SEDIMENTOLOGY, ICHNOLOGY, AND SEQUENCE STRATIGRAPHY OF THE MIOCENE OFICINA FORMATION, ORINOCO OIL BELT, EASTERN VENEZUELA BASIN

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Saskatoon

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ABSTRACT

The Lower Miocene Oficina Formation is widely distributed in the subsurface of the Orinoco Oil Belt of eastern Venezuela. Despite its economic importance as one of the most important hydrocarbon reservoirs worldwide, little is known about its sedimentologic, ichnologic and sequence-stratigraphic aspects. Sedimentary facies, trace fossils, depositional environments, stratal stacking patterns and surfaces of sequence stratigraphic significance have been analyzed in the Junín and Boyacá areas. The Oficina Formation is subdivided here into three members: Lower, Middle, and Upper. The Lower Member consists mainly of lowstand fluvial braided-channel deposits filling an incised valley. No evidence of marine conditions is present and the only biogenic structures detected are root trace fossils present at the top of a few fining- and thinning- upward channelized units. The Middle Member is much more heterogeneous, both vertically and laterally, comprising high-sinuosity estuarine-channel, tidal-flat, tidal-creek and tidal-sandbar deposits, stacked to form a retrogradational package and representing the transgressive systems tract. The Middle Member is characterized by widespread evidence of tidal influence (e,g, inclined heterolithic stratification) and by the presence of the impoverished *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies, both reflecting brackish-water conditions. This member is thought to represent deposition in an estuarine system. The Upper Member consists predominantly of highstand delta-plain deposits, stacked forming a progradational pattern. These deposits locally show intense bioturbation with a predominance of continental trace fossils, illustrating the *Scoyenia* Ichnofacies. Deltaic deposits display a mixed influence of tides and river processes. Previous studies invariably assumed a deltaic model for the whole Oficina Formation. However, integration of sedimentologic, ichnologic, and sequence-stratigraphic datasets suggests a more complex depositional evolution, comprising a fluvio-estuarine valley incised during a fall in sea level that became filled during the lowstand and subsequent transgression, culminating with deltaic progradation during the highstand.

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1 Introduction

Since Petróleos de Venezuela Sociedad Anónima (PDVSA) made their last exploratory campaign in the Eastern Venezuelan basin during 2005-2010, the Organization of the Petroleum Exporting Countries (OPEC) recognized that Venezuela has the largest hydrocarbon reserves in the world with 377,000 million of barrels, of which almost 78% are located in "La Faja Petrolífera del Orinoco" (Orinoco Oil Belt) in an area of 55,315 km^2, north of the Orinoco River, in the southern margin of the Eastern Venezuela Basin. One hundred and forty six new wells were drilled, more than 3,800 km of 2D seismic lines were acquired, and almost 3350 m of core were taken during the last exploratory period which added to previous exploratory data obtened to certify the oil reserves. The main reservoir is the lower Miocene Oficina Formation with nearly 90% of Original-Oil-in-Place (OOIP). In spite of its economic importance, the only studies of the Oficina Formation in the Orinoco Oil Belt are in the PetroZuata (PetroAnzoategui), PetroCedeño (formerly-Sincor), PetroMonagas (formerly Cerro Negro), Petrolera Sinovensa, and PetroPiar (formerly Ameriven) fields, whose current production is around 1,000,000 barrel/day (Figure 1.1B). The rest of the Orinoco Belt has only been addressed in a regional study (Latreille et al., 1983). The next planned step should be starting early production in other blocks where new data was acquired. Because of this, an integrated sedimentologic, ichnologic, and sequence-stratigraphic study is of great importance to improve reservoir characterization and performance.

1.1. Research Objectives

The main goal of this research is to integrate sedimentologic and ichnologic data within a sequence-stratigraphic framework in order to develop a geological model that allows a reconstruction of the paleoenvironmental and paleogeographic evolution of the Oficina Formation. To achieve this goal, it is necessary to integrate the new data acquired by PDVSA during recent years. These data include more than 40 new wells, 792 m of core, as well as biostratigraphic and petrophysical information.

The main objectives are to (1) describe and interpret the sedimentary facies of the Oficina Formation in the Boyacá area (blocks 5 and 6) and Junín area (blocks 1, 2, 3, and 4); (2) identify facies associations in terms of sedimentary processes and environments; (3) characterize trace fossils, ichnofacies, and their paleoenvironmental implications; (4) construct stratigraphic cross-sections based on core data, showing the geometry and architecture of the deposits; (5) construct stratigraphic cross-sections based on well logs that allow prediction of the distribution of reservoirs in areas without cores; and (6) propose a sequence-stratigraphic model.

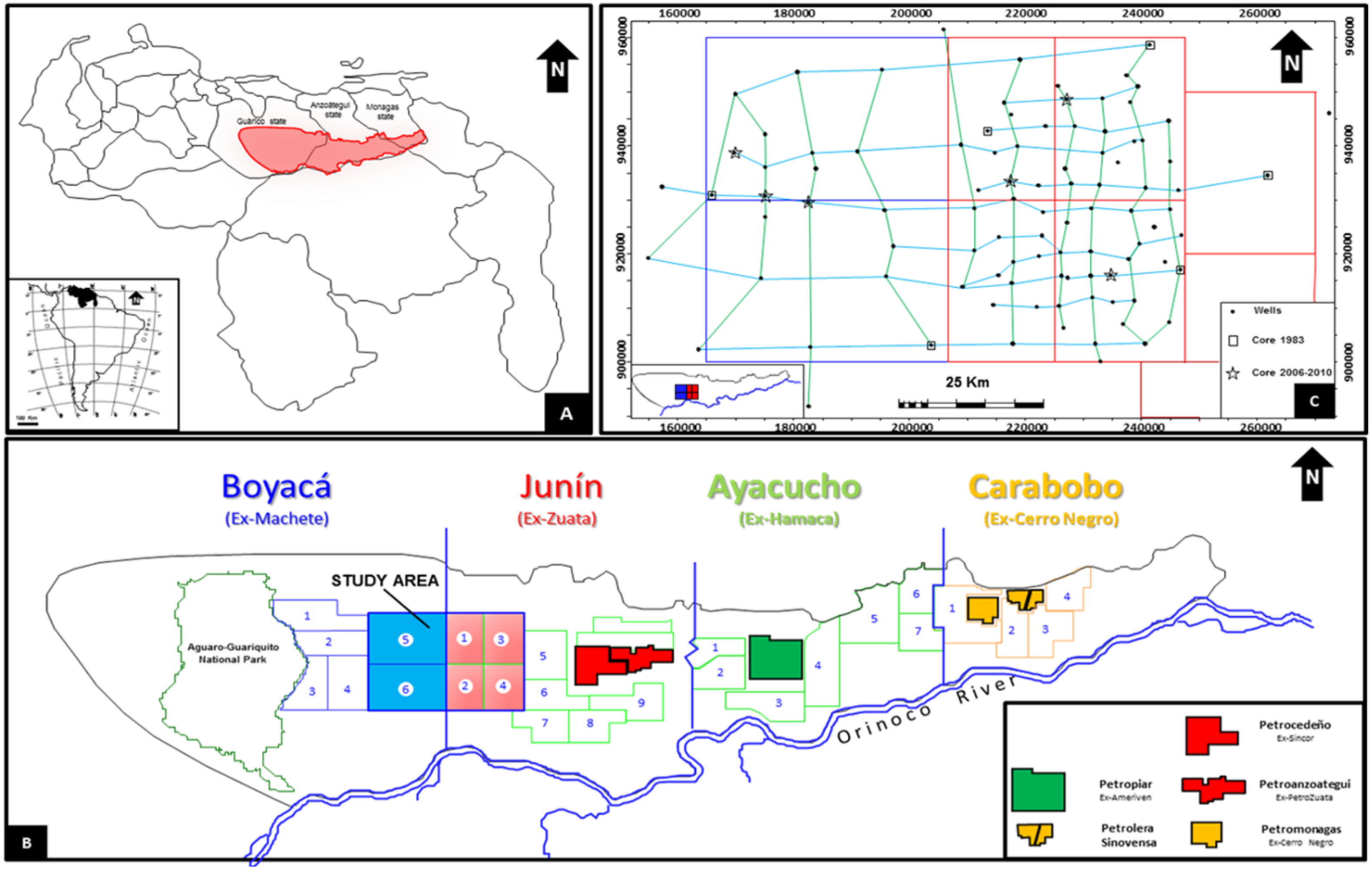


Figure 1.1 (A) Location of the study area. (B) Local and general map from Orinoco Oil Belt in Venezuela. Orinoco Oil Belt with area subdivision and blocks selected for this study. Additionally, there are companies that currently are operating in the Orinoco Oil belt. (C) Study area, blocks 5 and 6 Boyacá area (blue) and blocks 1, 2, 3 and 4 of Junín (red),. The green lines are north and south well cross sections and the light blue color represent east-west and well cross sections.

2 Literature Review

Many hydrocarbon reserves worldwide are found in sediments deposited in river-mouth environments, in both deltaic and estuarine settings. Therefore, detailed analyses of coastal depositional systems are necessary to estimate the spatial and temporal distribution of reservoir and non-reservoir lithofacies, for their definition according to petrophysical parameters, and for assessment of their production potential. Understanding sedimentary and oceanographic processes operating in marginal-marine settings is essential to assess reservoir quality. Discrete lithofacies in tide-influenced deltas and tide-dominated estuaries may be similar. This may lead to erroneous interpretation of the depositional environments, if detailed analyses of stratal stacking patterns and associated processes are not available. Study of sedimentary processes in modern environments is thus essential to obtain a more accurate and comprehensive understanding.

2.1 Deltas

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”. He analyzed different modern deltas, which had been previously described by Fisher et al. (1969), and recognized that the interaction between fluvial and marine processes may produce different kinds of deltas (‘river-dominated’ deltas, ‘tide-dominated’ deltas and ‘wave dominated’ deltas) (Figure 2.1).

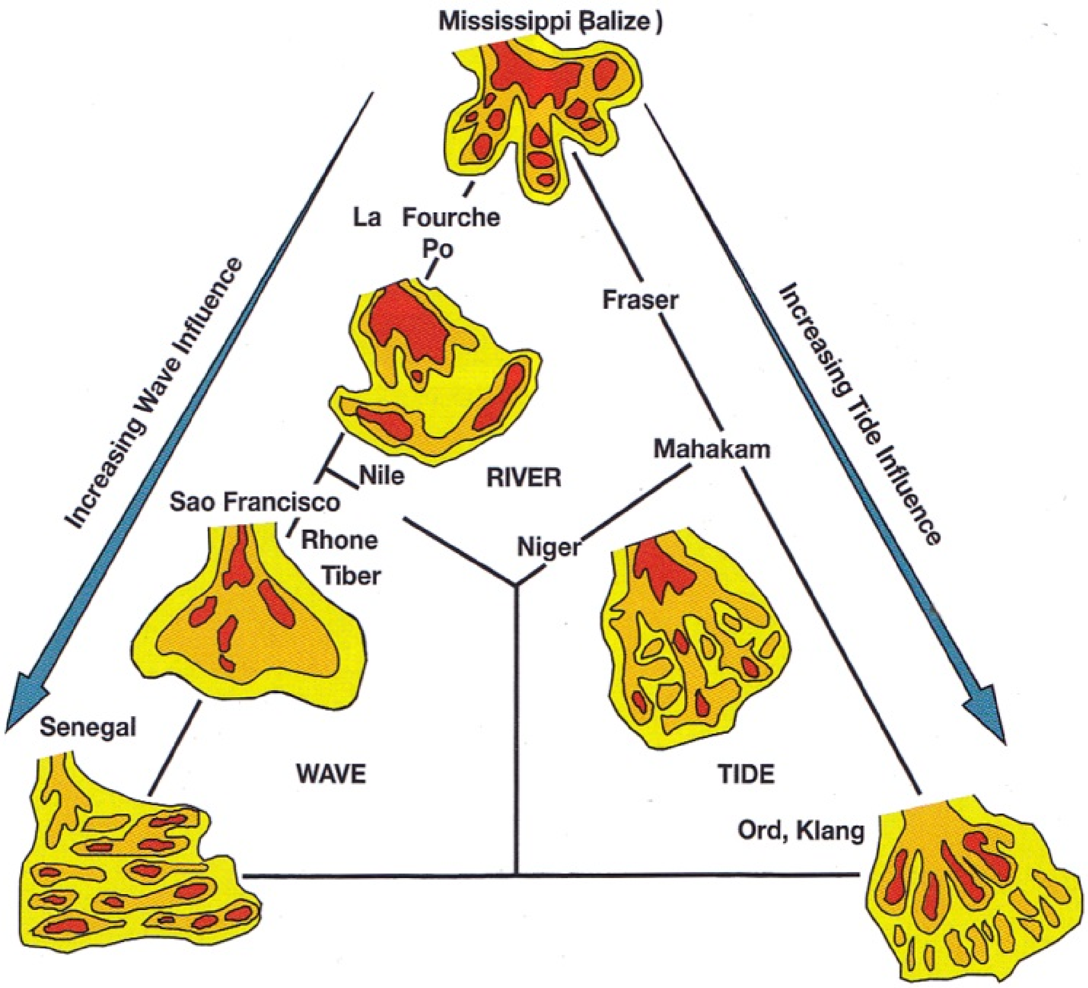


Figure 2.1 Classification of deltaic depositional systems (from Bhattacharya, 2010).

2.1.1 River-dominated Deltas

Water and sediment discharged into a lake or ocean is known as jet. Based on the behaviour of sediment-laden river water as it enters equal, denser and less dense basin water, Bates (1953) defined three types of flows. He established that if river water enters a basin with almost the same density, a homopycnal flow is present. If river water has higher density than the basin water, the river flows beneath the basin water, commonly during floods, generating hyperpycnal flows. In contrast, if river outflow is less dense than basin water, as when rivers flow into denser seawater or saline lake, the flow moves outward on top of the basin water as a horizontally oriented plane jet, and is known as hypopycnal flow.

Wright (1977) proposed that the delivery of sediments at the river-mouth in coastal areas with low tidal range and low wave-energy areas varies according to (a) outflow energy (velocity), (b) turbulent bed friction seaward of the river mouth, and (c) outflow buoyancy. If outflows are dominated by inertial forces, a narrow river-mouth bar of Gilbert type is formed. Inertial-dominated river mouths form where the slope is steep enough to allow expansion of the inflow in both the horizontal and vertical direction. This expansion commonly occurs where high-velocity rivers enter a freshwater body and/or carry substantial quantities of coarse-grained sediment (Orton and Reading, 1993). In contrast, if outflows are dominated by turbulent friction, a triangular “middle-ground” bar and channel bifurcation are developed. Friction-dominated river mouths occur where rivers enter water at very shallow depths so that the inflow can expand only in a horizontal direction (Orton and Reading, 1993). In addition, buoyant outflow generates elongate distributary channels with parallel banks which are known as subaqueous levees; few channel bifurcations; and narrow distributary-mouth bars that grade seawards to fine-grained distal-bar sands and prodelta clays. Bouyant dominated river mouths occur where the inflow extends as a plume (hypopycnal flow) into relative deep, generally marine waters (Orton and Reading, 1993).

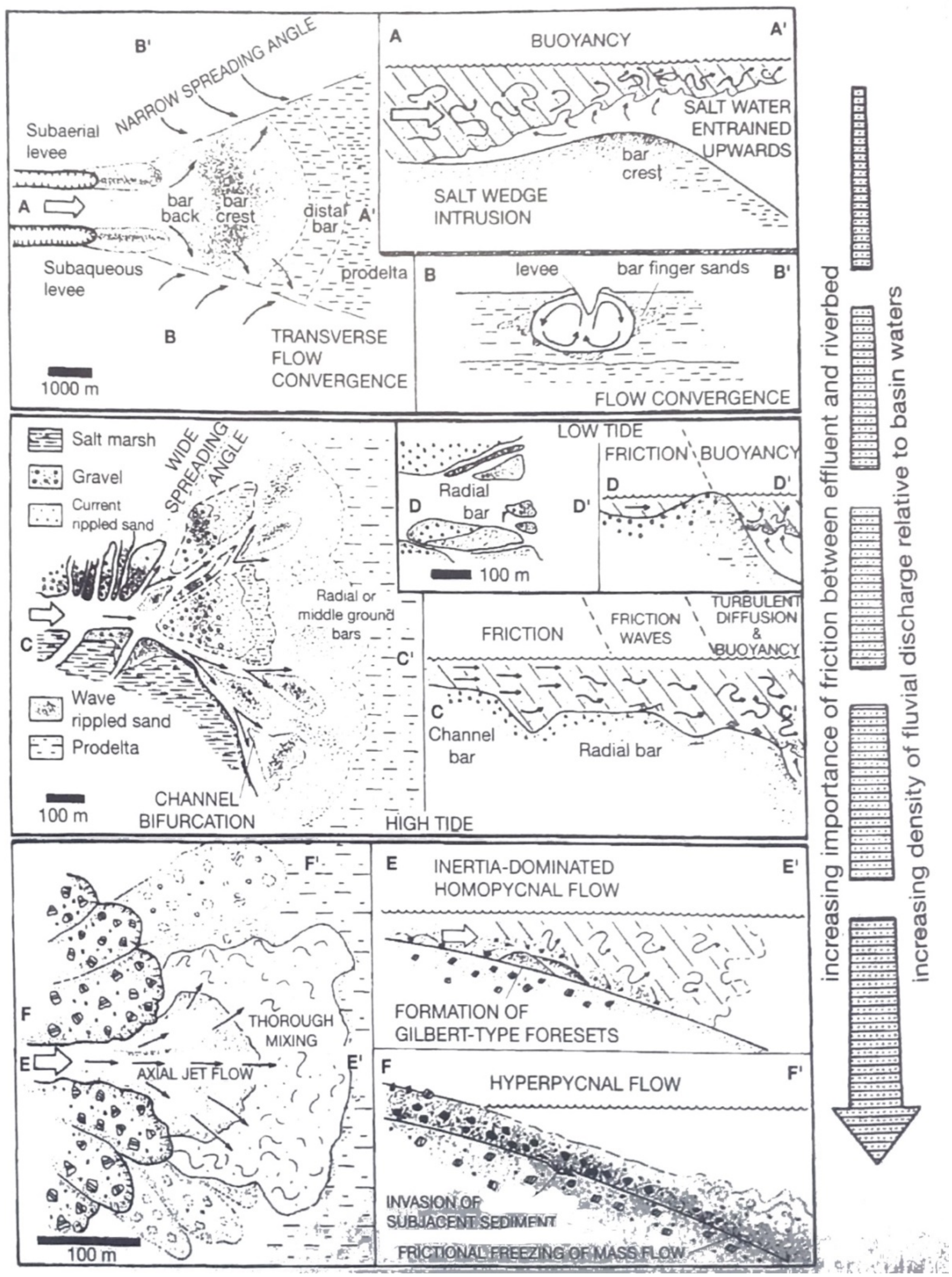


Figure 2.2 Schematic depiction of the complex relationship arising from sediment grain size, river outflow inertia (velocity), outflow friction with the bed, and outflow buoyancy. This represents the relationship between the kind of sediment load and the type of outflow that is dominant (from Wright, 1977).

2.1.2 Tide-dominated Deltas

Many processes and deposits may be modified if conditions of high tidal range or high wave energy are reached. If tidal currents are stronger than river outflow, 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 platform (Boggs, 2006; Bhattacharya, 2010).

Willis (2005) suggested several reasons why studies of river deltas influenced by tidal currents are less commonly recorded in the literature than wave-influenced deltas: (a) geoscientists cannot agree how to differentiate between estuary, delta, and tide-influenced environments systems in general; (b) deposits in tide-influenced environments are difficult to recognize; (c) unlike waves, tidal currents may extend their influence landwards into the distributary channel, and seawards in deeper-water areas below fair-weather wave base that lie beyond the delta front; (d) case studies from modern tide-dominated environments are scarce; (e) those who have worked in ancient deposits believe that tidal influence happens only during transgression within an estuary or upon eroding a delta top; and (f) key stratigraphic surfaces are difficult to recognize because of the abundance of autocyclically generated surfaces, complicating the establishment of large-scale sequence-stratigraphic divisions. Most studies in these settings have been made during the last ten years, but that research may yield insights into the complex array of subenvironments and the wide range of facies variability (Willis, 2005; Bhattacharya, 2010; Goodbred and Saito, 2012).

Tidal currents produce extensive erosion of river-supplied sediment in mesotidal and macrotidal settings. Tidal currents affect the river mouth, creating a series of straight to softly sinuous coast-normal tidal channels that are divided by elongated tidal bars (Dalrymple and Choi, 2007). Deposits formed under the influence of tidal currents are generally more heterolithic than those formed during river floods because tidal currents fluctuate over shorter time-scales (Willis, 1999).

2.1.3 Wave-dominated Deltas

Bhattacharya and Giosan (2003) reviewed modern deltas and demonstrated that wave-influenced deltas show different degrees of asymmetry in morphology and facies. A formula to evaluate the degree of asymmetry in wave-dominated deltas (A) was defined as the ratio between longshore transport rate (m^3 year $^{-1}$) and river discharge (Q in 10^6 m^3 month $^{-1}$), which helps explain the interaction between marine and fluvial interactions at the mouth of a deltaic distributary. In addition, this provides a tool to predict facies architecture that may be used in interpreting ancient depositional systems. Less mud is associated with the updrift areas, and this should lead to relatively sandy and potentially sharp-based shoreface deposits that may represent good targets for exploration. Figure 2.3 shows delta morphologies corresponding to different values of the asymmetry index (A).

