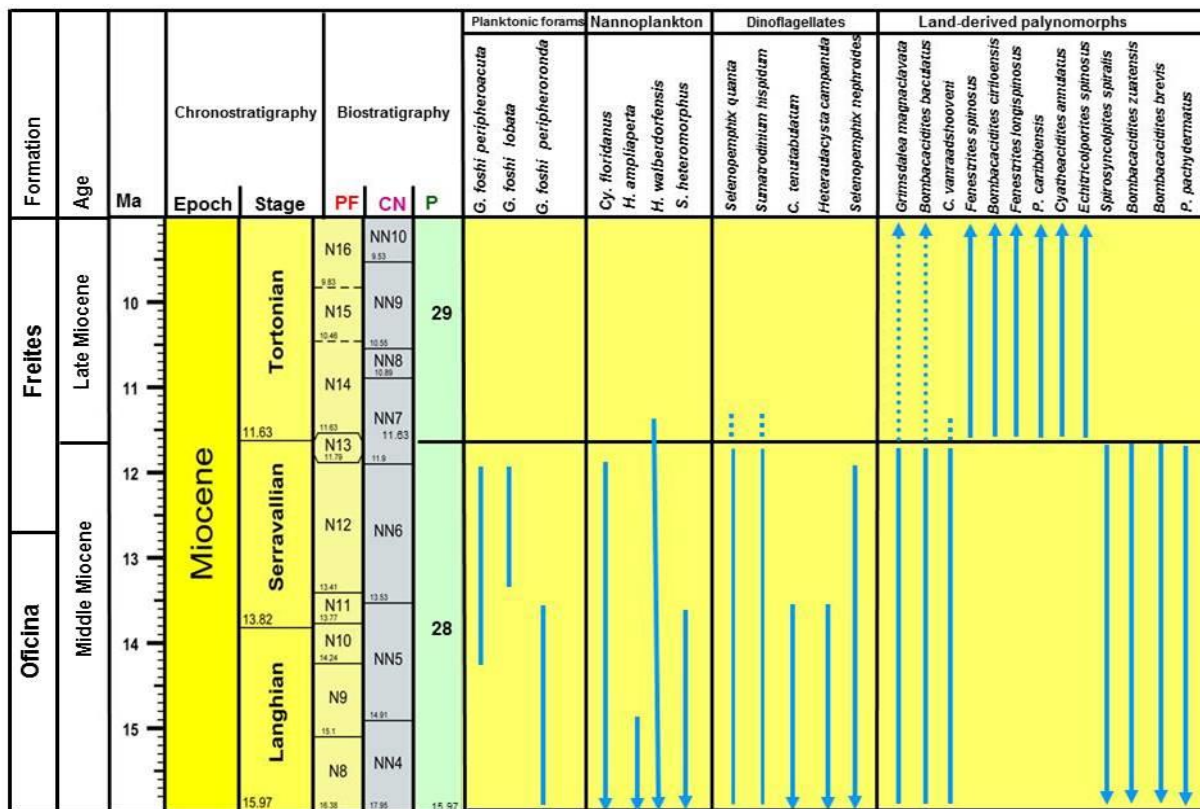
Figure 4.14. Stratigraphic range of the main palynomorphs, foraminifers and calcareous nannoplankton identified in the Oficina and Freites formations. PF (planktonic foraminifer zones), CN (Calcareous nannoplankton) and P (palynomorphs zones).

Table 4.2. Zones and bioevents for the Oficina and Freites formations.

Zones	Age	Calcareous nannoplankton	Planktonic foraminifers	Palynomorphs	Formation	Setting	Member	3er-order sequences
Above NN6	middle-late Miocene	Not applicable	Not applicable	*Fenestrites spinosus*, *Echitricolporites spinosus*, *Bombacacidites ciriloensis*, *Fenestrites longispinosus*, *Psilatricolporites caribbiensis*, and *Cyatheacidites annulatus* (first occurrence). *Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni*, and *Selenopemphix*	Freites	Not applicable	Not applicable	DS3

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				quanta are not restricted to the middle Miocene, but that extend into late Miocene				
Zone NN6	middle Miocene	*Cyclicargolithus floridanus* (NN6) last occurrence	*Globorotalia foshi peripheroacuta* (N12), *Globorotalia foshi lobata* (N12) and *Gs. ruber* (N12) last occurrence	Not applicable	Freites	Not applicable	Not applicable	DS3
Between the calcareous nannoplankton zones NN6 and NN5	middle Miocene	*Cyclicargolithus floridanus* (NN6) first appearances	*Globorotalia foshi peripheroacuta* (N12), *Globorotalia foshi lobata* (N12) and *Gs. ruber* (N12) first appearances	*Grimsdalea magnaclavata*, *Crassoretitriletes vanraadshooveni*, *Selenopemphix quanta* and *Bombacacidites baculatus* (first occurrence at the base of the middle Miocene)	Oficina	Tide-dominated delta	upper	DS2
Between the calcareous nannoplankton zones NN5 and NN4	middle Miocene	*Sphenolithus heteromorphus* (NN5)	*Globorotalia foshi peripheroronda* (N9 and *Globorotalia foshi foshi* (N10))	*Selenopemphix quanta*, *Crassoretitriletes vanraadshooveni*, *Grimsdalea magnaclavata* and *Bombacacidites baculatus* (first appearance in the middle Miocene)	Oficina	Tide-dominated delta	upper	DS2
Between the calcareous nannoplankton zone NN4 and the basement	middle Miocene	*Helicosphaera ampliaperta* (NN4) and *Helicosphaera walbersdorfensis* (NN4). calcareous nannoplankton are restricted to the estuarine zone	Not applicable	*Selenopemphix quanta*, *Bombacacidites baculatus*, *Crassoretitriletes vanraadshooveni*, *Grimsdalea magnaclavata* and *Sumatrodinium hispidum* (first appearance at the base of the middle Miocene). *Cribroperidinium tenuitabulatum*, *Heteraulacysta campanula*, *Bombacacidites zuatensis*, *Spirosyncolpites spiralis,* and *Psilatricolporites pachydermatus*, which have their last occurrence in the middle	Oficina	Fluvial to tide-dominated estuary and delta	Lower to middle	DS1

| Formation | | | | | | | Miocene, are also present.

Dinoflagellates are restricted to the estuarine zone | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|

Figure 4.15. Chart with bioevents and sequences interpreted. PF (planktonic foraminifer zones), CN (Calcareous nannoplankton zones) and P (palynomorphs zones).

4.7. Discussion

4.7.1. The third-order sequence-stratigraphic model

The third-order sequence-stratigraphic framework (Fig. 4.15) of the middle Miocene Oficina Formation in the Orinoco Oil Belt is based on biostratigraphy (bioevents), sedimentology (sedimentary facies), allostratigraphic surfaces (sequence boundaries, transgressive surfaces, maximum flooding surfaces) and systems tracts (LST, TST and HST). Two third-order depositional sequences were identified (DS1-2). The unconformities that bound the third-order

sequences, as well as the maximum flooding surfaces, can be correlated with the third-order global eustatic curve for the middle Miocene (Haq and Schutter, 2008), which comprise mostly sea-level lowstand to transgression during the Langhian and a sea-level highstand during the Serravallian stage. This pattern is remarkably consistent with stratal stacking pattern and associated depositional environments interpreted for the Oficina Formation. Third-order sequences identified in the Oficina Formation have a duration of 2.15 and 1.12 Ma, which is consistent with the standard estimated ranges of 0.5-3.0 Ma for sequences of this order (Haq et al., 1987; Vail et al., 1991).
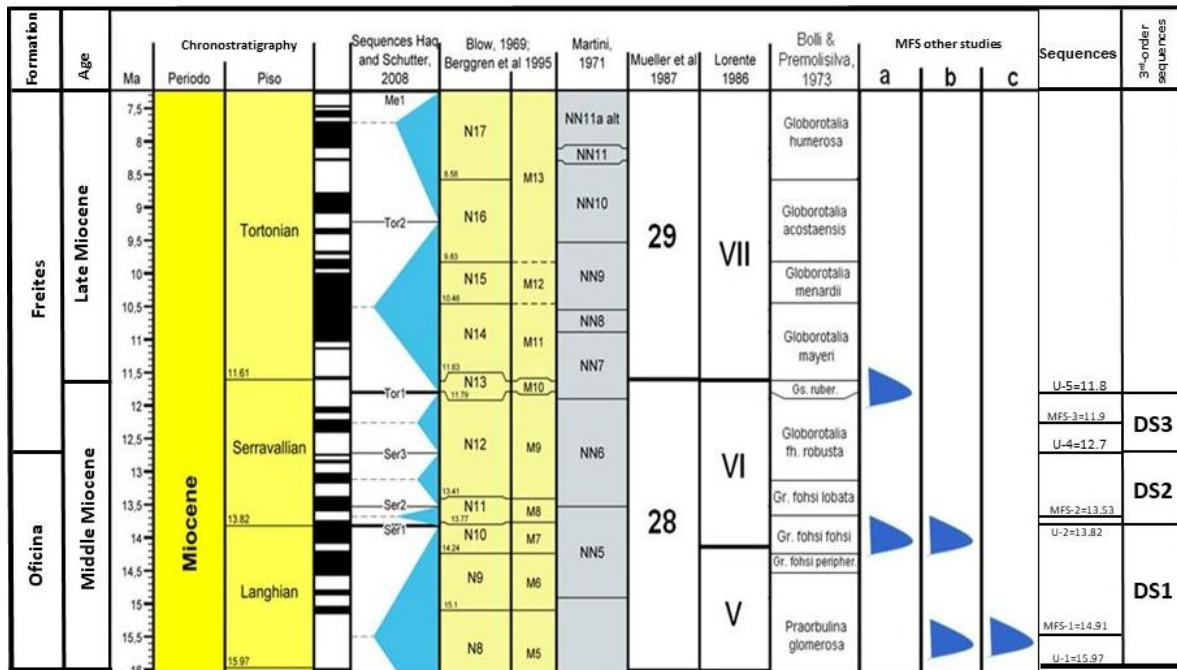
Figure 4.16. Integration of the three third-order sequences and maximum flooding surfaces of this study with maximum flooding surfaces of previous studies for the Oficina Formation in the Orinoco Oil Belt (a: Audemard et al., 1985; b: Campos et al., 1985 and c: Flores et al., 2000).

DS1 comprises a thick LST included in the lower member, a thick TST included in the middle member, and a thin (HST) at the top of the middle member. DS1 is associated with incised-valley systems, which were formed during a sea-level fall, forming fluvial valleys dominated by braided-channel deposits (FA1). They consist of pebbly, very coarse- to medium-grained sandstone, coal, mudstone and siltstone. The latter two are associated with floodplains and paleosols. These overbank deposits display the *Scoyenia* Ichnofacies. The middle interval of DS1 records a relative sea-level transgressive that took place during the Langhian stage of the middle Miocene. The shoreline and the tide limit migrated landward. Therefore, the fluvial valley systems

within the Orinoco Oil Belt were flooded by and became filled with tide-dominated transgressive sediments evolving into estuarine valleys that are constituted by meandering estuarine channels (FA2), tidal flats and tidal creeks (FA3), and outer estuarine sandbars (FA4). Overall, these facies associations comprise mudstone breccia, interbedded sandstone and mudstone, sandstone with mudstone drapes, inclined heterolithic stratification, and convolute lamination. Flaser, wavy and lenticular bedding, limestone and calcareous mudstone layers, syneresis cracks, and shell remains are present as well. The *Glossifungites*, *Teredolites*, *Scoyenia, Skolithos*, and depauperate *Cruziana* Ichnofacies have been recorded in the estuarine valley deposits (Solórzano et al., 2017).