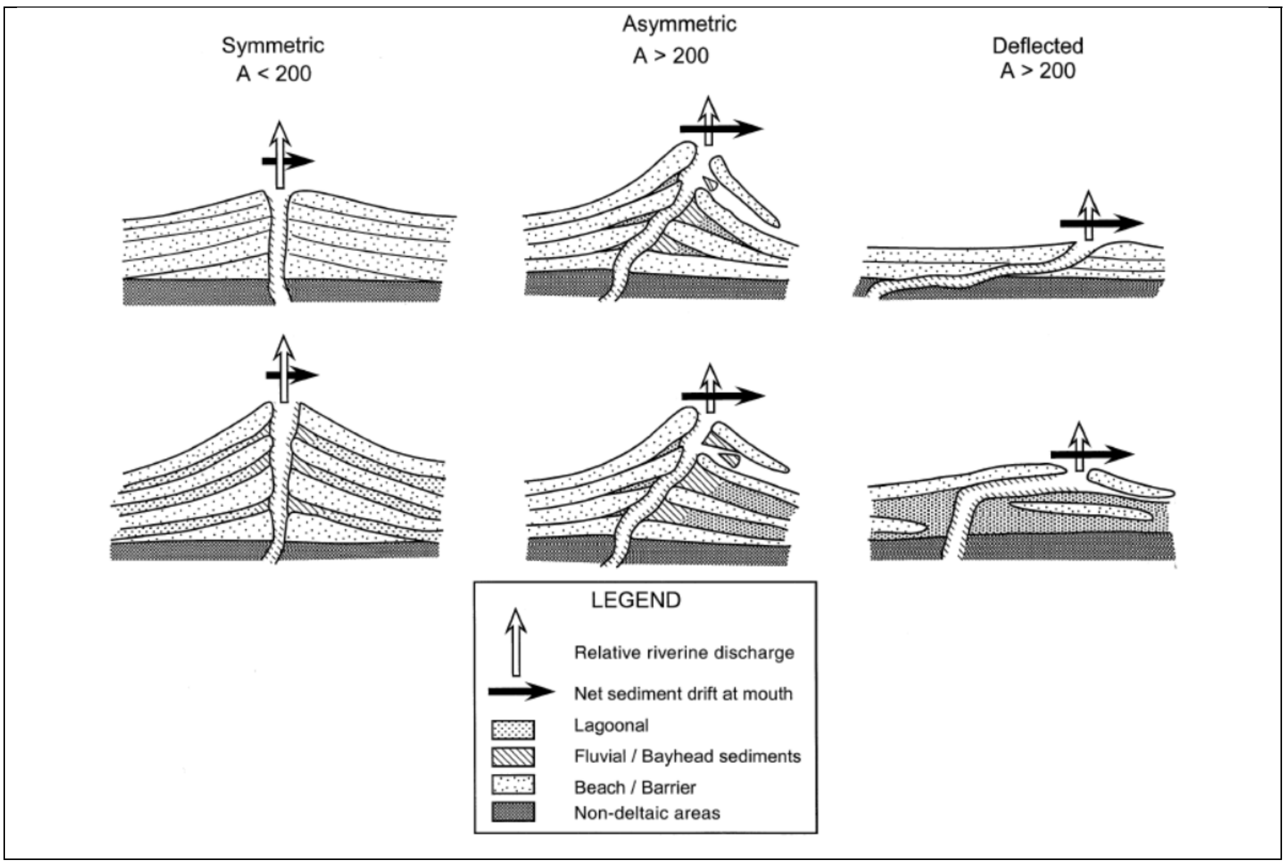


Figure 2.3. Morphology of wave-influenced deltas. Top row represents lower river discharge than bottom row. The river discharge plume acts a `groyne´ that traps sediments updrift (from Bhattacharya and Giosan, 2003).

The present of strong waves causes rapid diffusion and deceleration of river outflow, resulting in constricted or deflected river mouths. Distributary-mouth deposits are reworked by waves and are redistributed along the delta front by longshore currents to form wave-built shoreline features, such as beaches, barrier bars, and spits. A smooth delta front, consisting of well-developed, coalescent beach ridges may eventually be generated (Boggs, 2006; Bhattacharya, 2010).

2.2 Estuaries

Pritchard (1967) considered that the definition of an estuary should cover the following aspects: the distribution of salinity and density, circulation pattern, and the mixing processes. He therefore defined an estuary as “a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage”. A new approach was introduced later by Dalrymple et al. (1992), who defined an estuary as “the seaward portion of a drowned valley system which receives sediment from both fluvial and marine sources and which contain facies influenced by tide, wave and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies at its head, and up to the seaward limit of coastal facies at its mouth” (Figure 2.4). This definition is markedly different from Pritchard´s, de-emphasizing the importance of salinity and underscoring the distribution of facies and the role of tides. Dalrymple et al. (1992) defined two distinct but intergradational types of estuaries (wave- and tide-dominated). These facies models and their conceptual basis provide a practical means of highlighting the differences and similarities between estuaries. The infill of estuarine systems was regarded as highly predictable, resulting in a well-defined sequence-stratigraphic framework (see also Zaitlin et al., 1994). Subsequently, Dalrymple (2006) modified his earlier definition, stating that an estuary is a “transgressive coastal environment at the mouth of a river, that receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes. 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”. Dalrymple (2006) introduced this modified definition because he considered that the previous one was too restrictive for the study of ancient systems. In this new definition, the need of an incised valley is removed and deltaic distributaries flooded during a transgression are considered estuaries.

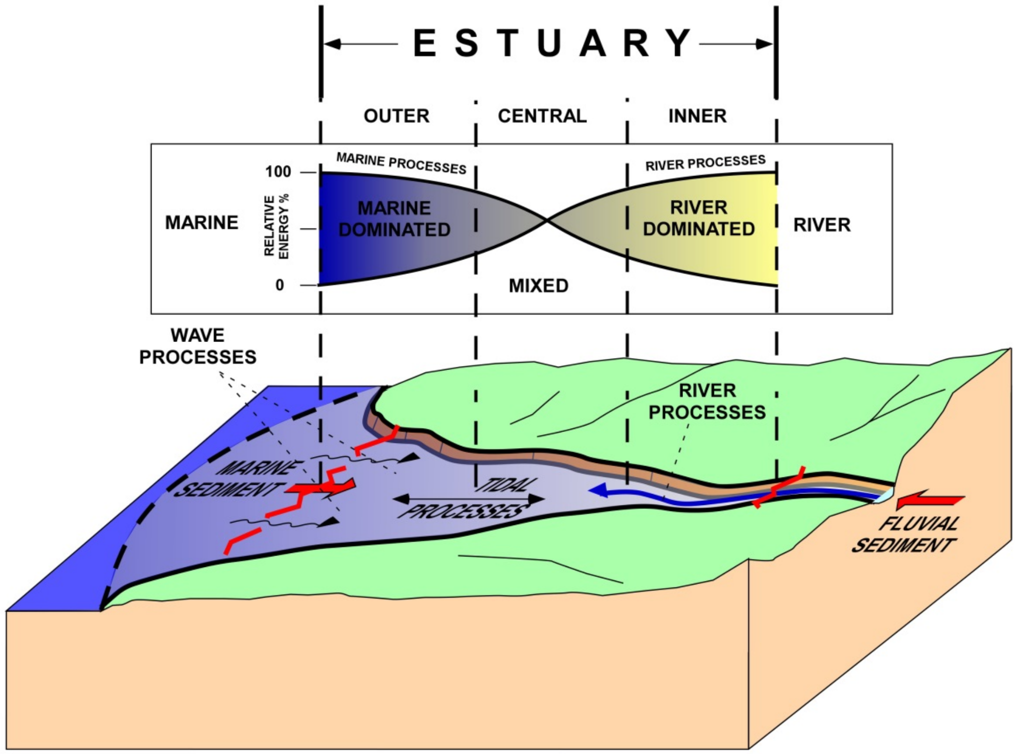


Figure 2.4 Block diagram showing subdivisions and depositional processes operating in an estuary (from Dalrymple et al., 1992).

2.2.1 Wave-dominated Estuaries

Dalrymple et al. (1992) subdivided wave-dominated estuaries into three zones that essentially reflect an energy gradient. A wave-dominated estuary displays a well-defined tripartite zonation: a marine sand body comprised of barrier, washover, tidal inlet and tidal delta deposits; a fine-grained (generally muddy) central basin; and a bay-head delta that experiences tidal and/or salt-water influence. In wave-dominated estuaries, tides have little influence and the estuary mouth is affected by high wave energy (Marine Domain), whereas river currents have high energy towards a landward direction (River Domain). In contrast, in the middle zone of the estuary, energy levels are at a minimum with limited influence of both rivers and waves (Mixed-Domain) (Figure 2.5). Sediments are constantly moving perpendicular to the coast and onshore towards the mouth of the estuary, where a subaerial barrier or slightly submerged bar is developed.

Overall, barriers protect the estuary from incoming waves. The barrier may remain open, but it depends upon tidal range and current velocity; a number of new inlets may form. The barrier may eventually close the estuary completely, resulting in the formation of a coastal lake or blind estuary.

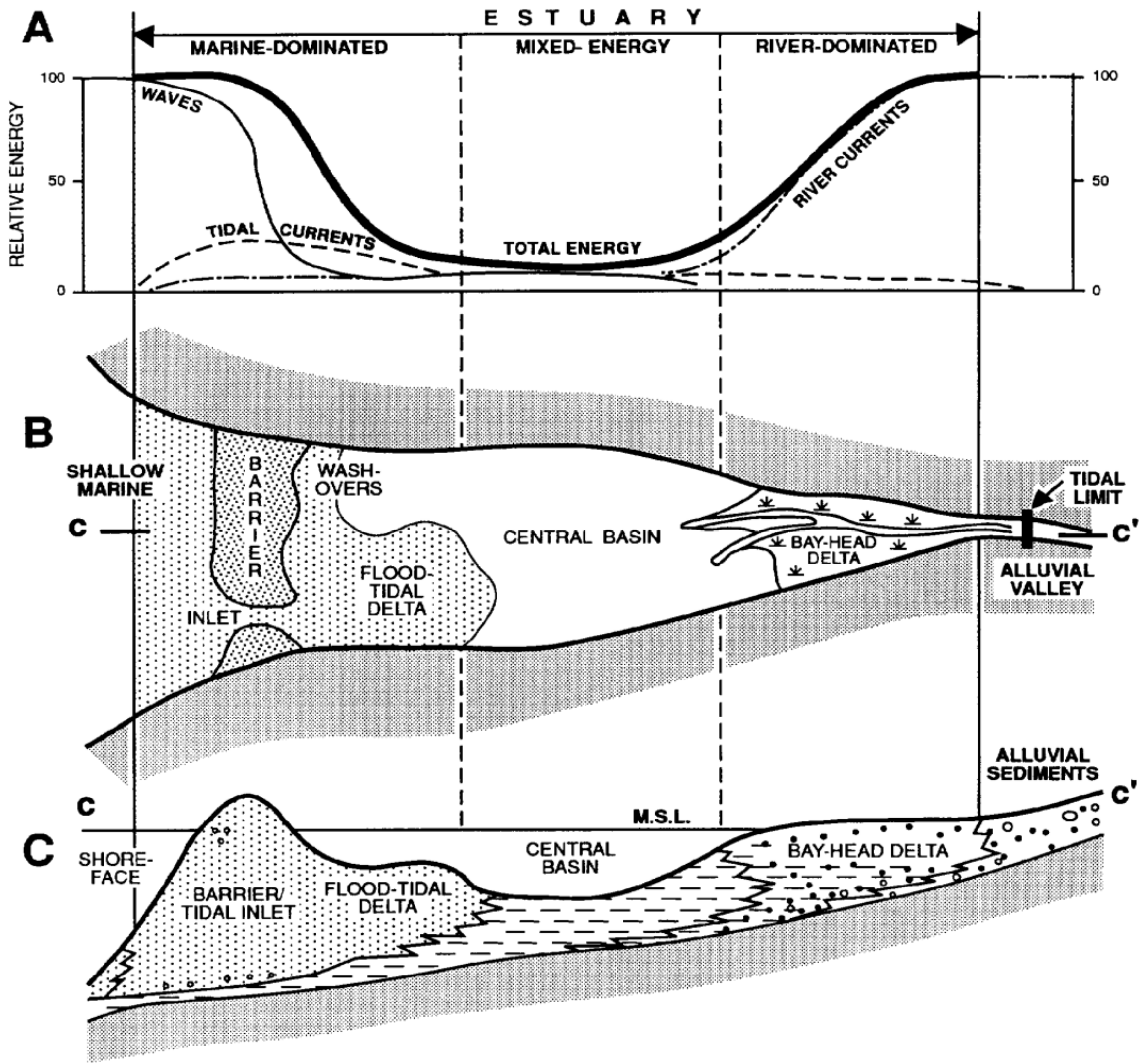


Figure 2.5. Distribution of (A) energy types, (B) morphological components in plan view, and (C) sedimentary facies in longitudinal section within an idealized wave-dominated estuary (from Dalrymple et al., 1992).

2.2.2 Tide-dominated Estuaries

All coastal systems in which there is appreciable tidal influence show the typical funnel-shaped geometry that characterizes tide-dominated estuaries. Where tidal current energy exceeds wave energy at the mouth of the estuary, a tide-dominated estuary is formed. These occur generally on macrotidal coasts. In the estuary, the water is generally mixed. In contrast to wave-dominated estuaries, 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). The equivalent of the central basin consists of a zone of tight meanders where bedload transport by flood-tidal and river currents is equal over the long term, whereas the inner, river-dominated zone has a single, low-sinuosity (`straight´) channel. A series of sand bars develop parallel to the length of the estuary from sand carried into the estuary from marine sources. These bars commonly dissipate tidal energy. In contrast, topographical constraints of tidal currents entering the estuary produce an increase in velocity for some distance up the estuary (Dalrymple et al., 1992). Figure 2.6 shows the hydrologic conditions and sediment bodies that develop in tide-dominated estuaries.

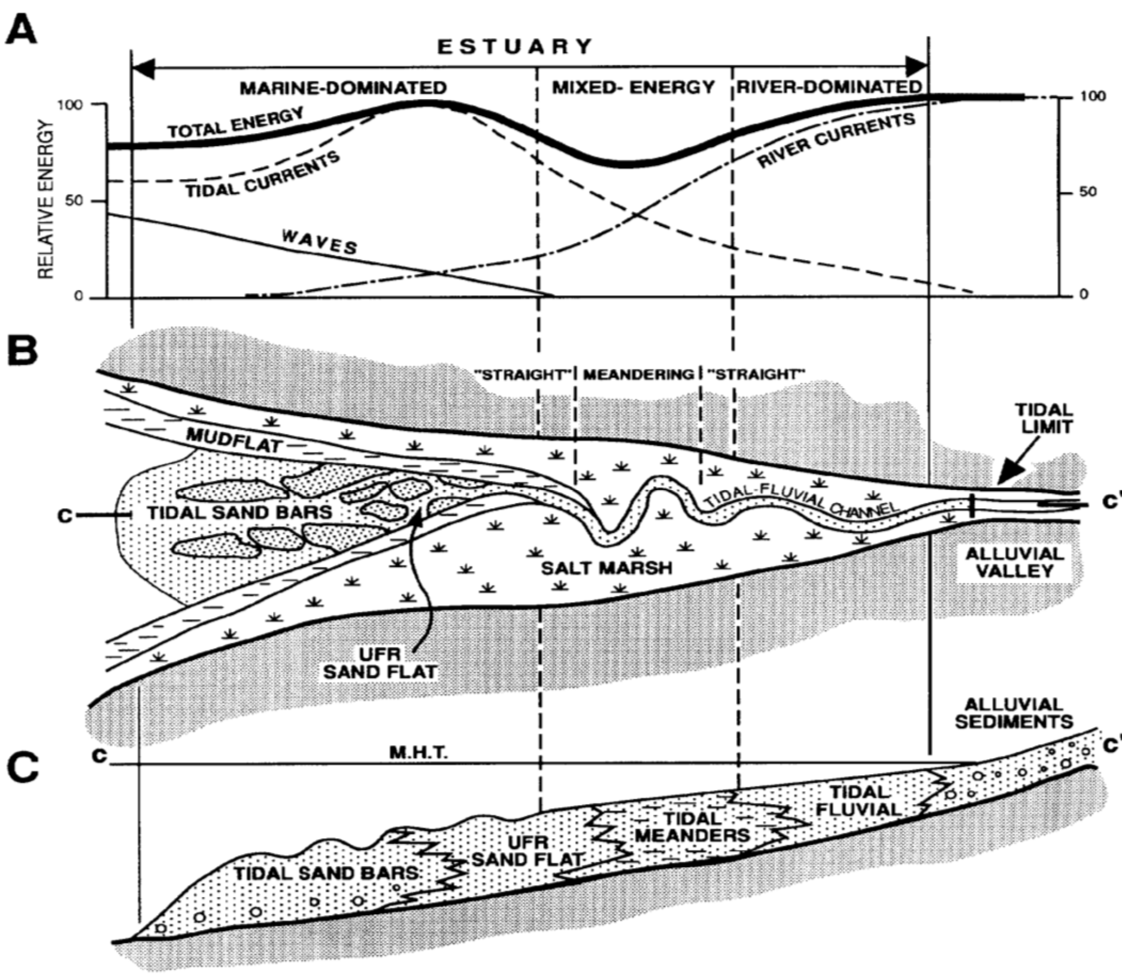


Figure 2.6 Distribution of (A) energy types, (B) morphological components in plan view, and (C) sedimentary facies in longitudinal section within an idealized tide-dominated estuary. URF= upper flow regime; M.H.T.= mean high tide (from Dalrymple et al., 1992).

2.3 Shoreline Trajectories

To obtain information about the distribution of lithofacies along the shoreline (Figure 2.6A), and the stratal stacking patterns within individual systems tracts and depositional sequences, it is necessary to know the role of the coastline trajectories and the space available for sediment accumulation (i.e. accommodation). With rising relative sea-level, a retrogradational stacking pattern is created. The shoreline is thus shifted landward, resulting in a transgression, whereby the distal sedimentary facies are deposited over the proximal ones (Figure 2.6B). On the other hand, both during the relative sea-level fall or during a rising relative sea-level that is outpaced by rate of deposition, a progradational stacking pattern is formed, and the proximal facies are deposited over the distal facies and the shoreline moves seawards resulting in regression. Consequently, progradation covers parts of the shelf or offshore edge (Figure 2.6.C) (Catuneanu, 2006).

Helland-Hansen and Martinsen (1996) defined five types of shoreline trajectories, namely accretionary and non-accretionary forced regression; normal regression; and accretionary and non-accretionary transgression. By “accretionary”, they mean that sediment provided to the shoreline takes part in defining the shoreline trajectory, and `non-accretionary´ implies that the existing topography guides the trajectory.

A forced regression takes place when relative sea level is falling at the shoreline (Posamentier et al., 1992). The shoreline moves seaward and obliquely downward. Above sea level, channel down-cutting, and valley incision probably happen in the downstream end of the alluvial systems as the fluvial channels attempt to adapt to successively lower base levels. However, net fluvial aggradation during a falling relative sea level may occur if the shoreline trajectory during forced regression has a gradient lower than that of the alluvial plain (Muto, 1988; Cant, 1991; Posamentier et al., 1992; Nummedal et al., 1993). According to this model, low shoreline trajectory gradients during an accretionary forced regression might be caused by slow rates of fall of relative sea level or very high sediment supply. In contrast, with a non-accretionary forced regression, a falling relative sea level in a shelf with a gradient lower than that of the graded alluvial profile allows alluvial accumulation on the former shelf. At and below sea level, the overall rate of sediment supply might be large during falling relative sea level, particularly if the sea-level fall is accompanied by source-area uplift. A sea-level fall exposing a horizontal or nearly horizontal surface also causes a non-accretionary forced regression, regardless of the rate of sediment supply. During falling relative sea-level, when sedimentation shifts to the basin floor, a non-accretionary forced regression happens at the shoreline. An accretionary forced regression occurs because sediment supply is significant during falling relative sea level, with a gradual downward move of the shoreline (Weller, 1960; Wilkinson et al., 1975; Vail et al. 1977). Most likely, non-marine sediment transport is restricted to a few large incised channels that terminate as discrete point sources where entering the receiving basin.

A normal regression happens during stable or rising relative sea level because the rate of sediment supply exceeds the rate of accommodation generated at the shoreline (Posamentier et al., 1992). As a consequence, the shoreline builds seaward horizontally or obliquely upward. Normally, a coarsening- and shallowing-upward succession is constructed. A t**ransgression** occurs because the rate of increase in accommodation is greater than the rate of sediment accumulation at the shoreline, which migrates landward. A transgressive erosional surface of reworking and redeposition normally separates shoreface and shelf sediments above the surface from the underlying sediments. This landward-migrating surface is named the "ravinement surface", which is built by wave action along at the retreating shoreface (Swift 1968; Nummedal and Swift, 1987; Demarest and Kraft, 1987). Non-accretionary transgression shows that the trajectory of the retreating shoreline is close to the subaerial surface that existed landward of the shoreline at the onset of transgression. Therefore, the overall angle of facies migration is calculated by the slope of the transgressed surface. Accommodation does not originate at the landward side of the shoreline during non-accretionary transgression, but it might be present during the original period of transgression (e.g., as bays, lagoon, coastal lakes). Accretionary transgression implies that the transgressing shoreline climbs stratigraphically upward and landward because of sediment supplied from the landward end of the system. Therefore, the shoreline trajectory diverges relative to the alluvial depositional surface at the onset of transgression. Accommodation is continuously created and filled behind the retreating shoreline.

As the shoreline moves in different directions through time, including variable composite stacking patterns with changing overall trends, some levels of erosion, slow deposition, or non-deposition of regional extent are formed (e.g., subaerial unconformities, maximum flooding surfaces, maximum regressive surfaces, ravinement surfaces, regressive surfaces of marine erosion, and depositional cycles), many becoming key stratigraphic markers. The maximum flooding surface is the most useful for cycle delineation in alternating regressive and transgressive successions because it is less likely to be modified or removed after its formation than the subaerial unconformity and the maximum regressive surface. If the subaerial unconformity is not protected by onlapping alluvial strata, it may be modified or removed during a later transgression and replaced by a ravinement surface, which is a useful surface for delineating depositional cycles in some cases. Specifically, to maintain chronostratigraphic significance, only those sediments accumulating on the seaward side of the retreating shoreface can be preserved during transgression.

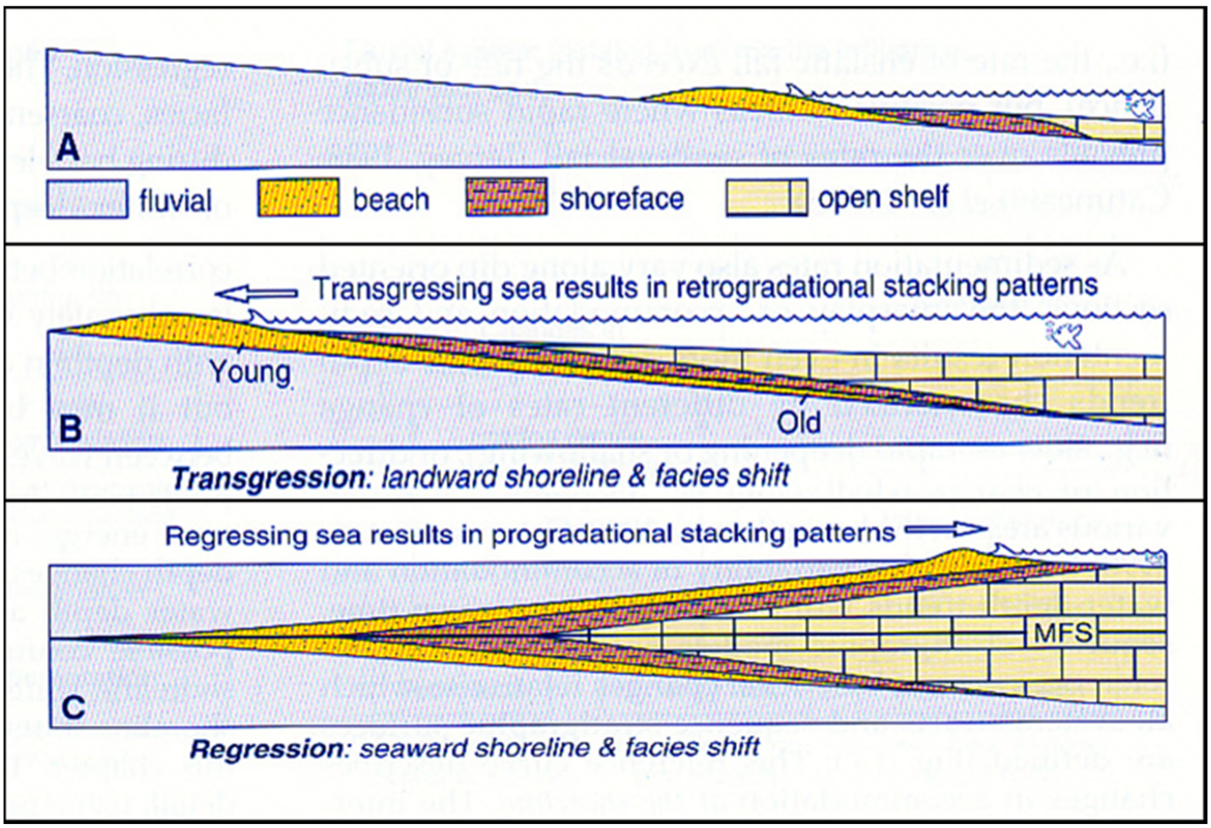


Figure 2.7 Regressions and transgressions. Shoreline trajectory and facies change according to sea-level rise and fall (from Catuneanu, 2006).