DS2 comprises a thin TST and a thick HST. DS2 was developed during a sea-level highstand that took place during the Serravallian Stage of the middle Miocene. The shoreline migrated towards the sea, allowing the establishment of the highstand systems tract in the upper member of the Oficina Formation all across the Orinoco Oil Belt. It is constituted by lower delta plain deposits (FA5), which display a progradational stacking pattern. Overall, this facies association consists of sandstone with mudstone drapes and inclined heterolithic stratification representing distributary channels and silstone and mudstone formed in distributary bays and floodplains. The latter one displays the presence of *Scoyenia* Ichnofacies.

In the Orinoco Oil Belt, allogenic processes control the larger-scale depositional systems within the basin, as well as the third-order sequences. These factors include climate, tectonics, and sea-level changes, which are related with energy flux, sediment supply, and accommodation. However, autogenic processes may have also operated at the scale of depositional environments and subenvironments. Probably, these processes could explain the differences between the number of third-order sequences between this study and those identified in the Petrocedeño Field of the Junín area, where eleven third-order sequences have been recognized (Martinius et al., 2012, 2013). Discrepancies between our study and that in the Junín area may also reflect the fact that sequences in the latter have been identified based on a different set of criteria. Whereas subaerial unconformities (SU) or maximum regression surfaces were chosen as sequence boundaries for sequences 1-5, maximum flooding surfaces (MFS) were chosen as sequence boundaries for sequences 6-10 because SU or correlative key stratigraphic surfaces could not be identified in well logs and core and/or mapped on seismic data. Some of the sequences identified in Petrocedeño are here re- interpreted as 4th order sequences. Within this framework, sequences 1-8 are considered 4th-order sequences within DS1, and sequences 9-11 within DS3. The resolution of any sequence

stratigraphic study can be adjusted according to the study area, from small-scale depositional environments and subenvironments to the scale of whole sedimentary basin fills, therefore providing a template that allows framing smaller-scale stacking stratal patterns within larger-scale models (Catuneanu, 2006).

4.7.2. Fourth-order sequence-stratigraphic model

Third-order DS1 consists of fluvial to estuarine deposits. The latter can be subdivided into at least three 4th order sequences using the *Glossifungites* Ichnofacies (Fig. 4.19), which represent transgressive surfaces of erosion that can be correlated in the Ayacucho area using well logs. Fourth-order sequences 1 and 2 have been interpreted by the presence of *Glossifungites* Ichnofacies within paleosols that delimit the base of the meandering estuarine channels (e.g. A4, A8). These sequences can be traced to other wells. In one well, the paleosols are replaced by a coal layer (e.g. A7).

Fourth-order sequence 3 has been interpreted by the presence of *Glossifungites* Ichnofacies within tidal flat deposits, delineating the base of the meandering estuarine channels (e.g. A8). This sequence can be traced into the Ayacucho area. Recognition of fourth-order sequences within the fluvial interval is complicated by the fact that no marker beds are available and that discrimination of allogenic and autogenic successions is not possible in most instances.

4.7.3. Incised-valley systems

Zaitlin et al. (1994) subdivided the fill of incised valleys into three segments. Segment 1 comprises outer incised valley, being located from the most seaward extent of valley incision to the beginning of highstand progradation. Segment 2 represents the middle-incised valley, being located from the beginning of highstand progradation at segment 1 to the estuarine limit landward during the time of maximum inundation. Segment 3 corresponds to the inner incised valley, being located landward of the transgressive marine-estuarine limit, and still linked with relative sea level change. In this context, the sedimentary succession of the Oficina Formation, in the whole Orinoco Belt represent the fill of segment 2, which is characterized by lowstand fluvial to transgressive estuarine deposits overlain by highstand deltaic deposits, as well as two maximum flooding surfaces within estuarine systems. However, further to the northeast and outside the Orinoco Oil Belt, in the Oritupano Field, the Oficina Formation consists of highstand shoreface to offshore and shelf

deposits (Solórzano et al., 2017). Therefore, these marine facies suggest the presence of segment 1.

4.7.4. Implications for petroleum exploration and reservoir characterization

Third-order sequences are very important to delineate the stratigraphic architecture at the reservoir scale. DS1 extends from Boyacá to Carabobo (Fig. 4.17), being thinner toward the Carabobo area and thicker in the Junín and Ayacucho areas. Based on north to south stratigraphic cross-sections (Figs 4.18-4.20), the thicknesses of DS1 increases towards the north and decreases towards the south. DS1 is thinner in the Carabobo (111-190 m) area than in the Junín (106-322 m) Ayacucho (194-467 m) areas. In the Ayacucho and Carabobo areas, DS1 overlie the metamorphic-igneous basement.