Marginal-marine, especially river-mouth depositional environments, are controlled by processes taking place in both marine and fluvial settings. However, such environments are also intermittently influenced by tidal cycles, storms, and seasonal flooding during both transgressive and regressive periods. Figure 2.8 shows a classification of the different depositional environments, their physiographic distribution, types of subenvironments associated with changing relative sea-level, fluctuating sedimentation rate, and the boundaries among the subenvironments (Catuneanu, 2006).

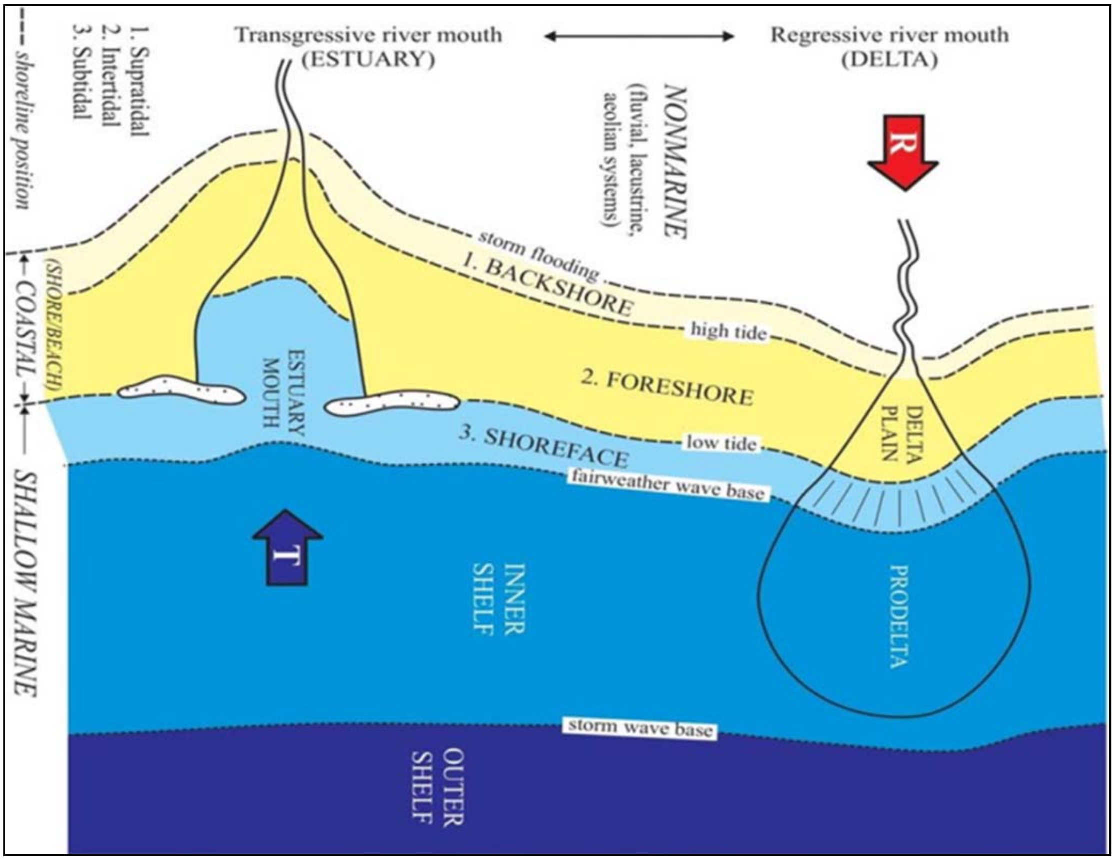


Figure 2.8 Transition from marine to nonmarine environments (from Catuneanu, 2006).

2.4 Tide-Dominated Deltas vs Tide Dominated Estuaries

Dalrymple and Choi (2007) summarized the physical, chemical and biological characteristics of river-mouth settings (Figures 2.9 and 2.10).

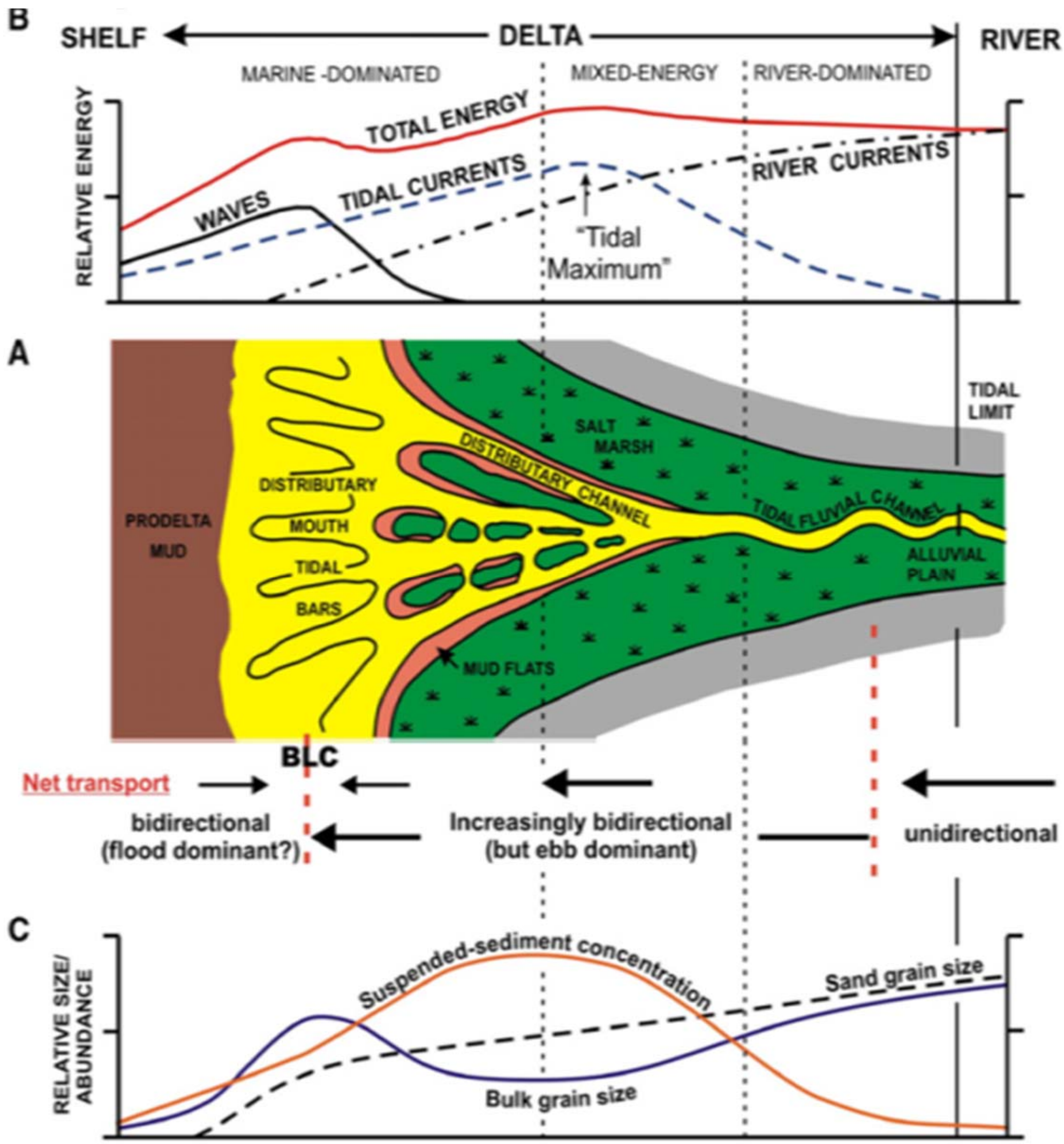


Figure 2.9 (A) Schematic map of a tide dominated delta. (B) Longitudinal variation of the intensity of the three main physical processes, river, tidal currents and waves. (C) Longitudinal variation of grain size of the sand fraction, the suspended sediment concentration and "bulk" grain size of the resulting deposits (from Dalrymple and Choi, 2007).

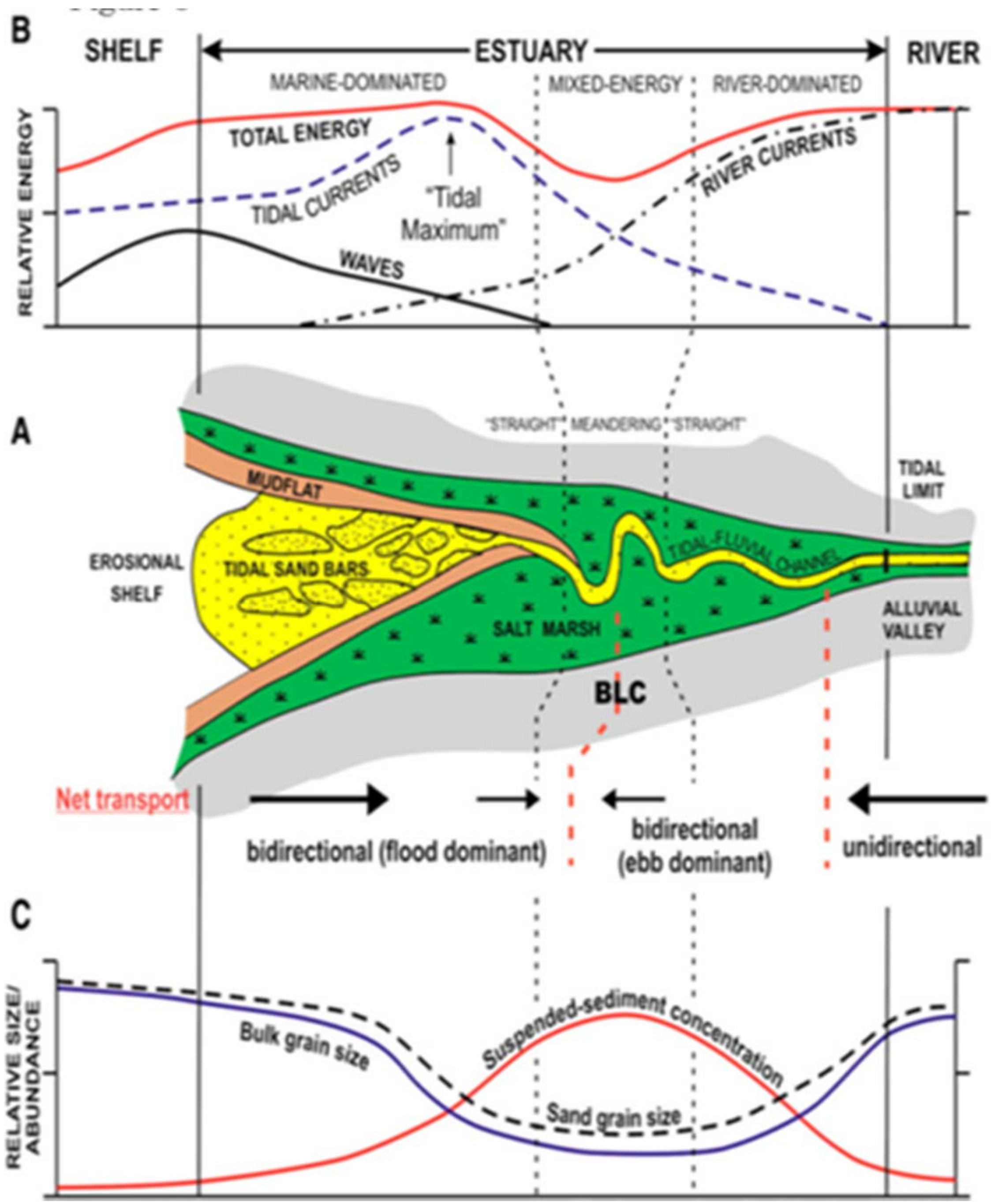


Figure 2.10 (A) Schematic map of a tide dominated estuary. (B) Longitudinal variation of the intensity of the three main physical processes, river, tidal currents and waves. (C) Longitudinal variation of grain size of the sand fraction, the suspended sediment concentration and "bulk" grain size of the resulting deposits (from Dalrymple and Choi, 2007).

2.4.1 Physical Processes

Three important physical phenomena, namely river processes, tides and waves, can fluctuate significantly in marginal-marine environments in terms of their relative influences. In addition, other factors of minor importance were not considered by Dalrymple and Choi, (2007) because they have limited impact in the studied settings (e.g., wind, ocean currents).

2.4.1.1 River currents

With their diminishing physical impact and decreasing hydraulic gradient approaching a standing water body, river-currents become progressively less effective. Additionally, water discharge is shared among many distributaries and tidal channels, reducing the strength of fluvial energy in both estuaries and deltas (Figures 2.9B and 2.10B).

2.4.1.2 Tidal Currents

Tidal currents affect both estuaries and deltas. The geomorphology of deltas and estuaries allows tidal currents to increase in strength from the sea to land, amplifying the friction between the funnel until the tidal currents reach the maximum tidal limit (Figures 2.9B and 2.10B). As a consequence, the tidal current-speed is maximum in the inner part to delta plain or in the middle of the estuary where channels bifurcate (Figures 2.9A and 2.10A).

2.4.1.3 Wave Action

Dalrymple and Choi (2007) considered that wave action in tide-dominated systems should not be ignored at the seaward end due to of the large, open-water fetch that characterizes the marine basin. Wave energy on the substrate increases landward from the shelf towards the shoreline (Figure 2.9B). Bhattacharya and Giosan (2003) proposed an alternative way to see how waves influence deltas and its geomorphological implications for facies reconstructions (see Section 2.1.3).

2.4.1.4 Resultant currents and sand transport directions

The sum of the velocities of the tidal and the river currents is the resultant current speed, although the speed of fluvial currents varies very little compared with the current speed that characterizes tidally influenced systems. The maximum limit of tides is not a fixed point, but an area that moves up- or downstream of the discharge, depending on the rivers inflow and the range of the tidal cycles.

2.4.2 Chemical Processes

Salinity increases seaward, but the mixing of freshwater and seawater are controlled by the interplay between tides and the amount of freshwater supplied. When freshwater discharge increases, the limit of salinity moves closer to the estuary mouth or seaward of the delta front; if freshwater discharge decreases, the limit of salinity influence moves upstream within the estuary or delta. Lettley et al. (2007) considered that estuarine water circulation comprises three main scenarios: salt wedge, partially mixed, and well mixed. In general, estuaries are affected mainly by fluvial flow and tidal currents, but also by waves. Denser more saline water remains at the bottom of the water body with freshwater on top of it. They mix during turbulence generated by tides. During periods of high freshwater discharge (such as diurnal periods during spring), grain size increases and the maximum extent of tides retracts towards the mouth of the estuary. In contrast, mud is deposited when the flow decreases; bed thickness then indicates the duration of the tidal cycles.

2.4.3 Biological Processes

Salinity affects the lives of organisms in transitional environments, where only a few can tolerate substantial salinity changes. Along marginal-marine environments, there are in and out water fluctuations in salinity. When freshwater discharge diminishes, salinity increases by tidal effects, producing an increase in the abundance and diversity of taxa and their size (see Buatois and Mángano, 2011, for a review). In brackish-water environments, the number of organisms decreases drastically because the biota is subjected to lower salinity-levels that are difficult to tolerate (Figure 2.11). Based on species diversity of benthic organisms, Sanders (1968) developed a hypothesis that high stability or predictability of the environment is conducive to high species diversity. Wolff (1983) outlined six key aspects of brackish-water ecosystems, which are relevant for ichnologic characterization of marginal-marine settings:

1 Many factors in brackish water environments are unstable and unpredictable;
2 Speciation in such environments is less probable than in more stable environment (Slobodkin and Sanders, 1969);

3 Extinction in such environment is more probable that in more stable environments (Slobodkin and Sanders, 1969);

4 Brackish water is a geological ephemeral phenomena, thus increasing the likelihood of disappearance of brackish water populations;

5 The number of species adapted to brackish water is lower than in their marine or freshwater counterparts, and

6 Marine stenohaline and freshwater organisms are excluded from brackish water environments because of these settings are characteristically unstable and unpredictable.

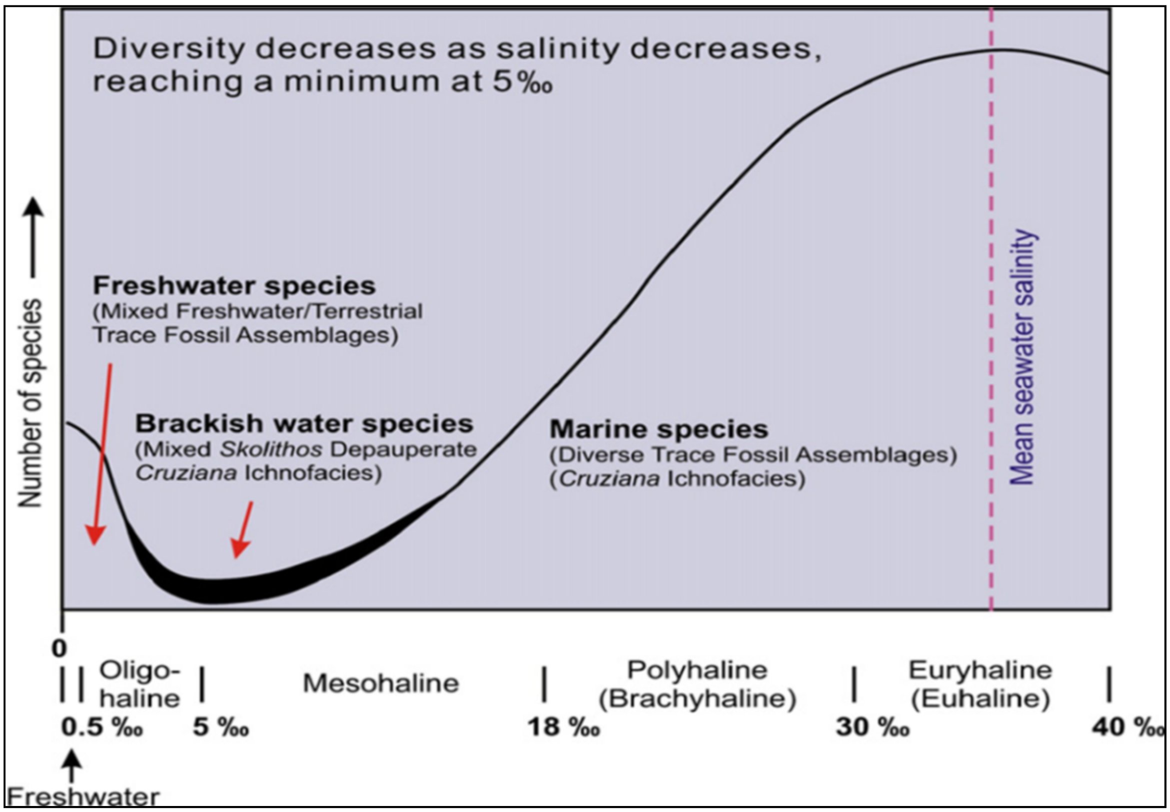


Figure 2.11 Classification of salinity levels and variation of species diversity through the freshwater to seawater transition (from Buatois et al., 1997).

3 Regional Stratigraphy and Depositional Setting

3.1 Stratigraphic Framework

This research focuses on the Oficina Formation and its lateral equivalent, the Chaguaramas Formation, in the Boyacá and Junín areas. A summary of the stratigraphy of the study area is available in the Stratigraphic Lexicon of Venezuela (Appendix I).

3.1.1 Precambrian Basement

Galavis and Velarde (1967) described the basement as igneous-metamorphic. They are part of Guayana shield, and contain highly feldespathic pink granite, granitic gneiss, and light and dark green schist. Escalona (1982) performed a petrographic analysis in a well core from the southern part of block 5 in the Boyacá area, recorded a greyish pink leucogranite forming the basement rock.

3.1.2 Paleozoic

Much of the subsurface in the Junin-Boyaca area consists of Paleozoic sedimentary rocks, mostly included in the Hato Viejo (not drilled in the Boyacá area) and Carrizal formations. Hedberg (1950) introduced and described the Hato Viejo Formation as gray-pink, light gray to dark gray fine- to coarse-grained sandstone. The sandstone is slightly calcareous, locally very micaceous and pyritic. The clasts are rounded and the rock is well cemented by quartz. Conglomerate is present locally. Calcite veins occur along fractures. Petrographically, the sandstone ranges from quartzose sandstone to feldspathic and glauconitic sandstone. The Hato Viejo Formation rests unconformably on the basement. The age of the HatoViejo Formation has long been regarded as uncertain due to the lack of fossils. However, De Di Giacomo (1985) identified lower Cambrian acritarchs in the overlying Carrizal Formation. The Hato Viejo Formation records deposition in a tide-dominated shallow-marine environment. The Hato Viejo Formation is overlaying by the Carrizal Formation that was defined by Hedberg (1942) from the Carrizal-1 well in the Anzoátegui state in the Orinoco Oil Belt. The Carrizal Formation is composed by light gray to brown shale and glauconitic medium- to very fine-grained sandstone. It is recognized in electric logs by a response in the gamma ray and spontaneous potential curves, which show intercalation of shaly sediments. Sinanoglu and Di Giacomo (1986) assigned an early Cambrian age to this unit. The Carrizal Formation was deposited in a tide-dominated shallow-marine environment.

Over Paleozoic rest Ipire Formation whose formational name was introduced by Motiscka (1985) and suggested abandonment of the name `La Quinta Formation´, proposed by Feo-Codecido (1984) to refer to these red beds. The Ipire Formation consists of irregularly alternating sandstone, siltstone, shale and locally conglomerate intercalations. Typically these deposits are reddish brown, with light gray to greenish layers in places. Arkosic sandstone has a (mainly dolomite) carbonate cement. The sandstone is fine- to very fine-grained, with angular to subangular clasts and is poorly sorted. This unit is highly variable in terms of facies. Cross-bedding, ripples, and flaser, wavy and lenticular bedding are common, reflecting flow fluctuations. Based on pollen and spores (*Corollina* spp., *Inaperturopollenites* spp., *Callialasporites* spp., *Poradeltoitos minor, Perinopollenites elatoides, Todisporites* spp., and *Vitreisporites pallidus*) from a well drilled in the Junin area, Van Erve (1985) assigned an early to late Jurassic age to the Ipire Formation. The interpreted depositional environment is fluvial and ephemeral lacustrine.

In the Eastern Venezuelan basin, rocks of Cretaceous age are represented by the Temblador Group, which rests unconformably on the Carrizal Formation. This group comprises the Tigre and Canoa formations. The Canoa Formation represents the beginning of the Cretaceous sedimentary cycle in the study area. This unit consists of conglomerate, very coarse to very fine-grained sandstone, siltstone and claystone. The latter commonly displays gray, green, yellow, brown, red, and purple gray mottling (Hedberg, 1950). Some intervals with light powdery and bluish gray mudstone contain plant remains. Van Erve (1985) assigned an Aptian-Albian age to this unit, based on pollen (*Tricolpites-Exesipollenites tumulus* zone). Hedberg (1947) suggested deposition in continental environments. The unit unconformably overlies the igneous and metamorphic basement, but locally, overlies the Hato Viejo, Carrizal or Ipire formations (Hedberg et al., 1947). The Tigre Formation consists of three members: La Cruz, Infante, and Guavinita. The La Cruz Member consists of lenticular kaolinitic coarse-grained sandstone, with minor interbedded black, carbonaceous and fossiliferous shale, passing upwards into fossiliferous black shale interbedded with calcareous, glauconitic, fine- to very fine-grained sandstone and fossiliferous shale (Patterson and Wilson, 1953). The Infante Member consists of gray limestone intercalated with dark gray shale. The Guavinita Member consists of massive, glauconitic, fine- to coarse-grained sandstone and gray to brown shale. Kiser (1987) and De Cabrera and Villain (1987) identified nannoplankton and foraminifera in wells drilled in northern

Guárico, suggesting a Turonian-Maastrichtian age. The microfauna indicates deposition in an outer shelf to slope setting (De Cabrera and Villain, 1987).

3.1.4 Cenozoic

In the Junin area, the Cenozoic units consist of the Merecure and Oficina formations, of Oligocene and Miocene age, respectively. However, in the area of Boyacá, this sedimentary cycle is represented by the La Pascua, Roblecito and Chaguarama formations (Figure 3.1).

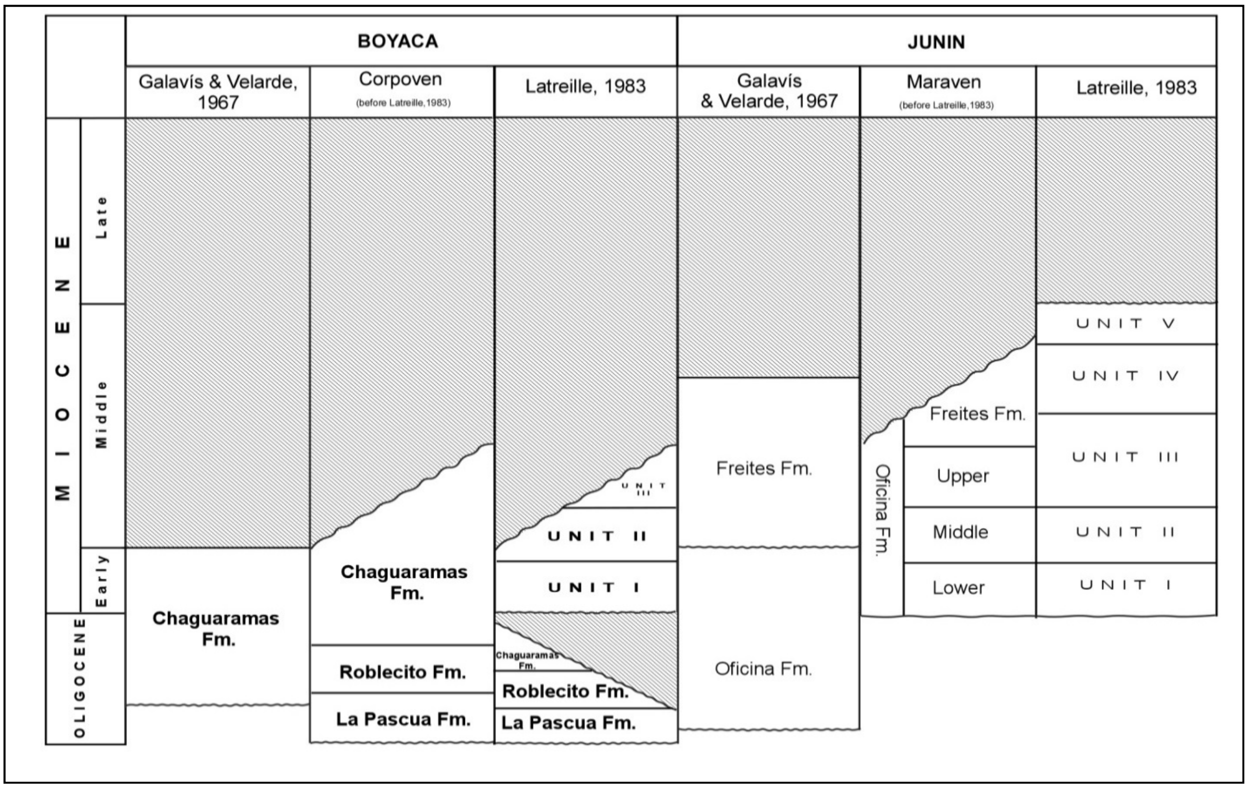


Figure 3.1 Different stratigraphic nomenclatures used in the Boyacá and Junín areas.

Based on lithostratigraphic correlation, three sedimentary cycles were defined within the Oligocene-Miocene interval in the Orinoco Oil Belt (Latreille et al., 1983; Fiorillo, 1984; Audemard, 1985; Isea, 1987). In this thesis, the lower Miocene Oficina Formation is subdivided into three members´, Lower, Middle and Upper.

Cycle 1 is represented by the La Pascua, Roblecito, and Chaguaramas formations, which rest unconformably on Cretaceous, Pre-Cretaceous or Precambrian rocks. The basal sandstone of the La Pascua Formation grades upward into a fining-upward package that culminates in a mudstone-dominated unit containing the maximum flooding interval (Roblecito Formation). The upper part of the cycle is represented by a regressive sandstone-dominated interval included in the Chaguaramas Formation or its lateral equivalent, the Oficina Formation.

The Miocene cycles were subdivided into five informal units, units I to II for Cycle 2, and units III to V for Cycle 3. Unit I is represented by a sandstone package that gradationally passes into a mudstone-dominated interval of unit II, representing a clear transgressive trend (Figure 3.2). In the nomenclature proposed here, Unit I is broadly equivalent with the Lower Member of the Oficina Formation, whereas Unit II comprises the Middle Member.

From a hydrocarbon perspective, Unit I is the most important one because of the large quantities of oil present in this sandstone-dominated interval. The contact between cycle 2 and cycle 3 is difficult to recognize, and is represented by a change in stacking pattern, resulting from the shift from the transgressive deposits of cycle 2 and the regressive sandstone of cycle 3, the latter being represented by Unit III, which is considered an equivalent of the Upper Member of the Oficina Formation. In turn, Unit IV represents the maximum flooding interval (equivalent to the Freites Formation in the northern part of the Junín Area) in cycle 3. Planktonic foraminifera from wells in the Ayacucho (Ex-Hamaca) and Carabobo (Ex-Cerro Negro) areas, indicate an Early Miocene age and a neritic environment for the Freites Formation and Unit IV (Audemard et al., 1985). This cycle culminates with the regressive sandstone of unit V (Figure 3.2).

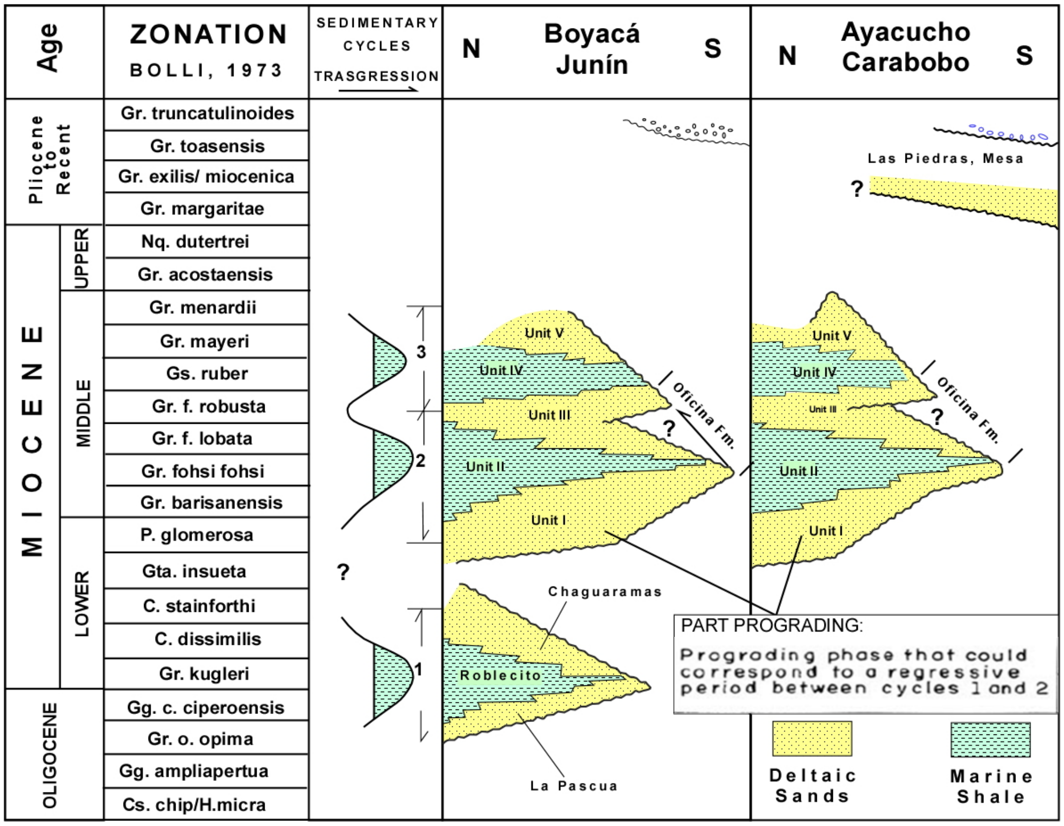


Figure 3.2 North-south distribution of the lithostratigraphic nomenclature and age of the sedimentary cycles in the Tertiary of the Orinoco Oil Belt (from Latreille et al. 1983).

4 Study Area and Methodology

The study area encompasses two blocks from the Boyacá area and four blocks from the Junín area (Figure 1B). These blocks are situated towards the west, near to the production fields (PetroCedeño and PetroAnzoátegui) in the Orinoco Oil Belt, but they do not produce oil themselves. The database consists of 100 wells, six of which were cored in the Oficina Formation or its lateral equivalent (Chaguarmas Formation), and were made available for this study (Figure 1.1C and Appendix II). Resistivity, density, neutron and gamma ray geophysical well logs were used to correlate the main tops and facies associations in the Oficina Formation. 2D Seismic lines (6000 km) were reviewed and five seismic tops were interpreted and integrated for correlating well logs, for creating maps based on these stratigraphic correlations. More than 792 m of well cores were studied in detail to identify lithology, physical sedimentary structures, bed boundaries, and trace fossils. Core data were used to calibrate geophysical well-log attributes. Fifty three samples were analyzed for palynology.

The degree of bioturbation was assessed following Taylor and Goldring (1993), based on a previous scale by Reineck (1963). A sedimentary unit characterized by no bioturbation (0%) corresponds to a bioturbation index (BI) of 0. Sediments that display sparse bioturbation with few discrete traces equal BI 1 (1 to 4%). Low bioturbation in deposits that still have preserved sedimentary structures equals BI 2 (5 to 30%). BI 3 (31 to 60%) refers to sediment with discrete trace fossils, moderate bioturbation, but still distinguishable bedding boundaries. A BI of 4 (61 to 90 %) is characterized by intense bioturbation, high trace-fossil density and common overlap of trace fossils, with primary sedimentary structures mostly erased. Deposits with completely disturbed bedding and showing intense bioturbation have a BI of 5 (91 to 99 %), and completely bioturbated and reworked sediment, owing to repeated overprinting of trace fossils would have a BI of 6 (100%).

4.1 Facies and Facies Associations

Based on grain size, sand/mud ratios, physical sedimentary structures, bed boundaries and trace fossils, eight facies (FA-FH) have been identified in the Oficina Formation (Table 1). In turn, FB has been subdivided in two subfacies (FB_1 and FB_2) and FF in four subfacies (FF_1 to FF_4). Based on stacking patterns and genetic relationships, five facies associations (FA1-FA5) (Table 2) were

Table 1 Summary of descriptions and interpretations of the nine facies defined in the Boyacá and Junín areas.

Facies	Sub-facies	Texture	Physical Sedimentary Structures	Ichnology	Thickness (m)	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	0.1-0.5		Lag deposits, cut bank margins of meandering estuarine channels
FB Cross-Stratified very coarse- to medium-grained sandstone	FB1 Planar, cross-stratified sandstone with granules	Very coarse- to medium-grained sandstone with dispersed granules, poorly sorted	Planar cross-stratification	No trace fossils	6-12	Locally parallel-laminated mudstone, generally oil impregnated.	Braided fluvial channels
	FB2 Trough cross-stratified sandstone with pebbles and mudstone clasts	Coarse- to medium-grained gravel–rich sandstone, poorly sorted	Trough cross-stratification	No trace fossils	3-6		
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	10-15	Mudstone drapes	Tidal channels 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*	0.3-2	Mudstone intraclasts	Estuarine and distributary channel pointbars and tidal sandbars
FE Convoluted fine- to very fine-grained sandstone		Fine- to very fine-grained sandstone, well sorted	Convolute lamination	Scarce *Ophiomorpha nodosa*	0.5-1.5		Soft-sediment deformation in estuarine channels and tidal flats
FF Interbedded mudstone and fine- to very fine-grained sandstone	Sand dominated: FF1 Parallel-laminated sandstone and mudstone	Fine- to very fine-grained sandstone, well sorted, rounded clasts	Rhythmically wavy laminated to very thinly interbedded with light to dark grey mudstone	*Planolites montanus, Teichichnus rectus, Rosselia socialis, Skolithos linearis, and* escape trace fossils	0.3-4		Tidal sand to mixed flats
	Sand dominated: FF2 Muddy sandstone	Fine- to very fine-grained mixture with mudstone	Sandstone is interlaminated to interbedded with light to medium grey mudstone	*Ophiomorpha nodosa,* undeterminate bioturbation mottling	0.3-4		Tidal sand to mixed flats
	Mud 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 unit	*Bergaueria* isp., *Planolites montanus*	1-12		Tidal mud flats
	Mud dominated: FF4 Bioturbated siltstone and mudstone	Siltstone and mudstone	Massive appearance	*Teichichnus rectus*, in undeterminate bioturbation mottling	0.3-7		Tidal mud flats
FG Carbonaceous, rooted silty mudstone and thinly laminated mudstone	FG1	Mudstone	Parallel-laminated, locally current ripples and flaser bedding.	*Planolites montanus, Teichichnus rectus, Thalassinoides* isp.,	3-4	Syneresis cracks, abundant organic debris, root trace fossils and scarce mudstone clasts	Outer-estuary margin
	FG2	Mudstone and siltstone	Parallel- laminated, light gray	*Beaconites antarcticum, Planolites montanus*	0.3-1.2	Siderite nodules and bands, desiccation cracks	Floodplains and interdistributary bays

FH Coal	Coal		*Thalassinoides* isp.	0.1-2		Swamps

defined. FA1 consists of fluvial braided-channels deposits, and is replaced upwards by estuarine meandering-channel deposits (FA2). FA3 represents tidal-flat and tidal-creek deposits, and FA4 consists of outer-estuarine sandbar deposits. The succession culminates with FA5, which represents delta-plain deposits. Sandstone classification is based on the Pettijohn (1987) scheme.

Table 2 Nomenclature of facies associations, description, interpretation, and sequence stratigraphic distribution in the study area.

<table>
<tr><th colspan="2">STRATIGRAPHIC UNIT</th><th colspan="2">FACIES ASSOCIATION</th><th>FACIES</th><th>INTERPRETATION</th><th>SYSTEMS TRACT</th></tr>
<tr><td rowspan="5">OFICINA FORMATION</td><td>Upper Member</td><td>FA5</td><td>Lower Delta Plain</td><td>FC, FD, FG2 and FH</td><td>Lower delta plain</td><td>HST</td></tr>
<tr><td rowspan="3">Middle Member</td><td>FA4</td><td>Outer Estuarine Sandbars</td><td>FC, FD, FG1 and FH</td><td rowspan="3">Estuarine complex filling incised valley</td><td rowspan="3">TST</td></tr>
<tr><td>FA3</td><td>Tidal Flats - Tidal Creeks</td><td>FC, FD, FE, FF1, FF2, FF3 and FF4</td></tr>
<tr><td>FA2</td><td>Esturine Meandering Channels</td><td>FA, FC, FD and FE</td></tr>
<tr><td>Lower Member</td><td>FA1</td><td>Fluvial Braided Channels</td><td>FB1, FB2, and FG2</td><td>Braided-fluvial channels filling incised valley</td><td>LST</td></tr>
</table>

4.2 Facies Associations: Descriptions and Interpretations

4.2.1 Facies Association 1: Fluvial Braided Channels – FA1 (Figure 4.1)

Description

Facies association 1 (FA1) is composed of erosively based, massive to high-angle planar cross-stratified, pebbly, very coarse- to medium-grained sandstone (FB1) and trough cross-stratified pebbly, coarse- to medium-grained sandstone (FB2). Typically these deposits are poorly sorted, although some intervals display good sorting. Petrographic analysis indicates that sandstones from this association are greywacke, lithrenite, sublitharenite, arkosic arenite, and quartz wacke (Medina, 2009). Mudstone content is low, although thin light gray mudstone layers locally separate cross-bedded sandstone. These sandstone units typically fine and thin upwards.

Sandstone bedsets are typically 6-12 m thick, forming amalgamated packages separated by internal erosive surfaces. Commonly the top of this facies association is marked by a sharp decrease in grain size and an increase in sorting that signal the occurrence of FA2. However, in places sandstone units culminate in 0.3-2 m thick, parallel-laminated mudstone and siltstone, locally containing root trace fossils (FG2). Also, thin (up to 2 cm thick) carbonaceous shale is rarely present. No trace fossils occur. FA1 is present in the Lower Member of the Oficina Formation. It is generally confined to paleotopographic lows on the Cretaceous unconformity in the northern part of the area and on Paleozoic and Precambrian units in the southern region.

Interpretation

The predominant coarse-grained sediments indicate high energy. The paucity of associated fine-grained deposits indicative of overbank areas suggests channels of low sinuosity in a braided fluvial system. Channel bifurcation and pebbly mid-channel bars are produced due to a local decrease in flow velocity. Channel bars are represented by thick accumulations of cross-stratified sands formed mostly by frontal accretion due to unidirectional currents. Thick amalgamation of sandstone units indicates the establishment of multi-storey channels. FA1 is interpreted as being deposited from two– (FB1) and three- (FB2) dimensional dunes that migrated along the bottoms of river channels or formed slipfaces of sandy braid bars or, more rarely, sandflat complexes (Miall, 1996, 2010). Similar channeled fluvial deposits have been recorded from the lower interval of the McMurray Formation in Alberta (Hubbard et al., 2011). Only locally is there evidence of thin floodplain and pond deposits on top of abandoned channel-fills (FG2). The root trace fossils at the top of some packages indicate brief episodes of soil formation. The general absence of trace fossils in FA1 implies that high sedimentation rates were detrimental to infaunal burrowers. In addition, freshwater conditions prevented colonization by a marine to brackish-water fauna. FA1 is identical to the fluvial-dominated braided channels facies association of Martinius et al. (2012) also recorded near the base of the Oficina Formation in the Petrocedeño Field.

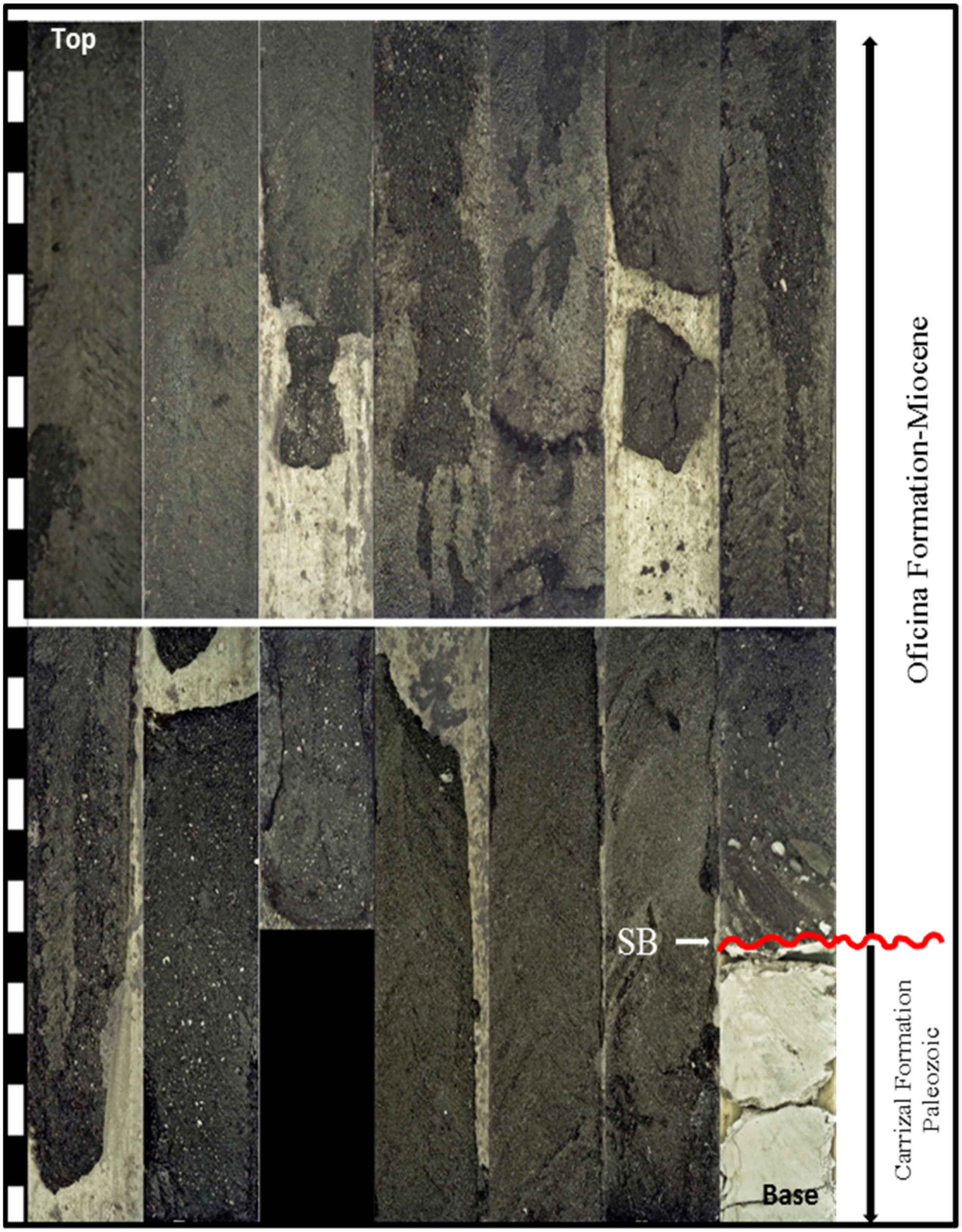


Figure 4.1 General view of Facies Association 1 (FA1). Note that sandstone is impregnated with hydrocarbon and is dark, while the mudstone is light. Core width is 10 cm. A Well, 389.5-393.5 m.