In the Junín area, DS1 rests on top of Cretaceous or Pre-Cretaceous strata. DS1 hosts the braided fluvial channels (Figs 4.6, 4.8, 4.13A, 4.21) of the fluvial systems and the tidally influenced meandering channels (Figs 4.6, 4.9, 4.13B, 4.21) of the estuarine systems, which form the main reservoirs within the Orinoco Oil Belt. The braided fluvial channel deposits of the lower member consist of fining-upward, massive to planar or trough cross-stratified, pebbly, and very coarse- to medium-grained sandstone, representing multiple depositional units or storeys of amalgamated sandstone that infilled the paleotopographical lows along the Cretaceous or Pre-Cretaceous unconformity (Figs 4.8, 4.21). These channel fills are 3-12 m thick. Contrary to the lower delta plain deposits of DS2, the tectonic setting and the deposition in a low-gradient foreland basin promoted an increase in grain size and amount of sand supplied to the fluvial system, producing sandstone-rich deposits because the low river gradient in the foreland basin leads to rapid deposition of the coarser fractions. Conglomerate and very coarse-grained sandstone record sedimentation close to the source of origin (Dalrymple et al., 2003). The sediment source for the Oficina fluvial systems comes from the Guayana shield. With the filling of the paleotopographical lows along the Cretaceous or Pre-Cretaceous unconformity, the estuarine channels became unconfined and the channel fills were formed by IHS (0.3-15 m thick) resulting from lateral accretion of point bars in meandering channels. These channel deposits consist of massive to trough or planar cross-stratified, very coarse- to very fine-grained sandstone, representing multiple depositional units or storeys of amalgamated sandstone (Figs 4.9, 4.21).

DS2 extends from Boyacá to Carabobo (Fig. 4.17). It is thicker toward the Carabobo area