4.2.2 Facies Association 2: Meandering Tidal Channels - FA2 (Figure 4.2)

Description

Facies Association 2 (FA2) is dominated by coarse- to fine-grained sandstone and mudstone with inclined heterolithic stratification (FD). The lower part of these facies association intervals is delineated by a 0.1-0.5 m thick, mudstone intraclast breccia and poorly sorted medium- to coarse-grained sandstone (FA), mantling the erosive base of the unit. Clasts are typically subangular to subround. Maximum size of mudstone intraclasts is 15 cm. FA is sharply overlain by FD, which represents the bulk of FA2. FD is 0.3-8 m thick (average thickness 6 m). In places, trough and planar cross-bedded medium- to fine-grained sandstone with mudstone drapes are present (FC). Locally, well-sorted, 0.5-1.5 m thick, fine- to very fine-grained sandstone with convolute lamination is present (FE). Convolute deposits are locally sparsely bioturbated (BI 1-2), locally containing monospecific suites of isolated specimens of *Ophiomorpha nodosa* (Figure 4.3). Facies Association 2 occurs near the base of the Middle Member of the Oficina Formation.

Interpretation

The overwhelming dominance of inclined heterolithic stratification (IHS) implies that FA2 represents point-bar deposits formed by lateral accretion in meandering channels (Thomas et al., 1987). IHS has been described from both modern (e.g., Choi and Dalrymple, 2004; Sisulak and Dashtgard, 2012) and ancient settings (e.g., Hovikoski et al., 2008; Hubbard et al., 2011; Musial et al., 2012), almost invariably from tide-influenced channels. These channels develop in open-coast tidal flats, delta plains and estuarine settings (Dalrymple and Choi, 2006; Dalrymple et al., 2012; Goodbred and Saito, 2012). The presence of FA2 overlying the braided fluvial channels of FA1 indicates a retrogradational stacking pattern, and suggests deposition within estuarine channels. Thick amalgamation of sandstone-mudstone units indicates the establishment of multi-storey channels. The mudstone breccia represents lag deposits, and is interpreted as having been formed by traction-dominated bed load from unidirectional currents along the cut-bank margins of the channels. A similar mudstone breccia is known from the Lower Cretaceous Athabasca Oil Sands of Alberta (e.g., Hubbard et al., 2011). The overall angularity suggests limited transport (Hubbard et al., 2011). The presence of foresets with mudstone drapes further implies deposition in tidally influenced point bars (e.g., Choi et al., 2004). The trough and planar cross-bedded sandstone intervals indicate that at times channel thalwegs were characterized by the migration of 3D and 2D dunes. This may have taken place during times of high fluvial discharge that may have pushed the maximum limit of tidal action in a seaward direction. Convolute beds are common in lateral accreting estuarine channels, and are typically interpreted as resulting from loading from rapid sedimentation or slumping (Hubbard et al., 2011). *Ophiomorpha nodosa* clearly indicates marine influence and is consistent with the estuarine interpretation, indicating that FA2 was emplaced seaward not only of the maximum tidal limit, but also of the maximum salinity limit (Buatois et al., 1997; Mángano and Buatois, 2004). The overall sparse bioturbation implies very narrow colonization-windows due to rapid sedimentation. FA2 is identical to the inclined heterolithic meandering channel facies association of Martinius et al. (2012), recorded in the middle interval of the Oficina Formation in the Petrocedeño Field.

Figure 4.2 (A). General view of Facies Association 2 (FA2). C well from 572.1-578.8 m. **(B)** Close-ups of medium- to fine-grained sandstone, showing cross bedding and paired mudstone layers (arrow). B Well, 492.8-493.1 m. Core width is 10 cm.

Figure 4.3 General view of FA2 with convolute lamination and *Ophiomorpha nodosa* in FE. B Well, 537.3-537.9 m.. Core width is 10 cm.

4.2.3. **Facies Association 3: Tidal Flat—Tidal Creek Complex – FA3** (Figure 4.4)

Description

Facies Association 3 (FA3) consists mostly of interbedded mudstone and fine- to very fine-grained sandstone (FF). This facies comprises four subfacies that include sandstone-dominated (FF1 and FF2) and mudstone-dominated (FF3 and FF4) heterolithics. FF1 and FF3 display a well-preserved primary fabric, but FF2 and FF4 are intensely bioturbated. Subfacies FF1 consists of very fine- to fine-grained sandstone interlaminated with light to medium grey mudstone (Figure 4.4A). This subfacies is 0.3-4 m thick (average thickness: 1.5 m). *Teichichnus rectus, Planolites montanus, Skolithos linearis, Rosselia socialis,* and escape trace fossils are present. Sandstone-mudstone contacts are sharp and undulatory. Units of this subfacies show both thickening- and thinning-upwards trends. In places, wave-ripple cross-lamination and low-angle cross-lamination are present with mudstone drapes. These deposits are sparsely bioturbated (BI 0-1), containing *Skolithos linearis* and escape trace fossils. Subfacies FF2 consists of muddy, fine- to very fine-grained sandstone. This subfacies is 0.3-4 m thick (average thickness 1.5 m). Sandstone-mudstone contacts are irregular, and generally blurred by bioturbation (Figure 4.4B). Bioturbation mostly consists of indistinct mottling (BI 4-5). In addition to undifferentiated burrow mottling, discrete specimens of *Ophiomorpha nodosa* are recognized. Subfacies FF3 consists of sandy interlaminated siltstone and mudstone (Figure 4.4C) in units. 1-12 m thick (average 2 m thick). The ichnofauna consists of *Bergaueria* isp., and *Planolites montanus*. Bioturbation intensity is moderate (BI 2-3). Fine carbonaceous debris is dispersed in the silty laminae. This subfacies is a finer-grained equivalent of subfacies FF1. Subfacies FF4 consists of mudstone and silty mudstone; sandstone is an accessory component (Figure 4.4D). This subfacies is 0.3-7 m (average 3 m thick). It is intensely bioturbated (BI 4-5) containing *Teichichnus rectus*, and undifferentiated burrow mottling. Planar and trough cross-stratified medium- to fine-grained sandstone with mudstone drapes (FC) are subordinate components of FA3. FC is 2-4 m thick and averages about 3 m thick. Coarse- to fine-grained sandstone and mudstone with inclined heterolithic stratification (FD), 0.3-2 m thick (average 1.5 m thick), are locally present. In places, 0.5-1.5 m thick (average 1 m thick), fine- to very fine-grained sandstone with convolute lamination (FE) is present. This facies commonly lacks bioturbation, but *Ophiomorpha nodosa* is present locally.

Interpretation

The heterolithic and rhythmic character of most of FA3, particularly its FF, implies tidal influence. These regular alternations of sandstone and mudstone in subfacies FF1 indicate alternation of tractive sand deposition with mudstone fallout during slack-water periods (Reineck and Wunderlich, 1968; Klein, 1971). These processes are also envisaged for subfacies FF2, but with a significant overprint by bioturbation. In contrast, subfacies FF3 and FF4 record, fallout deposition of mud in a low-energy setting. Unlike to FA2, FA3 is dominated by horizontally-bedded heterolithic facies rather than inclined heterolithic stratification. The scenario envisaged for FA3 is deposition in a protected area, most likely a tidal-flat complex that flanked estuarine channels and tidal sandbars, forming a belt of fringing facies to the valley axis (Dalrymple et al. 2012). The variability in grain size reflects deposition across broad areas of the tidal flat, encompassing the lower sand flat, the middle mixed flat and the upper mud flat. Some intervals show evidence of significant wave action, resembling the wave-dominated tidal flats that have been described from modern (Yang et al., 2005, 2006, 2008; Dashtgard et al., 2009; Buatois and Mángano, 2011) and ancient (Buatois and Mángano, 2011; Angulo and Buatois, 2012; Basilici et al., 2012) environments.

The Oficina deposits resemble those described from the Korean coast, where the shallower part of the sand flat is dominated by ripple-cross lamination and low-angle cross-lamination during the winter, whereas mud drapes form during slack water in the spring (Yang et al., 2005, 2006, 2008). The tidal-flat areas represented by FF1 were locally dissected by tidal creeks; these deposits are recorded by FC and FD. The absence of lateral-accretion bedding (inclined-heterolithic stratification) in FC indicates the existence of stable tidal creeks. Limited lateral accretion would have promoted the preservation of horizontally bedded tidal-flat deposits that otherwise may have been eroded by migrating channels. However, the local presence of channel units with inclined heterolithic stratification (FD) implies that some tidal creeks were filled by point-bar deposits resulting from lateral accretion (Thomas et al., 1987). Channels with both vertical and lateral accretion have been documented in fringing facies of tide-dominated estuaries (Dalrymple et al., 2012). Convolute beds are common in intertidal areas, and are typically interpreted as having been triggered by waves, accompanied by gravity-driven downslope movements (Choi et al., 2004). The vertical replacement of estuarine-channel deposits of FA2 by those of FA3 is consistent with a general pattern of abandonment of the estuarine-channel complex. In addition, the associated ichnofauna clearly indicates a marine influence. The ichnofauna from the wave-dominated tidal-flat deposits illustrates the *Skolithos* Ichnofacies, implying wave agitation and emplacement in a setting more exposed to the open waves (Figure 4.5). The ichnofauna from the more protected, low-energy tidal-flat deposits represents the depauperate *Cruziana* Ichnofacies (MacEachern et al., 2007; Buatois and Mángano, 2011). In addition, the alternation of non-bioturbated or sparsely bioturbated deposits with intensely bioturbated subfacies implies regular changes in the intensity of stress factors, with the bioturbated deposits reflecting periods of environmental amelioration. Salinity changes might have been the key controlling factor on benthic faunas, with sparsely to nonbioturbated deposits reflecting extreme brackish-water conditions. Tidal flats develop in many coastal settings, but the depauperate *Cruziana* Ichnofacies implies formation in the estuarine valley under brackish-water conditions (Mángano and Buatois, 2004; Desjardins et al., 2012). The local presence of *Ophiomorpha nodosa* in sandstone-dominated units reflects brief colonization windows in settings characterized by rapid sedimentation and relatively high energy, illustrating the *Skolithos* Ichnofacies. FA3 is a partial equivalent of the crevasse-splay and interdistributary fines facies associations described by Martinius et al. (2012) for the middle interval of the Oficina Formation in the Petrocedeño Field.

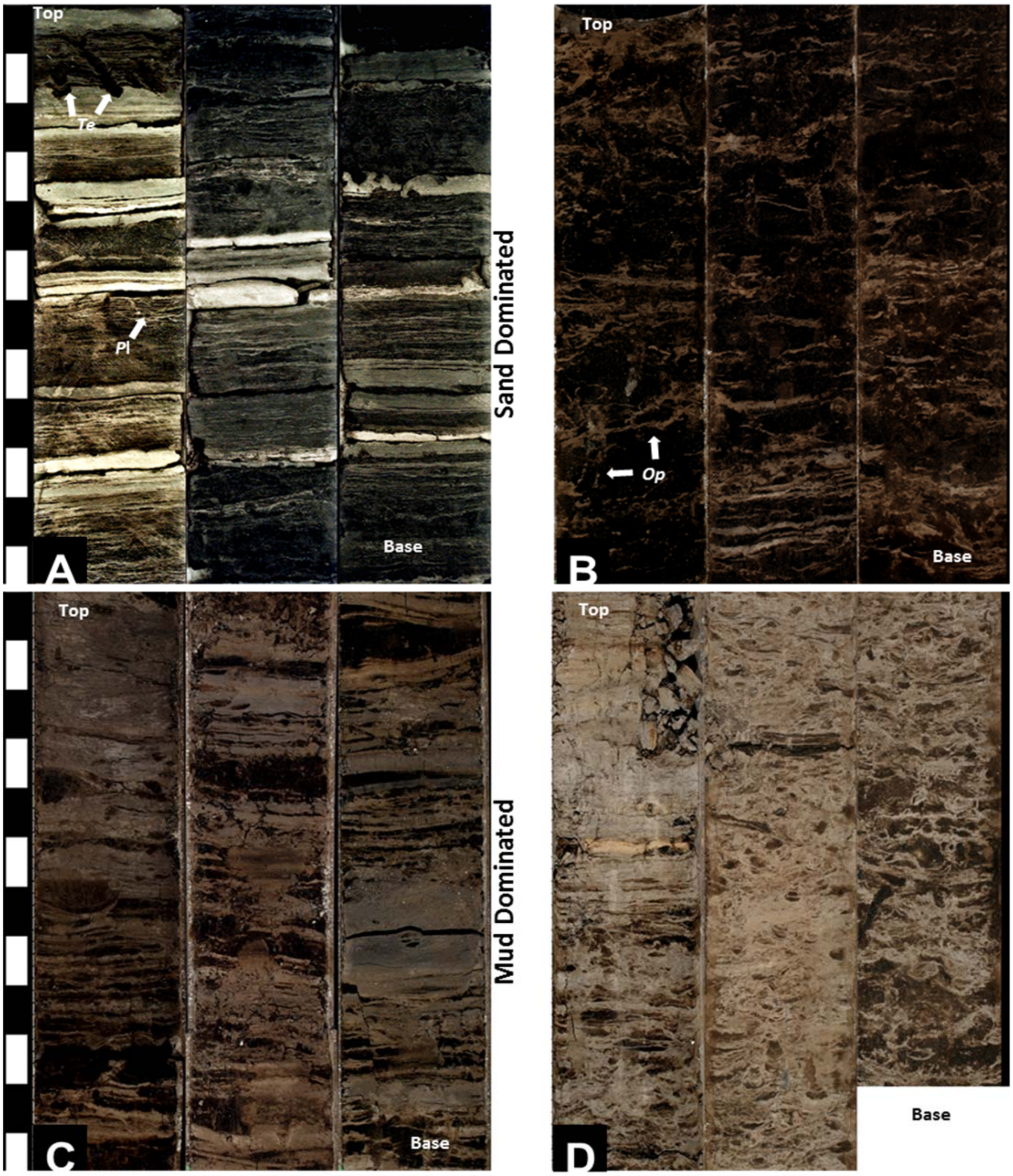


Figure 4.4. Facies Association 3 (FA3). (A) Rhythmically laminated/thinly interbedded, flaser-bedded fine- to very fine-grained sandstone and mudstone (FF1). Note low density of *Planolites montanus* and *Teichichnus rectus*. IZZ-232well, 351.4-352.3 m. (B) Moderately bioturbated, laminated/thinly interbedded, muddy sandstone and mudstone (FF2). Note horizontal segments of *Ophiomorpha nodosa*. B Well, 514.1-5148 m. (C) Thinly laminated/interbedded silty mudstone, showing low bioturbation intensity and syneresis cracks. (FF3). B Well, 435.8-436.7 m (D) Heavily bioturbated sandy mudstone (FF4) with undifferentiated burrow mottling and *Teichichnus rectus*. B Well, 542.2-542.8 m. Core width is 10 cm

Figure 4.5 Facies Association 3 (FA3). (A) General view of FF1 with *Skolithos linearis* and escape trace fossils (white arrows). Note the presence of low-angle cross lamination, wave-ripple cross lamination and mudstone drapes (B) Close-up showing escape trace fossils (white arrows) and low-angle cross lamination. B Well, 439.8-441.9 m. Core width is 10 cm.

4.2.4 Facies Association 4: Outer-Estuarine Sandbar Complex - FA4 (Figure 4.6)

Description

Facies Association 4 (FA4) is dominated by well-sorted, medium- to fine-grained sandstone and mudstone with inclined heterolithic stratification (FD) and erosive bases. This facies is thinner in FA4 (average 2 m thick) than in FA2. These deposits are sparsely bioturbated (BI 1-2), containing isolated specimens of *Teichichnus rectus* and *Rosselia socialis*, typically forming monospecific suites. Erosively based, well-sorted, trough to planar cross-bedded, medium- to fine-grained fine sandstone with mudstone drapes (FC) are also present. These sandstone units are 2-4 m thick (average 3 m thick). *Ophiomorpha nodosa* at the top of some sandstone units forms sparsely bioturbated intervals (BI 0-1). FD and FC pass upwards sharply to light grey and brown, silty and organic-rich carbonaceous mudstone (FG1) and coal (FH). Units of subfacies FG1 are 0.3-14 m (average 4 m thick). Syneresis cracks are present locally. The intensity of bioturbation in these fine-grained deposits is moderate (BI 3-4), with *Planolites montanus* *Teichichnus rectus*, and root trace fossils present. Towards the top of the FA4 interval *Thalassinoides* isp. is present, penetrating from an overlying erosive surface into the mudstone. In some cores, a 0.12 m coal layer (FH) is present at the top of the FA4 interval. A monospecific suite of *Thalassinoides* isp. is present in this coal layer.

Interpretation

FA4 reflects high rates of deposition, high energy and rapidly migrating bedforms, as recorded by FC and FD, and the low-energy sedimentation dominated by suspension fallout which locally alternates with bed-load transport and deposition, represented by FG1. Integration of sedimentologic, stratigraphic and ichnologic evidence implies deposition in an outer-estuarine sandbar complex flanked by tidal flats along the margins of a valley. The outer zone of the valley axis was characterized by free-standing tidal bars that accreted laterally (Dalrymple et al., 1992, 2012; Longhitano et al., 2012). The thick mudstone beds show that deposition of FA4 took place near the maximum turbidity because mud thickness increases towards the turbidity maximum zone and decreases towards the tidal-fluvial transition, where sand beds are thickest at the landward limit of tidal influence (Lettley et al., 2007; Dalrymple et al., 2012; La Croix and Dashtgard, 2014). Although the turbidity maximum is typically near the tip of the salt wedge, the broader zone of elevated turbidity and high suspended-sediment concentrations may stretch from the freshwater tidal zone near the tidal limit to the mouth of the estuary (Dalrymple et al., 2012). Root trace fossils indicate local development of immature soils along the valley fringes. The coal bed at the top of FA4 interval marks a time of high water-table with development of swamps under humid conditions. Ichnodiversity levels are similar to those of FA3. The ichnofauna from the low-energy tidal-flat deposits and from the tidal sandbars represent the depauperate *Cruziana* Ichnofacies (MacEachern et al., 2007; Buatois and Mángano, 2011). The more energetic channeled deposits are essentially unburrowed, but the local *Ophiomorpha nodosa* record brief colonization windows, most likely during times of inactivity in the channels. These monospecific suites are ascribed to the *Skolithos* Ichnofacies and have been described from similar brackish-water channel deposits on the Eastern Venezuela Basin (Buatois et al., 2008, 2012). In addition, the top of the FA4 interval is marked by erosive surfaces truncating swamp or mudflat deposit. They show the *Teredolites* and *Glossifungites* Ichnofacies, respectively. *Thalassinoides* isp. in these ichnofacies have been recorded in other areas of the Orinoco Belt (Buatois and Mángano, 2011). Erosional exhumation of the substrate was associated with high-energy events during the formation of a tide ravinement surface (Zaitlin et al., 1994; MacEachern and Pemberton, 1994; Buatois and Mángano, 2011). FA4 is probably an equivalent to the mouth bar facies association of Martinius et al. (2012), recorded in the middle interval of the Oficina Formation in the Petrocedeño Field.

Figure 4.6 General view of facies FC interpreted as deposits of an outer-estuarine sandbar complex. B Well, 558.3-561.1m. Core width is 10 cm.

4.2.5 Facies Association 5: FA5 – Lower Delta Plain (Figure 4.7)

Description

The lower part of the Facies Association 5 (FA5) interval is represented by fining- and thinning-upward, planar and trough cross-stratified medium- to fine-grained sandstone with mudstone drapes (FC) with erosive bases. Unlike its occurrence in FA1, where it forms thick units, this facies forms discrete, 0.6-1.3 m thick (average 1 m thick), units in FA5. Inclined heterolithic stratified coarse- to fine-grained sandstone (FD) is present, but forms thinner units (0.2-2 m thick, average 1 m thick) than in FA2. Sandstone-dominated units are separated by silty, light grey and brown carbonaceous to locally coaly, parallel-laminated to wavy-bedded, mudstone and siltstone, commonly containing root trace fossils (FG2). This fine-grained interval is 0.5-4 m thick (average is 2.5 m thick). Coal beds (FH) are common, forming 0.3-2 m thick layers (1.5 m thick average). Bioturbation is locally intense (BI 4-6), and the ichnofauna consists of horizontal *Planolites montanus* and abundant *Beaconites antarcticum*. Desiccation and syneresis cracks are present. Siderite nodules and bands (0.2-0.4 m thick) are also common. Coal layers tend to mark the top of the unit, and are more abundant near the top of the Oficina Formation. Coal beds are 0.1-2 m thick (average: 1.5 m thick). Overall, the sand/mud ratio for this interval is less than 1. FA5 makes up the Upper Member of the Oficina Formation.

Interpretation

The stratigraphic relationships with the underlying FA4 and the facies mosaic documented by FA5 imply that the latter records deposition in a lower delta-plain. The channeled deposits represented by FC and FD are interpreted as distributary channels with variable tidal influences. Although FC records migration of 2D and 3D dunes within distributary channels without tidal influence, FD represents lateral accretion in point bars within meandering tidal channels. In contrast to the channeled units of FA1 and FA2, channels in FA5 formed in many places discrete channel bodies either clustered or encased in muddy overbank deposits, but rarely amalgamated. Overall the deltaic system may be regarded as mixed tide- and river-influenced (Goodbred and Saito, 2012). The interbedded fine-grained deposits record sedimentation in floodplains and interdistributary bays. The syneresis cracks and the siderite nodules and bands are common in settings affected by fluctuating salinity (Plummer and Gostin, 1981). Waterlogged immature paleosols are indicated by root trace fossils. The abundant coal beds imply high water tables in paralic environments, such as in swamps. However, desiccation cracks indicate periods of subaerial exposure. The low sand/mud ratio of this interval implies that distributary channels were not abundant, pointing to the development of widespread wetlands region in the lower delta-plain. The monospecific suites of *Beaconites antarcticum* in the fine-grained deposits are indicators of the *Scoyenia* Ichnofacies. Therefore, some of these overbank areas were formed between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997; Buatois and Mángano, 2011). FA5 is a partial equivalent of several facies associations described by Martinius et al. (2012) in the upper Oficina Formation in the Petrocedeño Field, namely the crevasse splay, interdistributary fines, and transitional lower delta-plain to delta platform facies associations.

Figure 4.7 (A) General view of FA5. Note coal bed (FH) and sandstone encased within facies FG2**.** Inclined heterolithic stratification occurs on both top and near the bottom of core. B Well, 338.6-348.3 m. **(B)** Close up from Facies FG2 showing syneresis cracks and siderite bands.

5 Ichnology

Five ichnofacies are recognized in the Oficina Formation, the depauperate *Cruziana*, *Skolithos*, *Scoyenia*, *Teredolites*, and *Glossifungites* Ichnofacies. Their main characteristics, their distribution with respect to the facies assemblages, and environmental implications are summarized below.

5.1 Depauparate *Cruziana* Ichnofacies

Unlike to the archetypal *Cruziana* Ichnofacies of shallow-water, fully marine environments, which is characterized by a wide variety of ethological categories and high ichnodiversity and abundance, the depauperate *Cruziana* Ichnofacies, which typifies brackish-water settings, shows dramatic reduction in ichnodiversity and less variety of behavioral types (Seilacher, 2007; Frey and Pemberton, 1984, 1985; MacEachern et al., 2007; Buatois and Mángano, 2011). This ichnofacies occurs in protected areas of marginal-marine settings such as estuarine basins, bays and lagoons, where stressful conditions due to rapid fluctuations in environmental parameters inhibit benthic colonization (MacEachern and Pemberton, 1994; Buatois and Mángano, 2011).