than in the Junín and Ayacucho areas. Based on north to south stratigraphic cross-sections (Figs 4.18-4.20), the thicknesses of DS2 increases towards the north and decreases toward the south. DS2 is thicker in the Carabobo area (256-476 m) than in the Junín (29-134 m) and Ayacucho (140-273 m) areas. DS2 comprises tide-dominated distributary channels of the lower delta plain (Figs 4.12, 4.13D, 4.21). This type of channels tends to be the widest and deepest (Reynolds, 1999; Dalrymple et al., 2003). However, in the Oficina Formation, these planar and trough cross-stratified medium- to fine-grained sandstone channels are thin, scarce, rarely amalgamated, running on vast floodplains and prograded within a large brackish-water embayment rather than in the open sea (Fig. 4.21). The Oficina distributary channels are 0.2-4 m thick. The tectonic setting, labile source rocks and the deposition in a low-gradient foreland basin limit the size and amount of sand supplied to the delta, producing mudstone-rich deposits (Dalrymple et al., 2003). The hydrocarbon reservoir potential of these deposits is poor due to the abundance and lateral continuity of the mudstone levels.
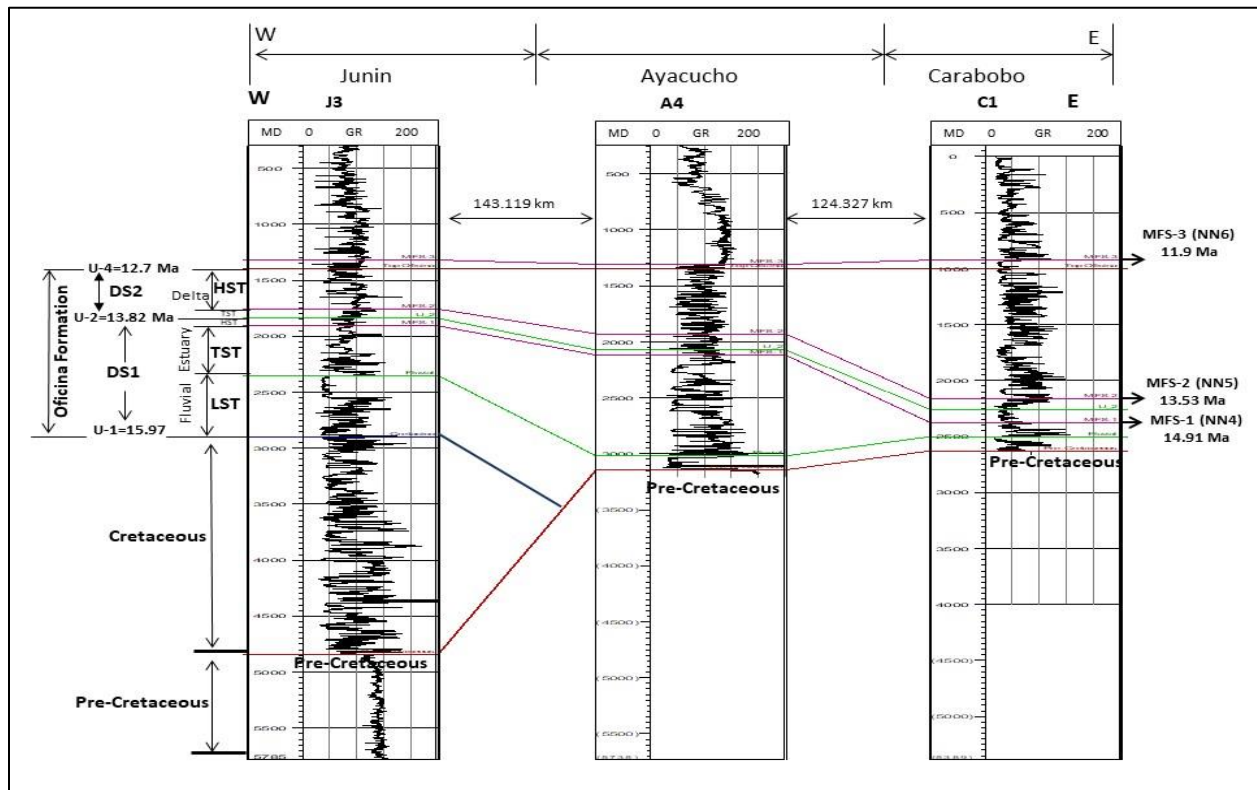
Figure 4.17. West to east regional stratigraphic cross-section displaying the third-order depositional sequences (DS1-2), the maximum flooding surfaces (MFS1-2) of the Oficina Formation, and MFS-3 (Freites Formation), which rest on the Cretaceous and basement unconformities along the Orinoco Oil Belt. Geophysical data shown in the gamma-ray log, from 0 to 200 API units.
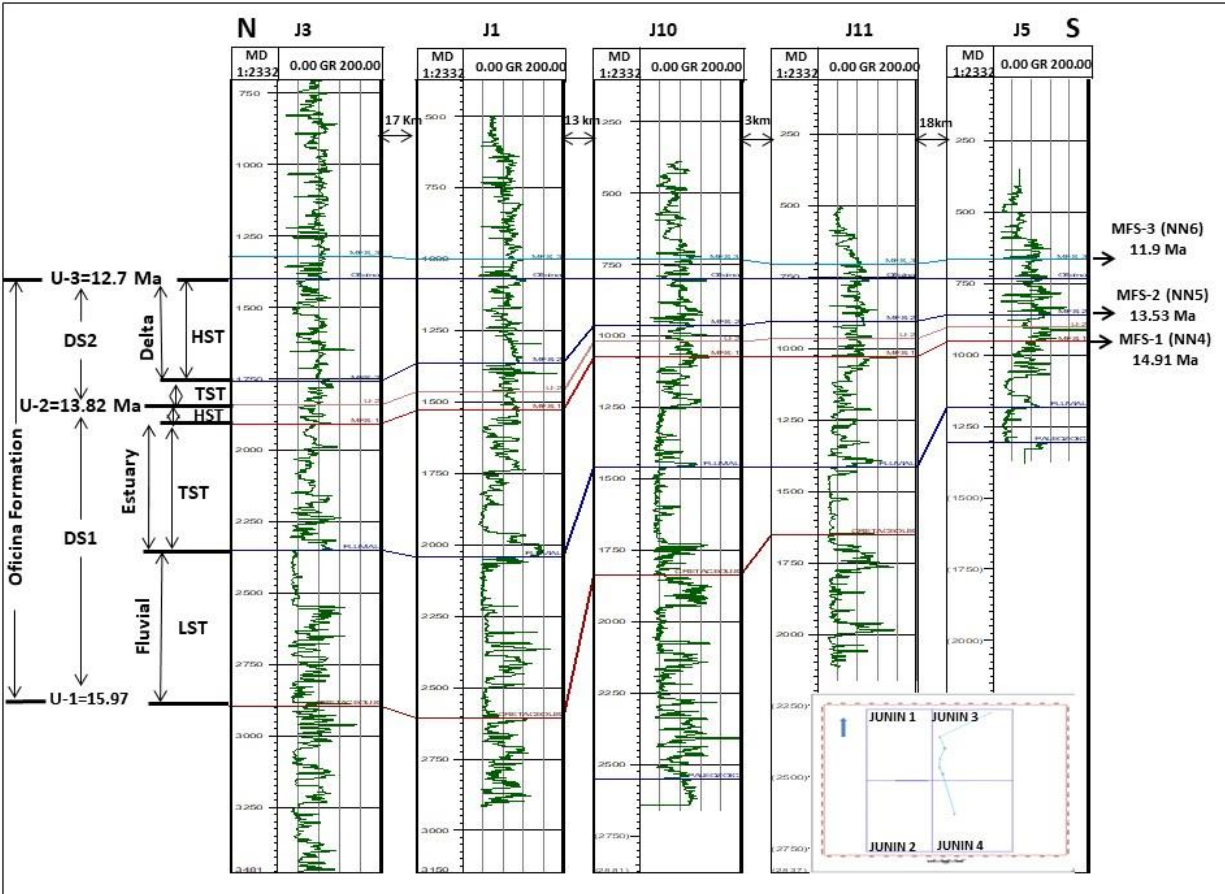
Figure 4.18. North to south regional stratigraphic cross-section of the Junín area displaying the third-order depositional sequences (DS1-2) and their associated depositional environments. Geophysical data shown in the gamma-ray log, from 0 to 200 API units.

The geometry and reservoirs connectivity are controlled by depositional processes, variations of sea-level change, tectonic setting, nature of the source area, nature of the basin, sediment grain size and climate, which produce problems for the subsurface reservoir characterization. In the Oficina Formation, amalgamated fluvial and estuarine channels represent multiple depositional units. The superposition of individual packages implies the existence of flow barriers, which may be caused by sandstone bodies switching or sea-level rises. Therefore, it is important to introduce process-related sedimentological bodies into the reservoir modelling workflow, which provide a realistic distribution of the channel fills, improve local vertical connectivity between individual sequences, and seals and baffles can be simulated (Labourdette et al., 2008). The development-drilling suggests that the reservoirs are much more complex and,

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although interconnected, are more compartmentalized (Kopper et al., 2001). However, drilling horizontal wells indicate that the reservoirs are laterally discontinuous and are not always predicted from the surface seismic data (Rodriguez., et al., 2017) A detailed study about reservoir connectivity and barriers is important because it will have a significant impact on recovery factors in the Orinoco Oil Belt, where reservoirs comprise heavy and extra heavy oils with a downhole viscosity of 400-7000 cps and a specific gravity of 4°-14°API.
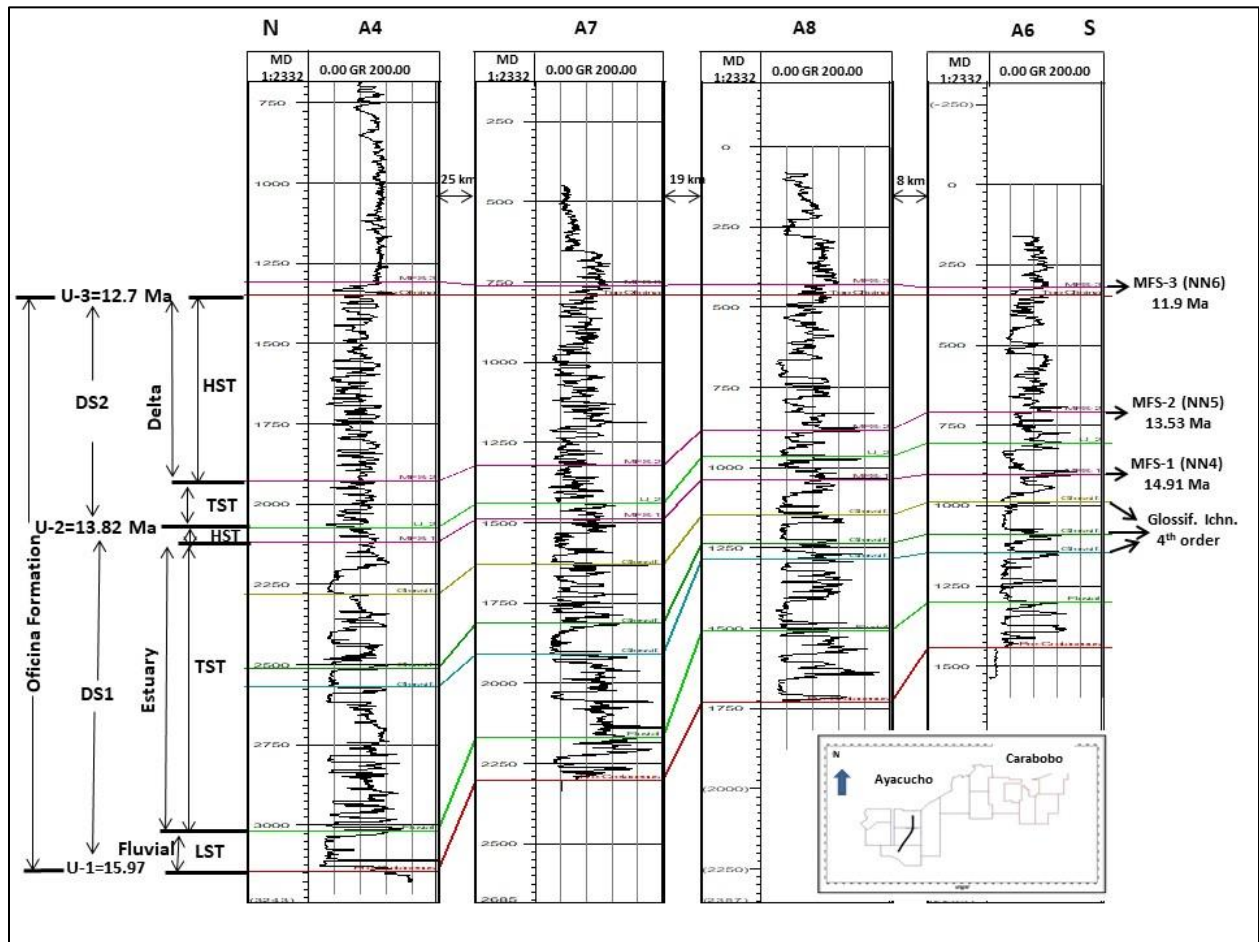
Figure 4.19. North to south regional stratigraphic cross-section of the Ayacucho area displaying the third-order depositional sequences (DS1-2) and their associated depositional environments and 4th order sequences in the estuarine deposits of DS1. Geophysical data shown in the gamma-ray log, from 0 to 200 API units.

Magna Reserva Project (2012) subdivided the Boyacá and Junín areas into three units, which rest on Cretaceous and Pre-Cretaceous rocks and are partially coincident with the two third-order sequences defined in this study. DS1, in the fluvial part, displays porosities between 38%