In the cores analyzed, the depauperate *Cruziana* Ichnofacies occurs in FA3 and FA4. It is present in deposits with variable bioturbation intensities (BI = 1-5). Overall ichnodiversity is very low and only four ichnotaxa were identified (*Teichichnus rectus, Rosselia socialis, Planolites montanus* and *Bergaueria* isp.); escape trace fossils occur locally. Whereas *Rosseia socialis* and the escape trace fossils tend to occur in the sandstone-dominated intervals, *Teichichnus rectus, Planolites montanus* and *Bergaueria* isp. are present in the more heterolithic deposits.

Teichichnus (Figures 5.1.B, 5.1.C and 5.1.E) is 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 facies-crossing ichnotaxon ranging from marginal-marine to deep-sea settings, it is absent in continental environments, and is therefore a good indicator of marine influence (Mángano et al., 2002).

Rosselia is as dwelling burrow produced by detritus feeders. Nara (1995) suggested that the most likely tracemakers are terebellid polychaetes. *Rosselia* is restricted to shallow-marine settings, in both restricted, brackish-water and open, fully marine environments (Dias da Silva et al., 2014).

Planolites is a feeding burrow (Fodinichnion) of deposit feeders, probably produced by infaunal polychaetes or other worm-like organisms (Pemberton and Frey, 1982). *Planolites* is a facies-crossing ichnotaxon that may occur from continental to deep-marine environments (Pemberton and Frey, 1982).

Bergaueria represents either a permanent or semi-permanent dwelling burrow (Domichnion) or a resting trace (Cubichnion) probably produced by sea anemones (Pemberton et al., 1988). *Bergaueria* is common in fully marine conditions in either wave or tide-dominated settings, although it may also occur in brackish-water environments, albeit with generally small size (Pemberton et al., 2001).

Integration of ichnologic and sedimentologic datasets implies that the depauperate *Cruziana* Ichnofacies is present where and when connected with the establishment of an estuarine depositional system. In particular, this ichnofacies occurs for the most part in the fringing facies of the outer estuary. Presumably, the high-energy conditions and the rapid sedimentation rates that characterize the axial zone of the estuary, typified by the development of tidal channels and sandbars, were detrimental for benthic colonization and only rare bioturbation is present in these deposits. Therefore, the tidal-flat areas (FA3) provided sites for benthic colonization by a very low diversity infauna that could survive stressful conditions characterized by marked salinity fluctuations, rapid changes in temperature, and periodic subaerial exposure (Mángano et al., 2002; Mángano and Buatois, 2004; Desjardins et al., 2012). Subtle increases in ichnodiversity and pronounced increases in bioturbation intensity may indicate environmental amelioration and tidal-flat emplacement closer to the estuary mouth, where salinity tended to approach those of normal-marine environments.

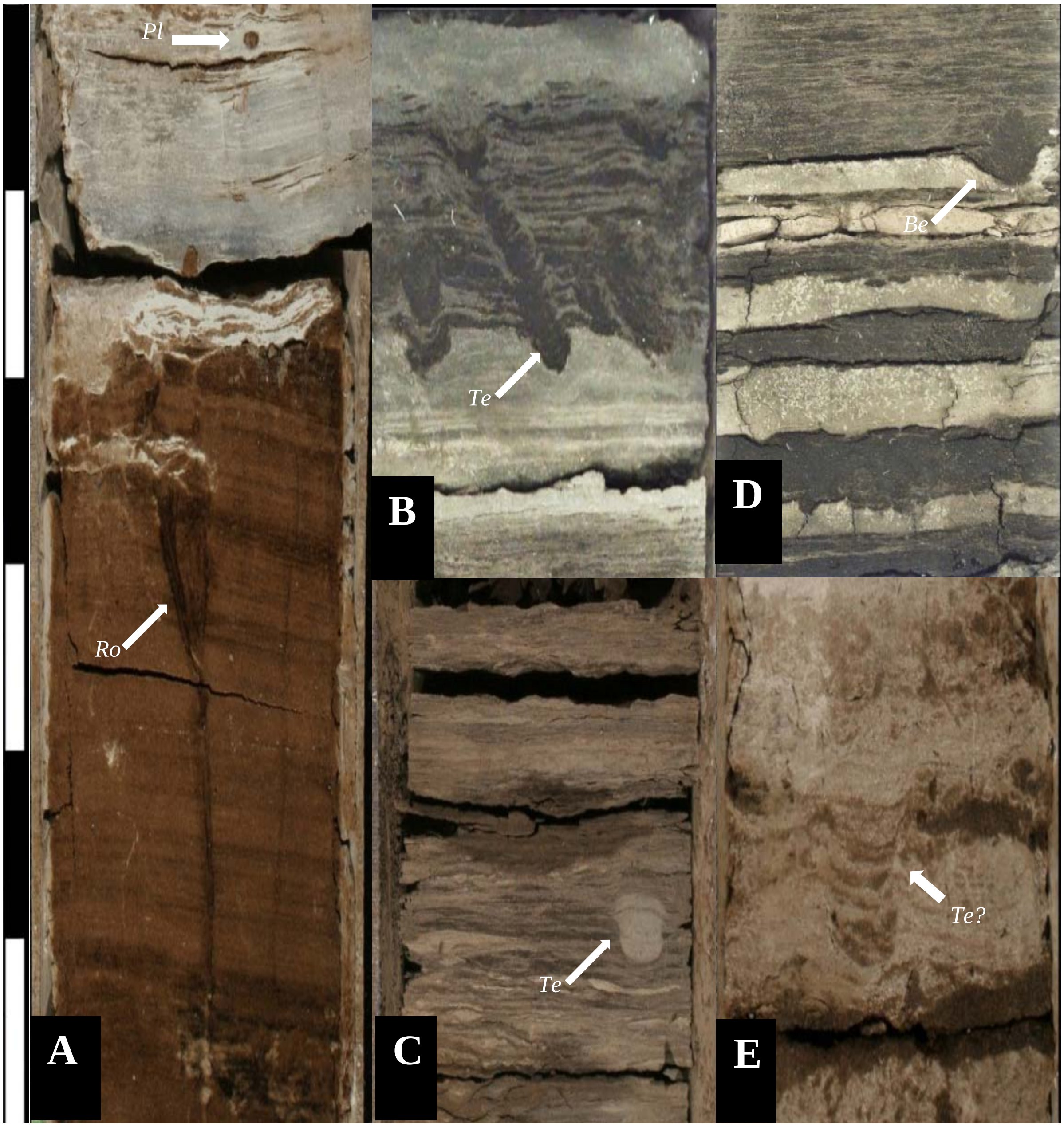


Figure 5.1. Elements of the depauperate *Cruziana* ichnofacies. (A). Close up of *Rosselia socialis* and *Planolites montanus.* B Well, 434 m, B (A Well, 351.4 m) C (B Well, 477.0 m), and (E) (B Well, 545.8 m) *Teichichnus rectus.* (D). *Bergaueria* isp. A Well, 356.3 m. Core width is 10 cm.

5.2 *Skolithos* Ichnofacies

The *Skolithos* Ichnofacies is characterized by the dominance of Domichnia, Equilibrichnia and Fugichnia- all ethological categories that comprise mostly vertical burrows of suspension feeders or passive predators, with low ichnodiversity and high abundance. This ichnofacies is typical of environments with relatively high of wave and current energy, such as the foreshore and shoreface of wave-dominated shorelines (Pemberton et al., 2001; MacEachern et al., 2007; Buatois and Mángano, 2011). In addition, the *Skolithos* Ichnofacies is present in marginal-marine environments where high energy level is dominant, such as in delta fronts, sandy bay margins, estuary mouth complex, and bay head deltas, (Pemberton et al., 2001; Buatois and Mángano, 2011).

In the cores analyzed, the *Skolithos* Ichnofacies occurs in FA2 and FA3. It is typically present in deposits having low intensities of bioturbation (BI = 1-2). It is represented by *Skolithos linearis* and *Ophiomorpha nodosa*, (Figure 5.2A-C). Escape trace fossils which are also present (Figure 4.5 B).

Skolithos is a dwelling burrow (Domichnion) of suspension feeders or predators vermiform (Alpert, 1974; Schlirf and Uchman, 2005). Insects or spiders can produce excellent sculptured terminations in vertical burrows in terrestrial environments, but *Skolithos* in marine environment is best explained as being made by phoronids or annelids (Schlirf and Uchman, 2005). *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).

Ophiomorpha is a dwelling trace of selective detritus-feeding decapods, such as modern callianassids (Dworschak, 2000; Dworschak et al. 2012). Typically these decapods construct deep burrows which are controlled by tidal range and low water table. When low tide occurs, wet sediments at depth buffer the organisms against desiccation and rapid changes of temperature (Pemberton et al., 2001). Unequivocal occurrences of the ichnogenus *Ophiomorpha* have only been reported from marine environments.

In the Oficina Formation, the *Skolithos* Ichnofacies occurs in the meandering estuarine channels of the valley axis (FA2) and in the tidal-flat and tidal-creek complex flanking the estuary axis (FA3) (Figure 5.3). In the case of the channeled deposits, the burrows were invariably emplaced in shifting sandy substrates characterized by rapidly migrating bedforms. In the tidal flats, elements of the *Skolithos* Ichnofacies are present in the higher energy sandy facies, typically exhibiting substantial wave reworking (Mángano et al., 2002; Mángano and Buatois, 2004; Buatois and Mángano, 2011; Desjardins et al., 2012).

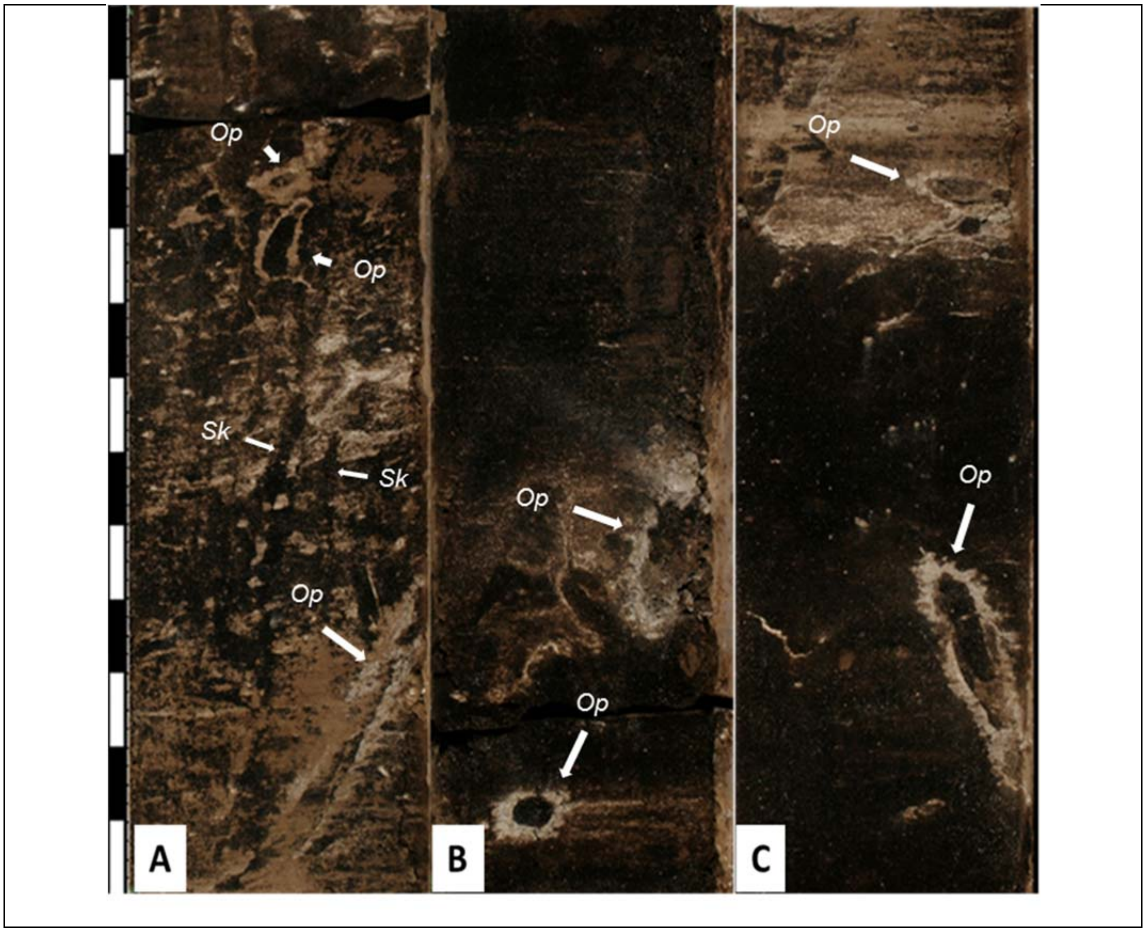


Figure 5.2 General view of *Ophiomorpha nodosa* in crevasse splay and abandoned channel deposits. (A) B Well, 534.9 m (B) B well 537.3 m, (C) B Well, 535.2 m. Note vertical and horizontal burrow orientations. Core width is 10 cm

5.3 *Scoyenia* Ichnofacies

The *Scoyenia* Ichnofacies is characterized by: abundance of horizontal meniscate backfilled traces produced by mobile deposit feeders; abundance of locomotion traces; presence of vertical burrows; a combination of invertebrate, vertebrate and plant traces; low to moderate ichnodiversity, and localized high abundance (Buatois and Mángano, 1995, 2011). Monospecific occurrences of meniscate trace fossils are common. The *Scoyenia* Ichnofacies is typical of fluvial and lacustrine systems, essentially in subaqueous sediments periodically exposed to air and terrestrial environments that are periodically submerged. It is therefore characteristic of intermediate aquatic to terrestrial environments (Frey et al., 1984, Frey and Pemberton, 1984, 1987; Buatois and Mángano, 1995, 2011). Typical settings of the *Scoyenia* Ichnofacies are overbank areas, lake-margins, and wet interdunes, among others (Frey et al., 1984, Frey and Pemberton, 1984, 1987; Buatois and Mángano, 1995, 2011). (Figures 5.4 and 5.5)

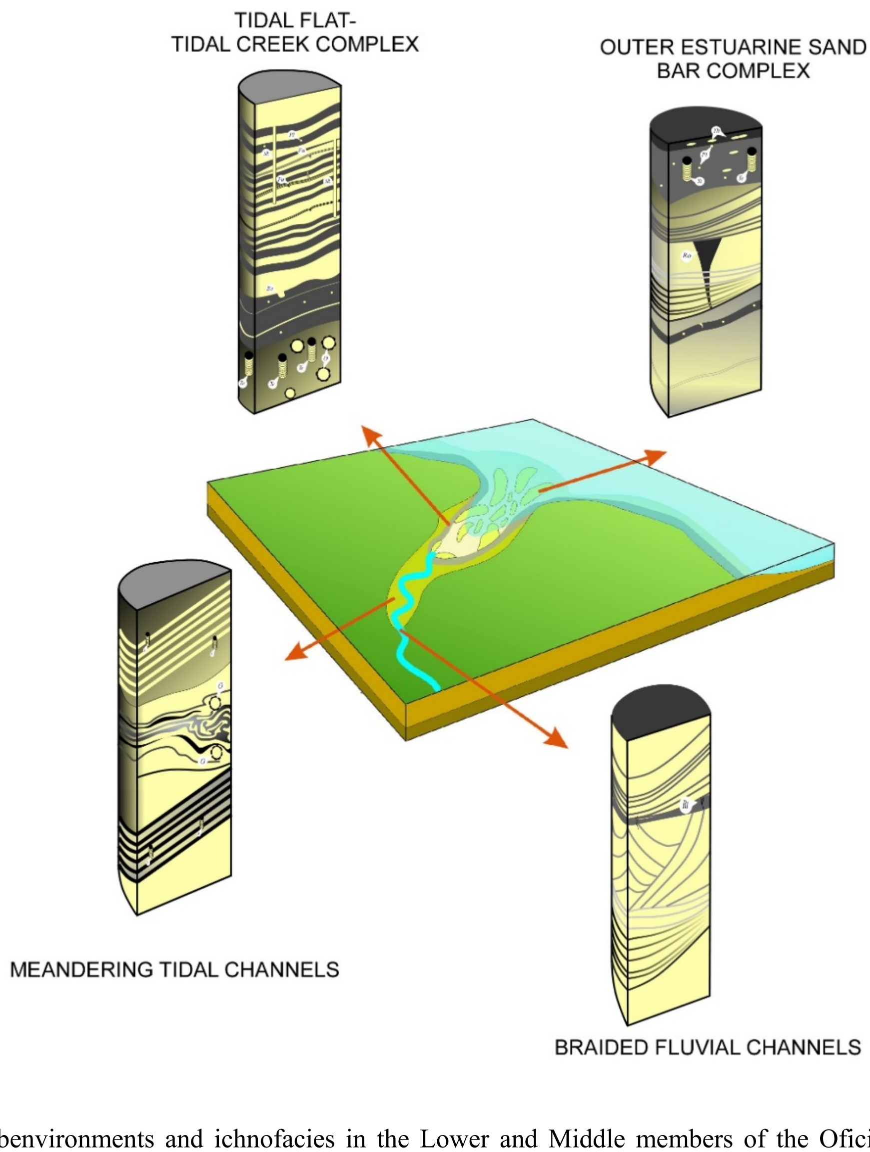


Figure 5.3. Subenvironments and ichnofacies in the Lower and Middle members of the Oficina Formation. The trace fossils present are *Teichichnus rectus, Rosselia socialis, Planolites montanus, Bergaueria* isp., *Skolithos linearis, Ophiomorpha nodosa,* and escape structures. *Thalassinoides* isp. occurs in the transgressive surfaces. Estuarine block diagram after Buatois and Mángano (2011).

In the analyzed cores, the *Scoyenia* Ichnofacies occurs in FA5, being particularly common towards the top of the Upper Member, although it is also present around the middle interval of this member. It is represented by monospecific suites of *Beaconites antarcticum*. The bioturbation index in these deposits is typically high (BI = 6). This ichnofacies was previously recorded in the Petrocedeño field for the Upper Member of the Oficina Formation (Buatois, 2005).

Beaconites is a simple, walled, meniscate, backfilled feeding structure (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* is a typical ichnogenus of nonmarine environments (e.g., Buatois and Mángano, 2004).

In the study area, the deposits containing *Beaconites antarcticum* were formed in overbank areas of the delta plain. The presence of the *Scoyenia* Ichnofacies in deposits having evidence of tidal influence indicates an environment located between the maximum salinity limit and the maximum tidal limit (Buatois et al., 1997; Buatois and Mángano, 2011).

LOWER DELTA PLAIN DEPOSITS

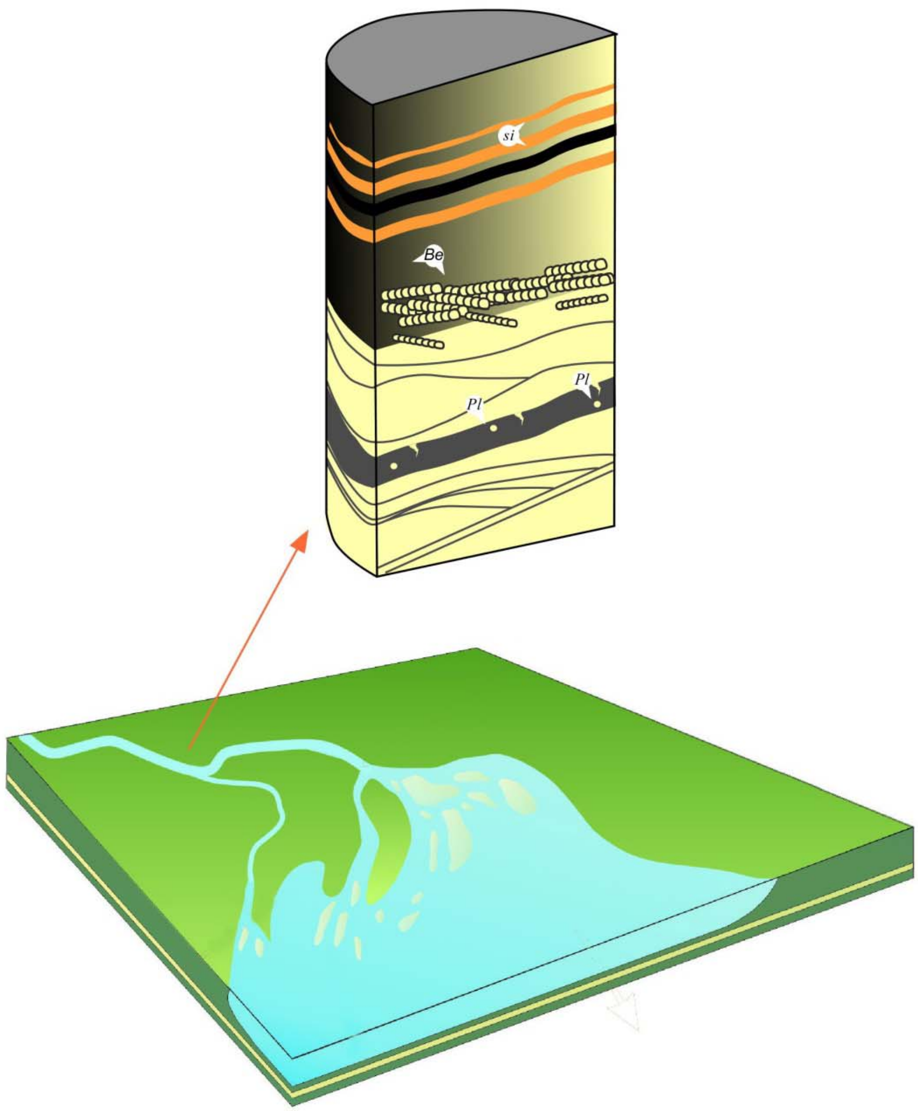


Figure 5.4 Subenvironments and ichnofacies in the Upper Member of the Oficina Formation. The trace fossils present are *Beaconites antarcticum* and *Planolites montanus.* Estuarine block diagram after Buatois and Mángano (2011).