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and 28%, API ranges 13-4, temperatures between 95° F and 150° F and viscosity values from 400 to 2800 cps. The best thicknesses of net oil sand are in the area of Boyacá, but the best physical and chemical properties are in the Junín area (API 8 and 12). DS1, in the estuarine level, displays porosities between 36% and 28%, API ranges 13-14, temperatures between 90° F and 140° F, and viscosity values from 1000 to 7000 cps. The best thicknesses of net oil sand are in the Junín area. There is no available information for DS2.
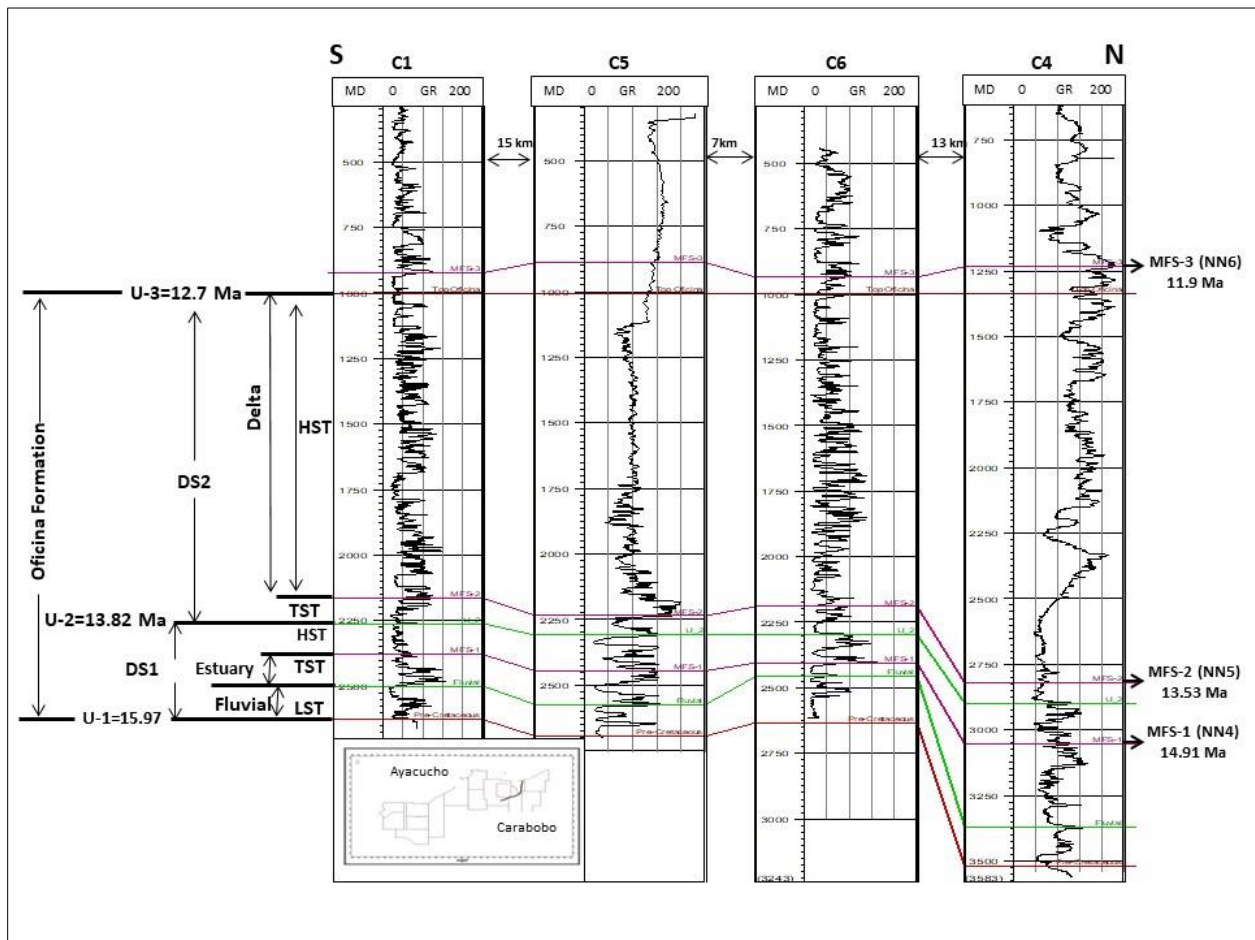
Figure 4.20. North to south regional stratigraphic cross-section of the Carabobo area displaying third-order depositional sequences (DS1-2) with their associated depositional environments. Geophysical data shown in the gamma-ray log, from 0 to 200 API units.

The Ayacucho and Carabobo areas are divided into several units, which rest on the basement. The western Ayacucho area is divided into three units and the eastern Ayacucho area and the Carabobo area into two units (Magna Reserva, 2012). These units are coincident with DS1 and DS2. DS1

displays porosities between 37% and 24%, API ranges 12-8, temperatures between 100° F and 170° F and viscosity values from 1000 to 4000 cps. The best thicknesses of net oil sand are in the Petromonagas, Cerro Negro, Petroindependencia, and Petrosinovensa areas. There is no available information for DS2.
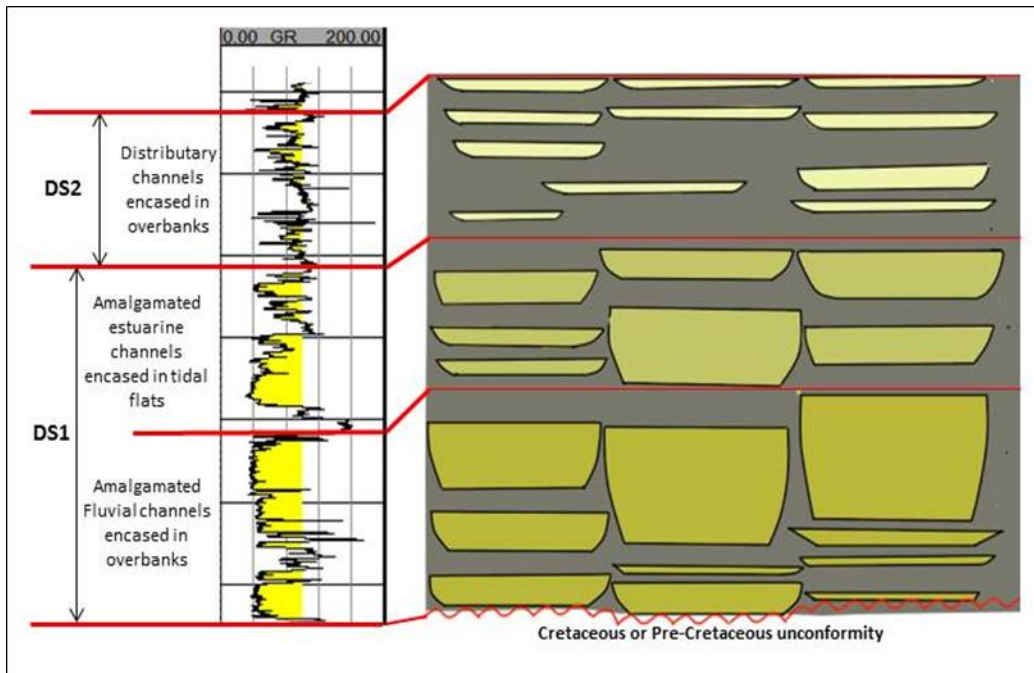
Figure 4.21. Geometry and distribution of fluvial, estuarine, and distributary channels within the sedimentary succession of the Oficina Formation.