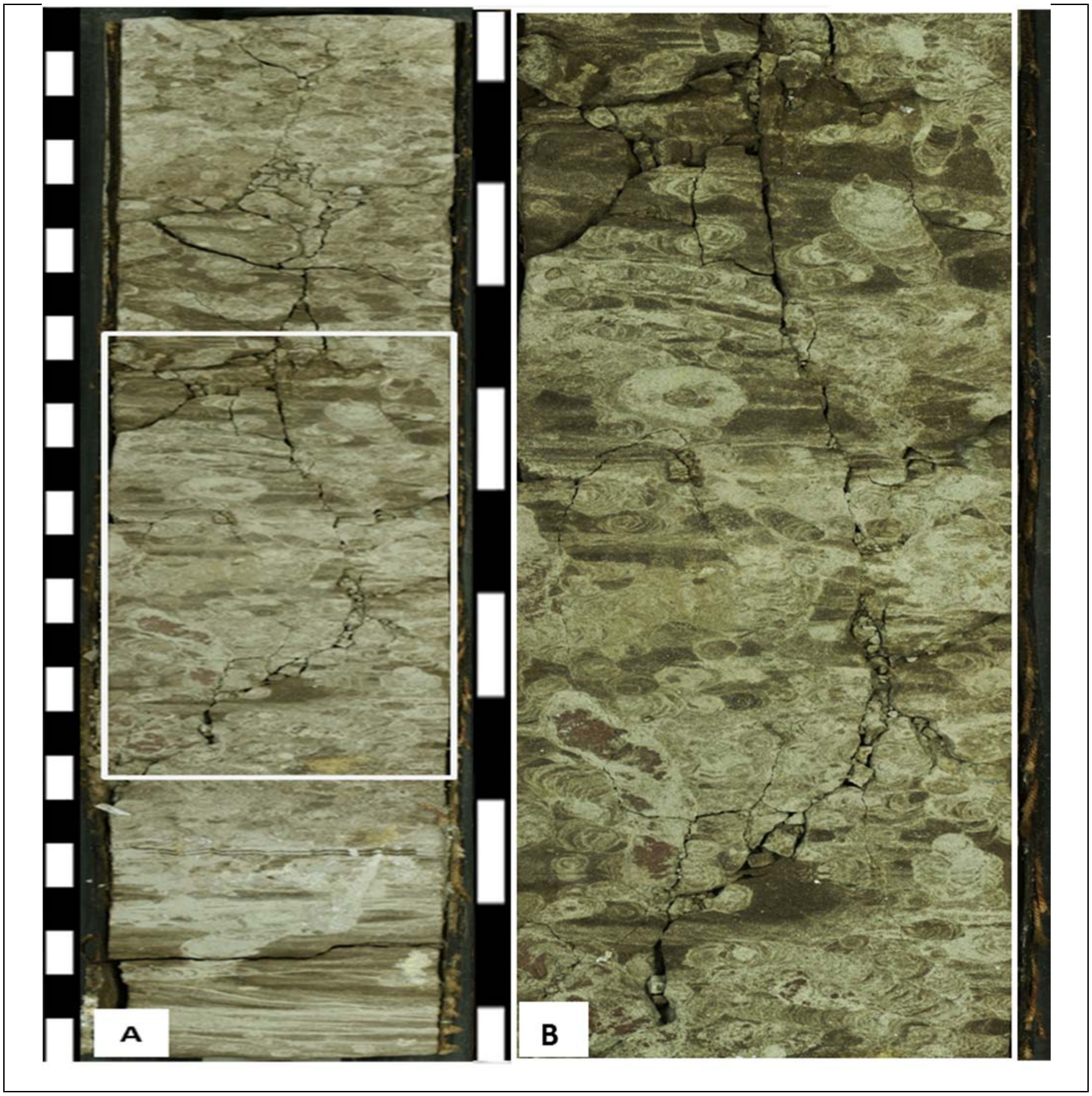
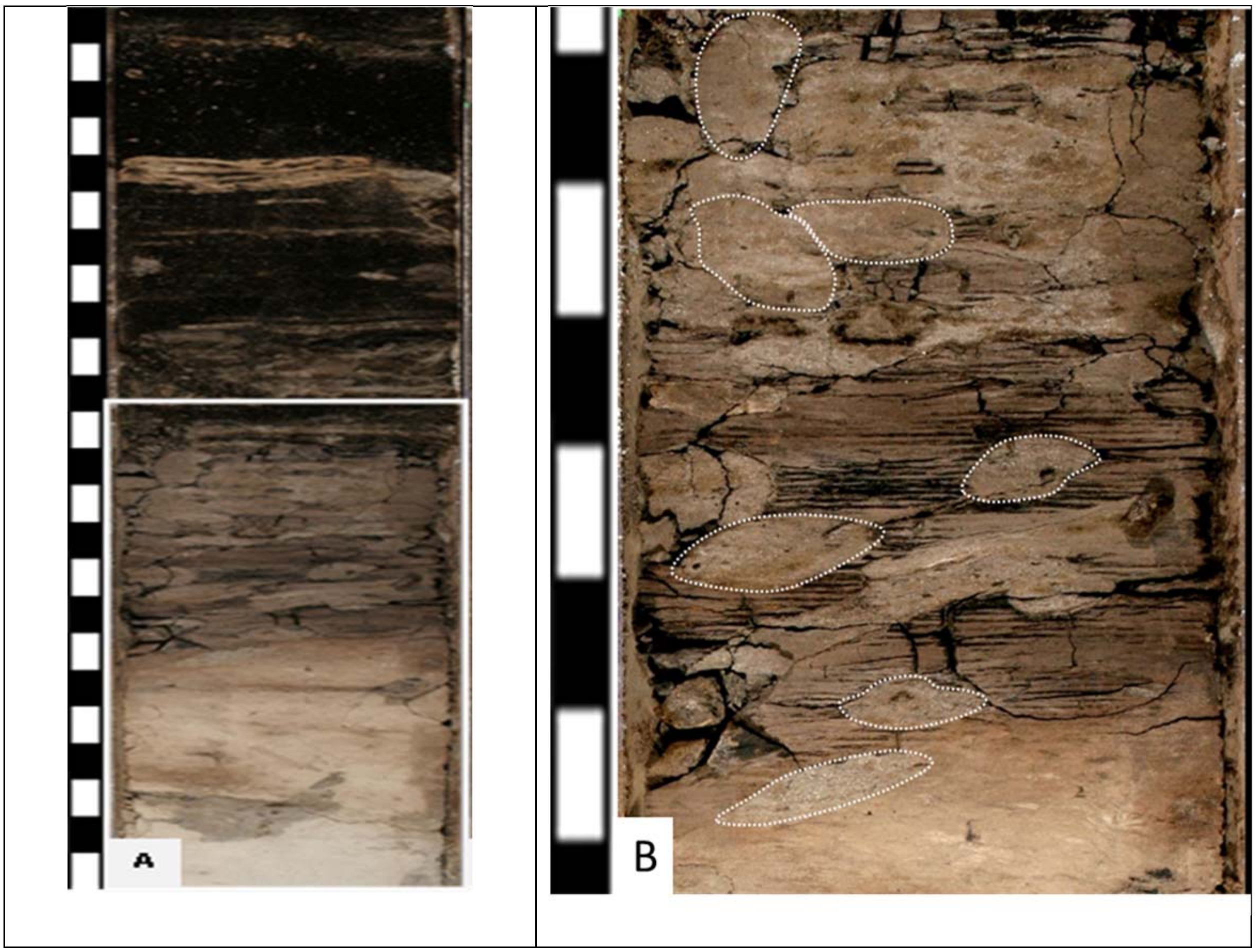


Figure 5.5 (A) General views of *Beaconites antarcticum*. H well, 576 m. ((B) Close-up of *Beaconites antarcticum.* Note the high abundance of these meniscate traces fossils in mudstone. Core width is 10 cm.

5.4 *Teredolites* Ichnofacies

The *Teredolites* Ichnofacies is characterized by the dominance of clavate borings, very low ichnodiversity (most commonly monospecific suites), and a typically high abundance (Bromley et al., 1984; Buatois and Mángano 2011). Typical producers are pholadid bivalves, although crustaceans may also be involved. This assemblage is associated with omission surfaces and transgressive surfaces of erosion, formed in marginal-marine environments, such as lagoon, bays, estuaries, and deltas (Savrda, 1991; Buatois and Mángano 2011).

In the Oficina Formation, the *Teredolites* Ichnofacies occurs in FA4, near the top of its Middle Member. It is represented by *Thalassinoides* isp., where it occurs in moderate densities (BI = 3-4). *Thalassinoides* isp. penetrates a coal layer, and borings are passively filled with sediments from the overlying sandstone (Figures 5.3, 5.6 A and B). In the cores analyzed, the *Teredolites* Ichnofacies delineates transgressive erosion surfaces cutting swamp deposits.



Figuere 5.6 (A) The *Teredolites* Ichnofacies delineating transgressive surfaces of erosion cutting into swamp deposits. A Well, 495 m. (B) Close up of *Thalassinoides* isp. penetrating a coal bed.

5.5 *Glosifungites* Ichnofacies

The *Glosifungites* Ichnofacies is characterized by sharp-walled, unlined, passively filled, dwelling burrows of suspension feeders or passive predators; dominance of robust, vertical to subvertical, simple and spreite U-shaped burrows; presence of branched burrow systems; presence of burrows with well-developed bioglyphs; low ichnodiversity, and typically high abundance (MacEachern et al., 1992, 2007; Buatois and Mángano, 2011). It is developed in firm but unlithified substrates; in siliciclastic settings it characterizes previously buried and dewatered sediments that have been available to tracemakers after erosional exhumation (Pemberton and Frey, 1985; MacEachern et al., 1992). In shallow-marine environments, the *Glossifungites* Ichnofacies is present in regressive surfaces of erosion formed during forced regressions, lowstand erosion surfaces due to relative sea level fall, transgressive surfaces of erosion, and co-planar surfaces or amalgamated surfaces of lowstand and transgressive erosion (MacEachern et al., 1992, 2007; Pemberton et al., 2004; Buatois and Mángano, 2011). The *Glossifungites* Ichnofacies also occurs in deep-marine environments associated with incised submarine canyons (Hayward, 1976; MacEachern et al., 1992; Pemberton et al., 2004; Buatois and Mángano, 2011).

In the study area the *Glossifungites* Ichnofacies is present near the top of the Middle Member and near the base of the Upper Member of the Oficina Formation, where it occurs in high densities (BI 4-3). In the cores studied, the *Glossifungites* Ichnofacies is represented by monospecific suites of *Thalassinoides* isp. (Figures 5.3 and 5.7). In the Oficina Formation, the *Glossifungites* Ichnofacies delineates transgressive surfaces of erosion at the base of transgressive lags consisting of shell debris located in the eastern area.

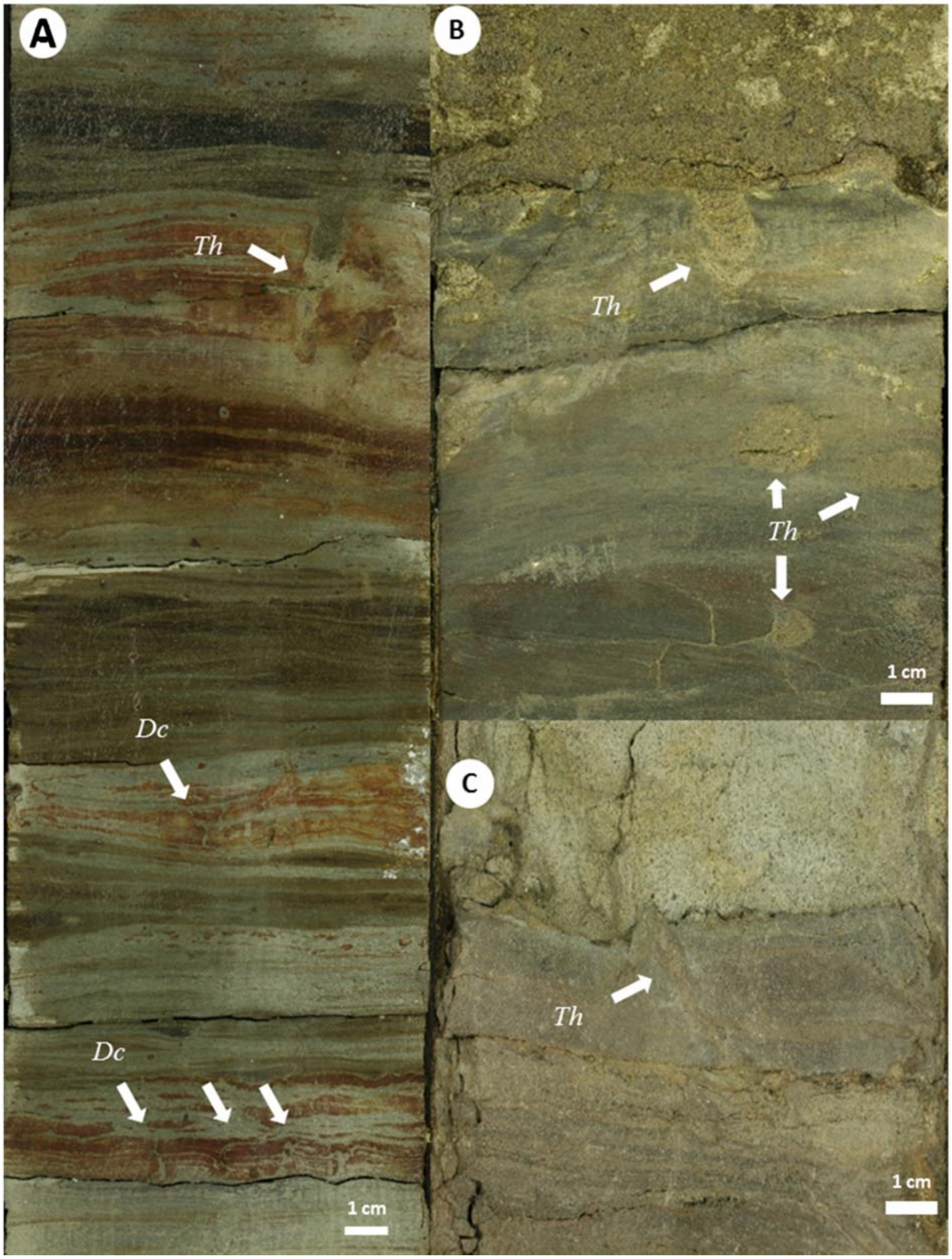


Figure 5.7 (A) *Thalassinoides* isp. (Th) in the *Glossifungites* Ichnofacies. Note presence of desiccation cracks (Dc) in the mudstone. H well, 566 m. (B) H well, 586 m and (C) Close up of *Thalassinoides* isp. Colonization took place after erosion exhumation and transgression.

6 Correlation and Sequence Stratigraphy

6.1 Correlations

Based on well cores and cutting descriptions, facies association and facies, structural information and well logs, four picks were determined. These picks were correlated using twenty one regional well-log transects across the Junín and Boyacá areas, which enabled drafting of structural maps for each of the tops (Appendix III)

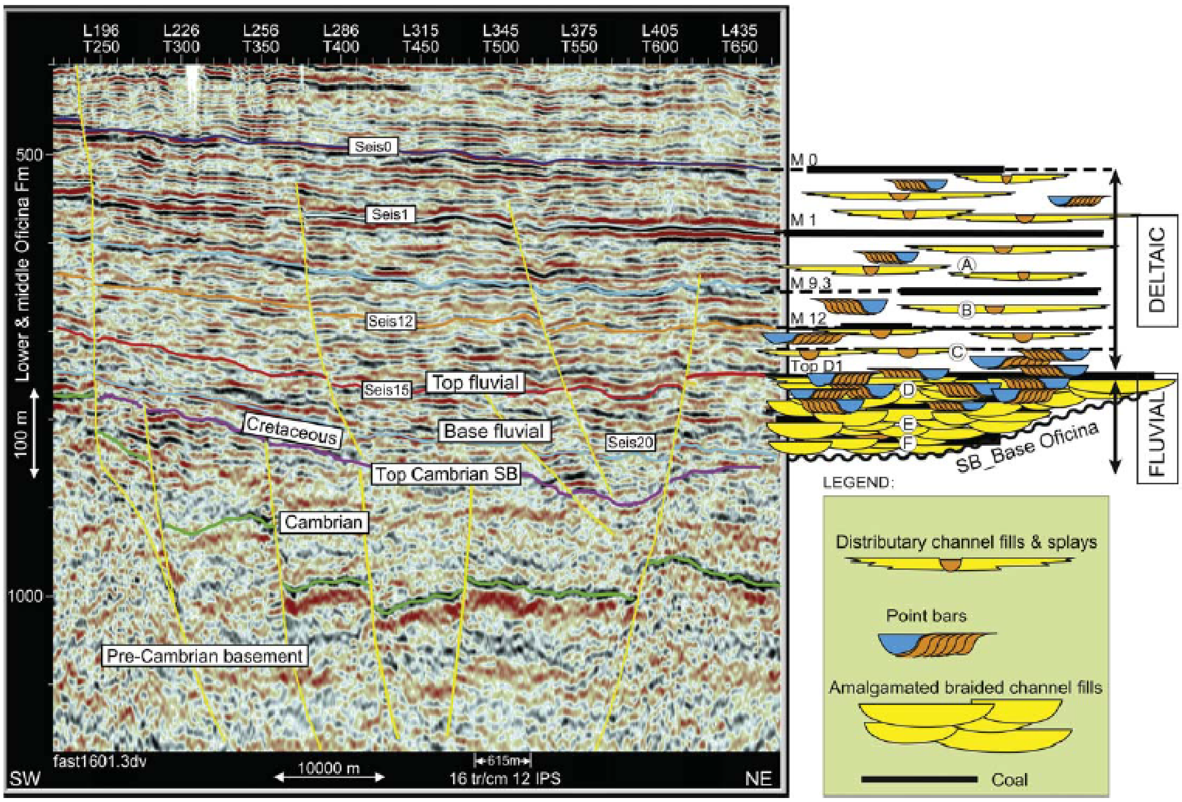


Figure 6.1 Seismic line showing seismic pick and incised valley at Petrocedeño field (from Martinius et al., 2012)

West to east correlations indicate significant lateral variations of facies, mostly controlled by depositional environment and accommodation. North-south correlations show that sediment thickness increases towards the north but can change laterally.

The Pre-Cretaceous top is a chronostratigraphic marker defined by biostratigraphic studies (Intevep, 2001). It is an excellent seismic reflector, characterized by the impedance contrast between Paleozoic or Jurassic meta-sedimentary rocks, and the overlying sedimentary succession (Figure 6.1). This seismic reflector marks the top of the Carrizal Formation in the Junin area, whereas in the Boyacá area, it delineates the contact between the Cretaceous succession and Jurassic rocks of the Ipire Formation. The Cretaceous top is a chronostratigraphic limit defined by biostratigraphic studies (Intevep, 2008). It marks the contact between the Oficina Formation and the Tigre and Canoa formations. The top of the Cretaceous succession is characterized by a continental sandstone with high content of kaolinite, which is one of the parameters used in well core descriptions to differentiate the Mesozoic from the Cenozoic. It has been used in other fields, such as Petrocedeño field, further to the east (Martinius et. al., 2012). Strong seismic impedance across the K/T boundary was used to correlate strata throughout the area. The other three tops are the most important ones for this study because they define the sequence stratigraphic framework of the Oficina Formation.

6.2 Sequence Stratigraphic Interpretation

The Oficina Formation is regarded as a single 2nd-order depositional sequence. In turn, 3rd-order sequences can be recognized, as demonstrated in the Petrocedeño area (Martinius et al., 2012). Although correlation between the different areas can be done by using surfaces identified for 2nd order depositional sequences, 3rd-order sequences are more difficult to correlate from one area to the other. However, 3rd-order sequences are important to delineate the stratigraphic architecture at the reservoir scale. Three systems tracts were identified in the Oficina Formation. The lowstand systems tract includes fluvial braided-channel deposits (FA1) of the Lower Member. The transgressive systems tract includes three facies asociations, namely meandering estuarine channels (FA2), tidal flat-tidal creek complexes (FA3) and an outer-estuarine sandbar complex (FA4), all comprising the Middle Member. The highstand systems tract is represented by prograding deltaic deposits (FA5) of the Upper Member. The Oficina Formation records deposition within an incised fluvio-estuarine valley followed by deltaic progradation (Figures 6.2, 6.3 and 6.4).

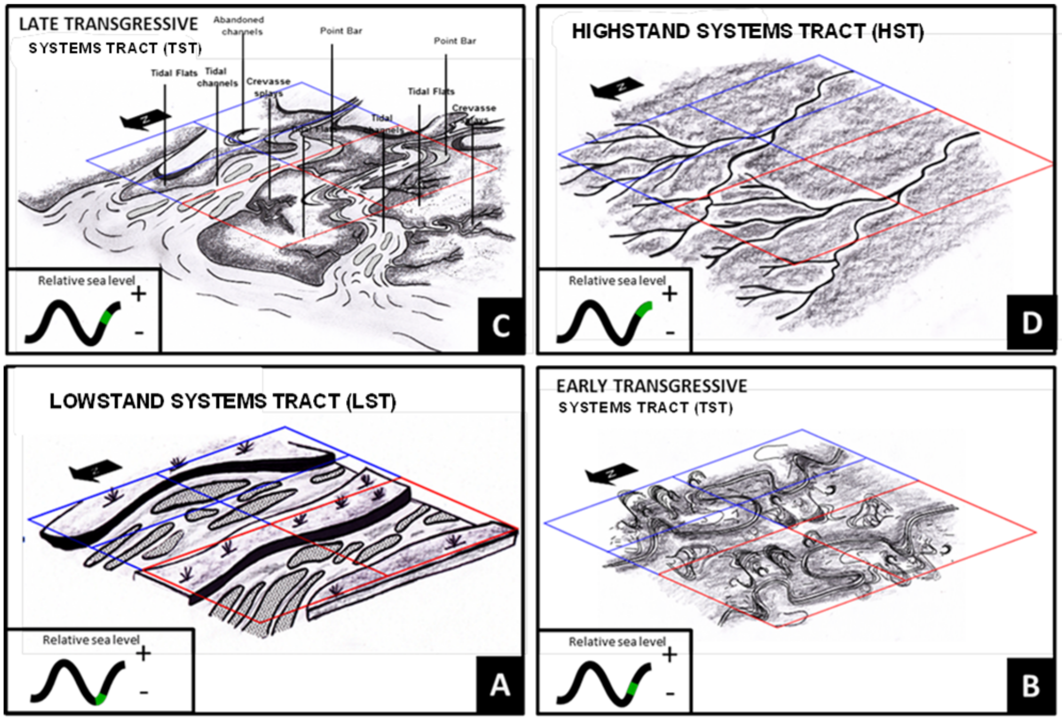


Figure 6.2 Paleogeographic sketch illustrating the geologic evolution of the Oficina Formation during lowstand systems tract (A), early transgressive systems tract (B), late transgressive systems tract (C), and highstand systems tract (D).

6.2.1 Lowstand Systems Tract (LST)

During a fall in relative sea level that took place close to the Oligocene-Miocene transition, the underlying pre-Cenozoic deposits became incised forming a fluvial valley. The irregular erosional surface represents a sequence boundary (SB). Evidence of incision in the study area is difficult to detect because of limited high-quality seismic information. However, in the Petrocedeño area located directly to the east, the incision surface is seen in 3D seismic plots (Martinius et al., 2012). In both blocks, Junín and Boyacá, the sequence boundary is overlain by coarse- to very coarse-grained sandstone and pebbly sandstone, although there may be areas where transgressive sediments rest directly on the sequence boundary, representing a co-planar surface (amalgamated sequence boundary and transgressive surface of erosion, also known as FS/SB). The fluvial deposits, which make up the lowstand systems tract (LST), filled topographic lows due to the incision of a valley without significant aggradation (10-20 m thick). Limited preservation of LST fluvial deposits is common in tide-dominated estuaries because of subsequent transgressive erosion resulting from tidal ravinement (Tessier, 2012).

The valley incision surface at the base of the Oficina Formation is mostly covered by nonbioturbated, coarse-grained sand-dominated deposits represented by FA1. The fluvial deposits were mostly preserved where they were buried beneath the landward-onlapping TST estuarine channel deposits. Sediment transport during LST was exclusively from a fluvial source, with systems prograding from the S-SW to the N-NE.