4.8. Conclusions

The Oficina Formation in the Orinoco Oil Belt is of middle Miocene age (15.97-12.7 Ma), encompassing the Langhian and Serravallian stages, and is interpreted as a single second-order depositional sequence further divided into two third-order depositional sequences (DS1-2). DS1 is limited by sequence boundaries U-1 (15.97 Ma) to U-2 (13.82 Ma) and includes MFS-1 (14.91 Ma). This sequence consists of thick LST and TST, and a thin HST. It records fluvial valleys created during a relative sea-level fall, and the LST consists of fluvial braided channels, swamps, paleosols, and floodplains. This interpretation is reinforced by the presence of the *Scoyenia* Ichnofacies. These valleys became drowned and transformed into estuarine systems (TST) during the Langhian transgression. The retrogradational stratal stacking pattern of estuarine valleys is

part progradational lower delta plain strata, consisting of distributary channel, interdistributary bay and floodplain deposits. The presence of the freshwater *Scoyenia* Ichnofacies indicates progradation. Third-order sequences provide a better understanding of reservoir distribution in the Oficina Formation and show a good match with the middle Miocene third-order global eustatic curve of Haq and Schutter (2008). Based on the model of Zaitlin et al. (1994), the sedimentary succession of the Oficina Formation in the Orinoco Oil Belt is regarded as representing segment 2.

Transition

Chapter 4 includes the third-order sequence-stratigraphic model, based on the integration of sedimentologic, stratigraphic, ichnologic, and biostratigraphic datasets. The next chapter (Chapter 5) provides final remarks, and a summary of main findings and conclusions obtained during this research.

Chapter 5

5. Conclusions

An integrated sedimentologic, ichnologic and sequence-stratigraphic analysis allows providing a better characterization of the middle Miocene Oficina Formation in terms of paleoenvironmental characterization and stratigraphic architecture. This is of fundamental importance because this unit represents one of the largest hydrocarbon reserves in the world. This more comprehensive model will allow better reservoir characterization and sound predictions for future exploration.

The Oficina Formation in the Orinoco Oil Belt consists of nine facies (FA-FI), grouped in five facies assemblages (FA1-5), whereas the Oficina Formation in the Oritupano field comprises eleven facies (FJ-FS), grouped in four facies assemblages (FA6-9). The Oficina Formation in the Orinoco Oil Belt is interpreted as recording lowstand fluvial deposits in the lower member, passing upward into transgressive tide-dominated estuarine deposits in the middle member, and highstand lower delta-plain deposits of a tide-dominated delta in the upper member. The sedimentary succession in the Oritupano Field represents the upper member of the Oficina Formation, which reflect highstand progradation, thus correlating with the highstand deltaic deposits identified in the Orinoco Oil Belt. Whereas the deltaic system in the Orinoco Oil Belt prograded into a brackish-water embayment, deposits in the Oritupano Field records more marine conditions, namely wave-dominated deltaic deposits in the lower part, passing upward into shoreface to offshore and shelf deposits formed along adjacent strandplains.

The Oficina Formation illustrates both softground and substrate-controlled ichnofacies. The former is key for paleoenvironmental characterization of continental, marginal-marine and open-marine settings. Deposits from fluvial environments and the freshwater portions of tide-dominated estuarine and distributary channel environments are locally intensely bioturbated, displaying very low-diversity occurrences of the *Scoyenia* Ichnofacies. Brackish-water delta-plain and estuarine deposits display lesser degrees of bioturbation and low ichnodiversity, illustrating the depauperate *Cruziana* and *Skolithos* Ichnofacies. Delta-front and prodelta deposits display the presence of the *Skolithos* and archetypal *Cruziana* Ichnofacies, which alternated with the depauperate *Cruziana* Ichnofacies, indicating fluctuations between brackish-water and near-

normal marine conditions. Shoreface, offshore and shelf deposits are characterized by intense bioturbation and overall high diversity, illustrating the *Skolithos* and archetypal *Cruziana* Ichnofacies, further supporting normal-marine conditions. Sedimentary facies distribution in marginal-marine environments is mainly salinity-independent, but the distribution of benthos is not. Therefore, biogenic structures provide key information to reconstruct salinity conditions. Tidal currents and brackish-water conditions within estuarine environments allowed the establishment of an opportunistic and impoverished marine benthic community.

The whole Oficina Formation in the Orinoco Oil Belt comprises one second-order depositional sequence, which has been subdivided into two third-order depositional sequences, namely DS1 and DS2. The sequence boundaries (U-1, U-2 and U-3) and maximum flooding surfaces (MFS-1 and MFS-2) are associated with the global eustatic curves previously identified. These maximum flooding surfaces were interpreted based on the planktonic foraminifers and calcareous nannoplankton zones. DS1 is bounded by U-1 (15.97 Ma) and U-2 (13.82 Ma) and includes MFS-1 (14.91 Ma). DS1 consists of lowstand fluvial valleys formed during a relative sea-level fall, which were replaced by transgressive estuarine valleys during a relative sea-level rise at Langhian stage. Thin highstand deltaic deposits also occur in the uppermost interval of DS1. DS2 is bounded by U-2 (13.82 Ma) and U-3 (12.7 Ma) and includes MFS-2 (13.53 Ma). DS2 comprises thin transgressive deposits (lower part) and thick highstand deltaic deposits (upper part) formed during a relative sea-level fall at Serravallian stage.

The fluvio-estuarine and deltaic systems of the Oficina Formation display similarities in sedimentologic, stratigraphic and ichnologic characteristics with other tide-dominated, ancient marginal-marine strata and modern settings. These deposits were formed under a wide variety of latitudinal and tectonic settings. Sea-level changes and tidal currents played a key role on sedimentation of these units. Regardless of the overall ichnologic similarities across a broad spectrum of latitudinal settings, it has been noted that the distribution of shallow-marine ichnofaunas may be controlled by climate.

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