6.2.2 Transgressive Systems Tract (LST)

With the onset of the rapid Miocene eustatic rise, the incised valley became flooded as the supply of sediment was outpaced by the rate of creation of accommodation potential. A rapid rate of base-level rise resulted in the landward migration of the shoreline with the concomitant migration of the tide limit in order to produce an estuarine system within the incised valley. Estuarine deposits initially filled the available space within the incised valley and subsequently onlapped against the valley walls. As the sea transgressed the incised valley, sediment was reworked from the basement rocks becoming trapped within the incised valley. During the transgression, fluvially derived sediment co-existed with sediment sourced from the marine direction. These deposits are placed within the transgressive system tract (TST) since the retrogradational vertical stacking pattern of these deposits shows the replacement of fluvial deposits by estuarine deposits, implying that a marine transgression occurred in the valley. TST estuarine deposits are recorded by FA2, 3 and 4. In addition to the overwhelming dominance of tidal structures, the presence of the depauperate *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies provides further evidence of marine influence. Retrogradational stacking patterns, such as those displayed in the Oficina Formation, are known from several other incised fluvio-estuarine valleys (Allen and Posamentier, 1993; Zaitlin et al., 1994; Tessier, 2012; Tessier et al., 2012).

The transgressive surface (TS) forms the base of the TST and separates estuarine deposits above from the underlying fluvial braided channel deposits of the LST. The drowned zone of the valley is sharply overlain by a tide ravinement surface (TRS; Zaitlin et al., 1994). This surface is typically delineated by a transgressive lag containing abundant shells and pebbles. In the study area, the tide ravinement surface is mantled by very coarse-grained sand and truncates either muddy sediments or a coal bed. In both cases, abundant horizontal *Thalassinoides* isp. are present, penetrating from the colonization surface. In the case of the muddy sediments, the transgressive surface is thought to truncate low-energy intertidal deposits of the valley fringe, representing the *Glossifungites* Ichnofacies, whereas in the case of the coal layer, the surface is eroding swamp deposits, representing the *Teredolites* Ichnofacies (MacEachern et al., 1992; MacEachern and Pemberton, 1994; Buatois and Mángano, 2011). This surface was found in only two cores located towards the eastern most part of the study area (Figure 1.1C). These lag deposits seem to form a relatively continuous key horizon that can be correlated throughout the study area in wells. The basin dipped gently towards the north-northeast, whereas mountain uplift was active in the north, causing the sea to retreat and effectively shutting down marine influence in the western part of the Eastern Venezuela basin. Finally, the top of the TST is indicated by the maximum flooding surface (MFS), which in the case of the Oficina Formation in the study area is within a mudstone-dominated interval resting on top of the TST. The MFS is a key surface that allows correlation throughout the Orinoco Oil Belt.

6.2.3 Highstand Systems Tract

The rate of creation of accommodation was eventually outpaced by sediment supply, resulting in seaward migration of the shoreline and establishment of the highstand systems tract (HST). This is shown by a change from a retrogradational stacking pattern to a progradational stacking pattern. HST deposits are represented by FA5, which records deposition in a prograding delta system, comprising distributary-channel, swamp, and floodplain deposits with a combined river and tidal influence. The presence of the *Scoyenia* Ichnofacies provides further evidence of the passage to coastal-plain environments with a strong fluvial input.

6.2.4 Incised Valley Segments

Zaitlin et al. (1994) proposed a subdivision of incised valley fill in segments. Segment 1 is present from the most seaward extent of valley incision, close to the lowstand mouth of the valley, to the point where the shoreline stabilizes at the beginning of highstand progradation. Segment 2 is present between the inner end of segment 1 (i.e. the initial highstand shoreline) and the estuarine limit (i.e. the landward limit of recorded tidal influence) at the time of maximum inundation. Segment 3 occurs in the innermost region of the valley, being located landward of the transgressive marine–estuarine limit, but in an area which is still influenced by changes in base level associated with relative sea-level change.

Integration of sedimentologic and sequence-stratigraphic datasets indicates that the Oficina valley fill in the study area represents, for the most part, segment 2 in the model by Zaitlin et al. (1994). The typical succession of the Oficina Formation in the Junín and Boyacá areas comprises, from base to top, LST fluvial deposits, TST estuarine deposits and HST deltaic deposits, which is the pattern expected for segment 2. In addition, only towards the east of the study area, the TRS is present, indicating the outer zone of segment 2. Further to the east, outside the study area, there is evidence of more marine facies, signalling the presence of segment 1. The absence of the wave ravinement surface and the fact that the MFS occurs within estuarine sediments and not in the fully marine realm, further support emplacement in segment 2. However, in the southernmost part of study area, the Oficina succession consists of fluvial deposits (FA1) at the bottom and prograding delta plain deposits (FA5) at the top, without clear evidence of marine estuarine facies in between, indicating that this area belongs to segment 3.

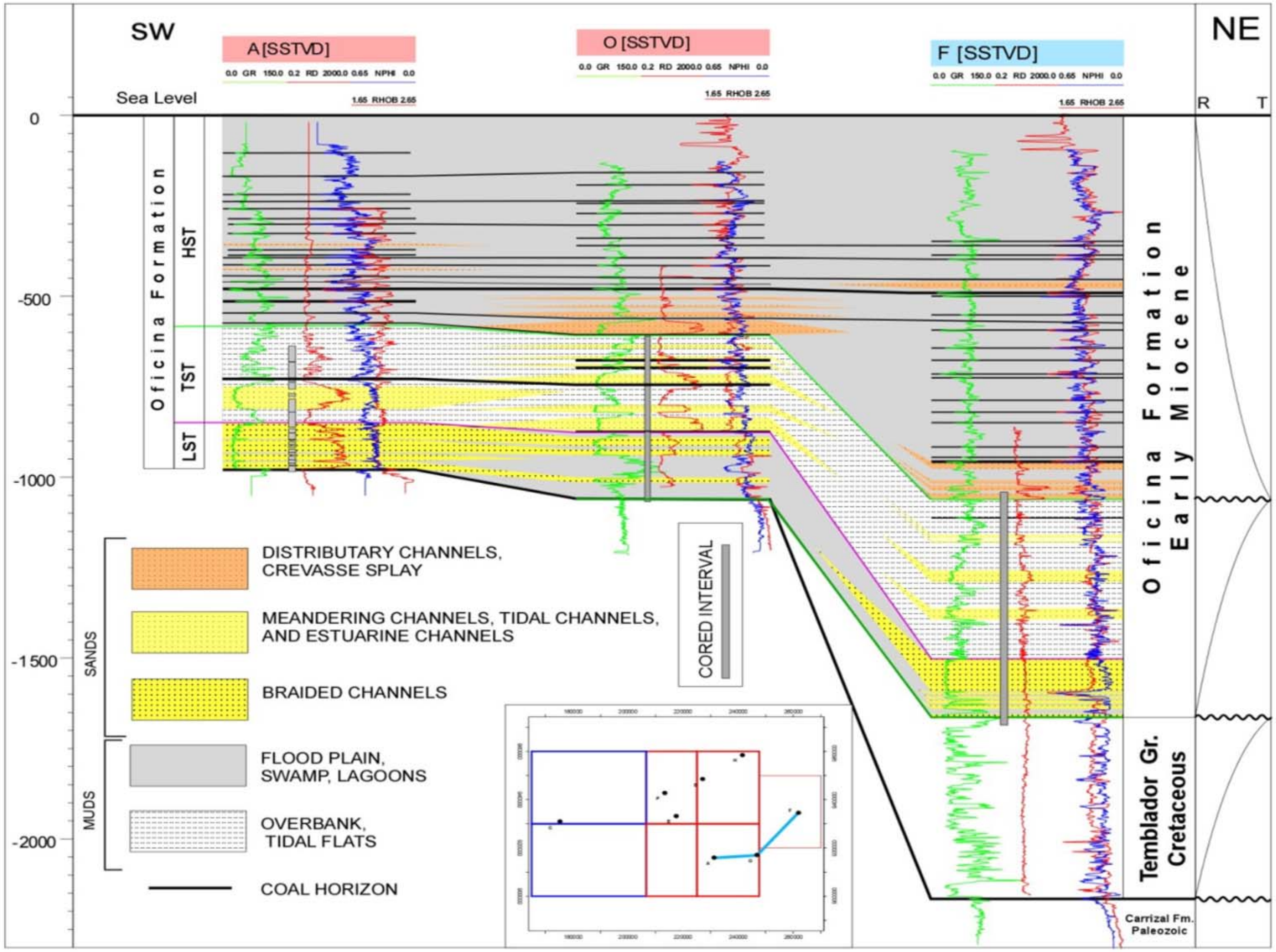


Figure 6.3 Well correlations using well cores and showing the sequence-stratigraphic interpretation.

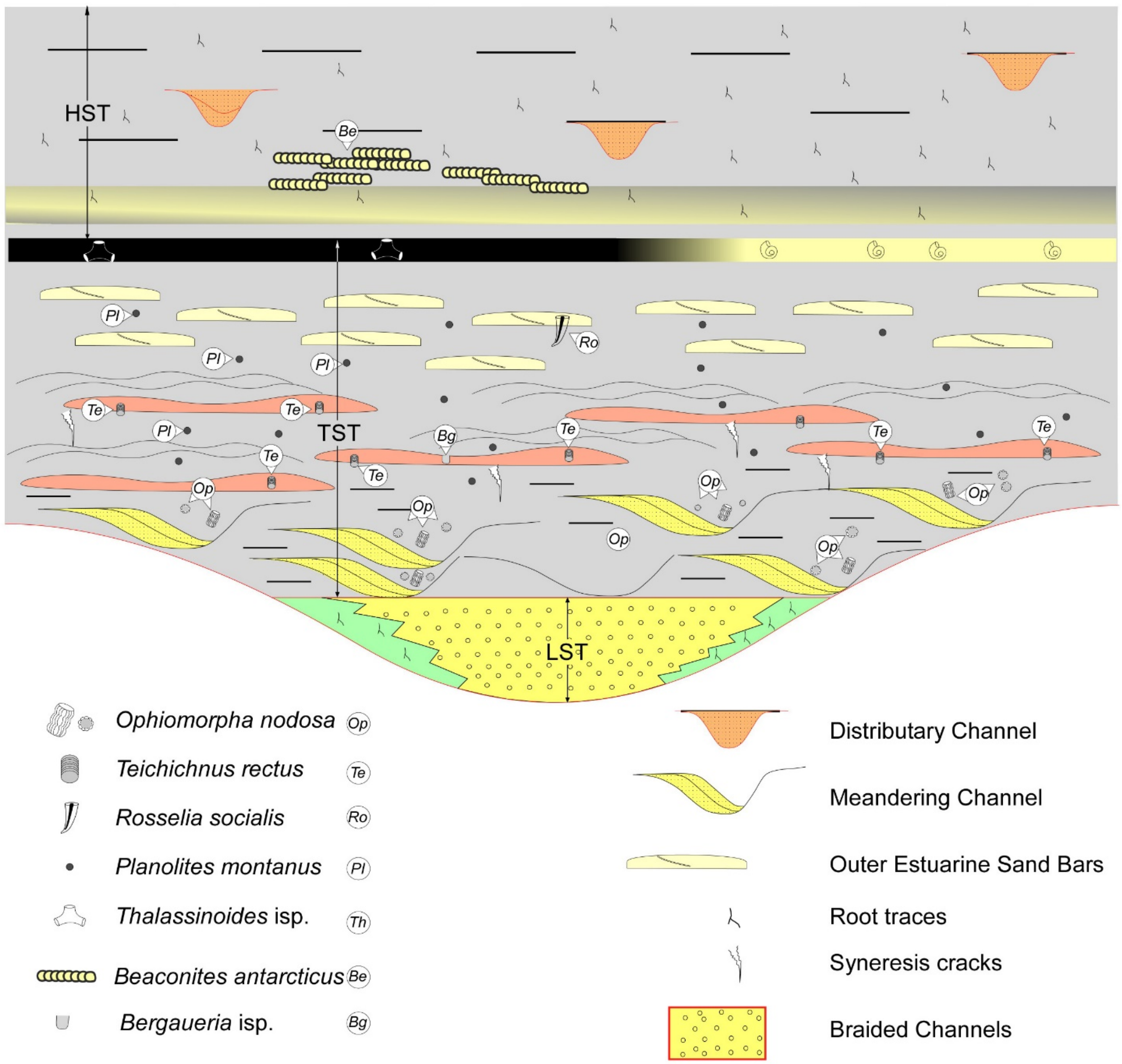


Figure 6.4 Summarized schematic illustration of the sequence-stratigraphic architecture of the Oficina Formation.

7 Discussion

Integration of sedimentologic, ichnologic, and sequence-stratigraphic datasets yields valuable insights into the paleoenvironmental characterization of the Oficina Formation reservoirs. In fact, this approach has been instrumental in proposing that the traditional deltaic model for this unit is not supported by the integration of multiple lines of evidence. The retrogradational stacking pattern documented in the Boyacá and Junín areas (Lower and Middle members) is inconsistent with a deltaic model because the latter necessarily reflects the advancement of clastic wedges towards the water body, therefore implying a progradational stacking pattern (e.g., Bhattacharya, 2010).

However, Vega and De Rojas (1987) proposed for the PetroAnzoategui area (ex-Petrozuata) that prolific sands "were deposited within a fluvial to coastal plain with deltaic development", despite their recognition that the Oficina Formation was deposited during an overall transgression that occurred during the Miocene and with its peak during deposition of the Freites Formation, which has been eroded in the study area. More recently, Martinius et al. (2012) published a sedimentologic and sequence-stratigraphic model for the Oficina Formation in the Petrocedeño field (ex-Sincor) in which the lower half of the Oficina Formation was interpreted as braided fluvial deposits that pass upwards into channelized deposits showing progressively more evidence of tidal influence, interpreted as delta-plain deposits that are replaced upwards by delta-front deposits with abundant distributary-channel fills. In that model, the supposed delta-plain and delta-front deposits would onlap the underlying fluvial deposits, displaying a backstepping pattern which is inconsistent with a deltaic model. In the model proposed here the braided-channel sandstones of the Petrocedeño field correlate with the LST braided deposits of the Boyacá and Junín areas and the overlying tidally influenced deposits are interpreted as part of the TST estuarine deposits. Martinius et al. (2012) proposed that the delta-front was subsequently drowned, resulting in an estuarine system with bay-head delta mouth bars, which were ultimately inundated by fully marine shale. In the model developed here for the Boyacá and Junín areas, these sandbodies are interpreted as outer-estuarine subtidal sandbars, which is more consistent with the stratal stacking pattern. In addition, bay-head deltas do not typically form in tide-dominated estuaries, because the inner portion of these systems is constrained to a single channel, precluding formation of any type of mouth bar (Dalrymple et al., 2012). The fully marine shale of the Petrocedeño field correlates with the mudstone unit containing the MFS, which was formed within the incised valley in the study area. This lateral change in the facies associated with the MFS is consistent with emplacement of the Boyacá and Junín areas in segment 2 of the valley system, whereas the Petrocedeño field most likely corresponds to the innermost portion of segment 1.

The distinction between estuarine and fluvio-deltaic environments has important implications for petroleum geology, including the distribution of sand bodies. Estuarine tidal sand bars are aligned parallel to depositional dip, whereas delta-front sands are typically aligned along strike. This differential distribution of sand bodies is critical in mapping subsurface trends. Evidence for tidal dominance in the Oficina Formation estuary includes the overwhelming dominance of tide-generated structures, such as inclined heterolithic stratification and mudstone drapes. Wave influence is restricted to a few intervals showing tidal-flat deposits that have been subjected to significant wave reworking. As noted by Tessier (2012), wave-built sandbodies are not uncommon on the margin of tide-dominated estuaries.

There is general consensus that the upper interval of the Oficina Formation displays a progradational stacking pattern, reflecting deltaic progradation. In contrast to the estuarine portion of this unit, which shows a clear dominance of tidal processes, the deltaic system seems to display a combination of tidal and riverine processes. Channeled deposits with inclined heterolithic stratification are present, but they occur together with other channel-fill deposits that lack any indicator of tidal influence, reflecting instead a strong imprint of riverine discharge. The fact that coastal systems tend to be tide-dominated during transgressions and river-dominated during regressions has been recorded elsewhere (Porębski and Steel, 2006).

Finally, it is worth mentioning that the Orinoco Oil Belt displays an almost identical facies stacking pattern to the other largest heavy oil reservoir in the world, the Athabasca oil sands of Alberta. As is the case of the Oficina Formation, the Lower Cretaceous McMurray Formation is subdivided into lower, middle and upper members (Carrigy, 1959). The lower member records deposition within fluvial systems (Crear and Arnott, 2007), whereas the middle member is dominated by estuarine-channel sedimentation with widespread development of inclined heterolithic stratification (Hubbard et al., 2011). The upper member shows a switch from retrogradational to progradational stacking patterns as a result of deltaic progradation (Ranger and Pemberton, 1997).

Additional similarities between the Oficina and the McMurray formations are not restricted to sedimentary facies and sequence-stratigraphic architecture, but are also seen from an ichnologic perspective. Both units contain brackish-water ichnofaunas characterized by reduced ichnodiversity and the presence of relatively simple forms produced by trophic generalists, among other features (Pemberton et al., 1982; Ranger and Pemberton, 1988; Lettley et al., 2007). However, whereas the Oficina Formation contains extensive evidence of continental ichnofaunas of the *Scoyenia* Ichnofacies, these seem to be absent in the McMurray Formation.

8 Conclusions

(1) Eight sedimentary facies (FA-FH) have been identified in the Oficina Formation in the Junín and Boyacá areas. In turn, FB has been subdivided in two subfacies (FB1 and FB2) and FF in four subfacies (FF1 to FF4).

(2) Based on stacking patterns and genetic relationships, five facies associations (FA1-FA5) (Table 2) were defined. FA1 consists of fluvial braided-channels deposits (Lower Member), and is replaced upwards by estuarine meandering-channel deposits (FA2), tidal-flat and tidal-creek deposits, (FA3) and outer-estuarine sandbar deposits (FA4) of a tide-dominated estuary (Middle Member). The succession culminates with FA5, which represents delta-plain deposits of a mixed tide- and river-influenced delta (Upper Member).

(3) The depauperate *Cruziana* Ichnofacies and the *Skolithos* Ichnofacies were identified in the estuarine deposits, providing unequivocal evidence of marine influence. The *Scoyenia* Ichnofacies is present in the delta-plain deposits, indicating the establishment of a continental infauna.

(4) Integration of ichnologic and sedimentologic data indicates brackish-water and marginal-marine conditions for the Middle Member. Ichnofacies information, sedimentary structures suggestive of tidal influence (e.g., inclined heterolithic stratification, flaser bedding, mudstone drapes) and salinity changes (i.e., syneresis cracks), and the spatial distribution of the sedimentary facies all provide evidence for the establishment of a brackish-water estuary during deposition of the Middle Member.

(5) Recognition of marginal-marine estuarine deposits in the Oficina Formation has a great impact in understanding the geological evolution of the unit and its sequence-stratigraphic framework. A retrogradational stacking pattern is indicated by the presence of fluvial-channel deposits passing upwards into estuarine facies. The whole Oficina Formation is interpreted as a 2^{nd}-order depositional sequence whose base consists of a sequence boundary formed due to incision of a fluvial valley during a relative sea-level fall. Valley fill comprises LST fluvial

deposits followed by TST estuarine deposits. The sequence culminates with HST progradation of a deltaic system.

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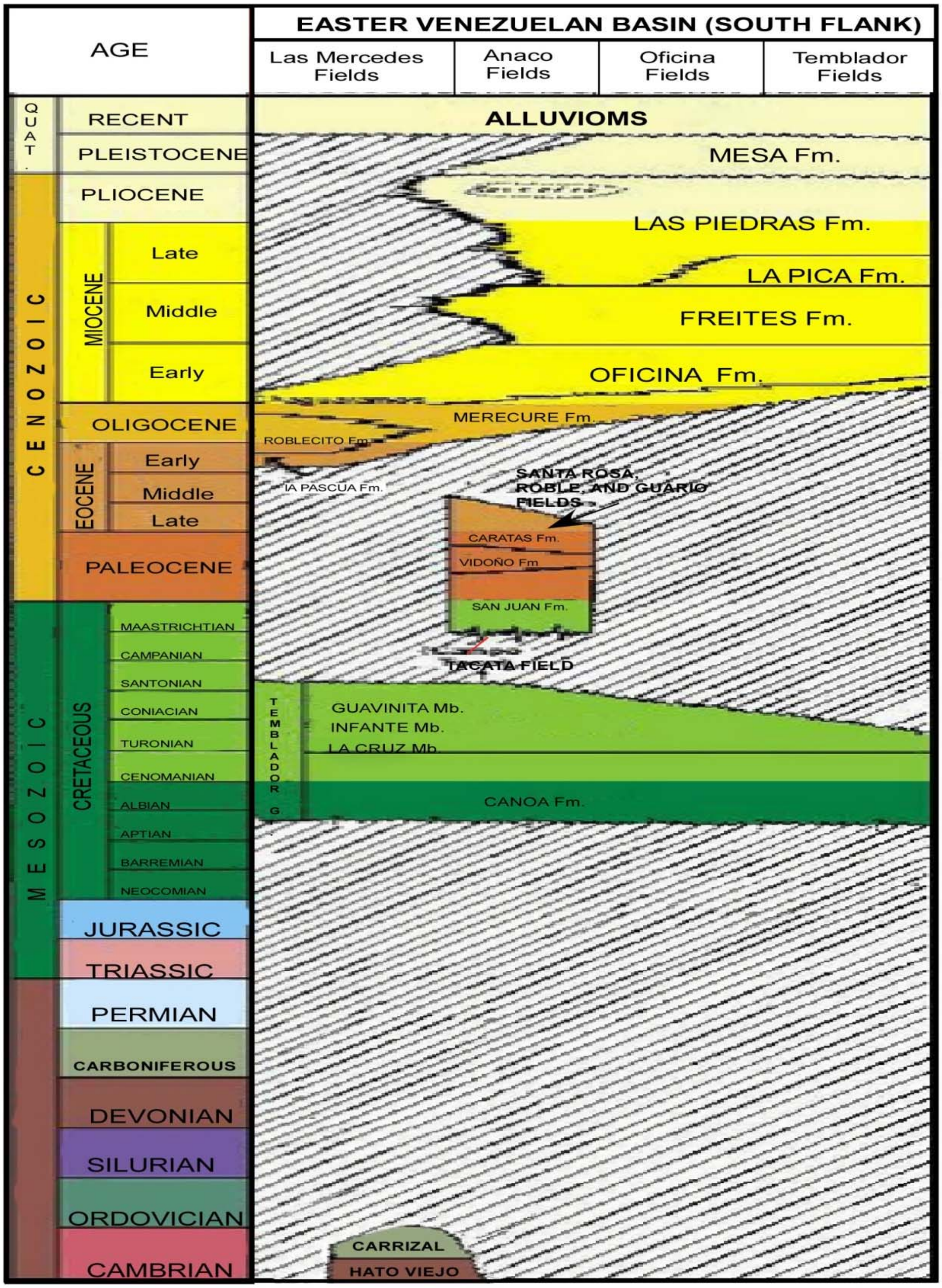
APPENDIX I

Summarized stratigraphic column of eastern Venezuela Basin (modified from Stratigraphic Lexicon of Venezuela).



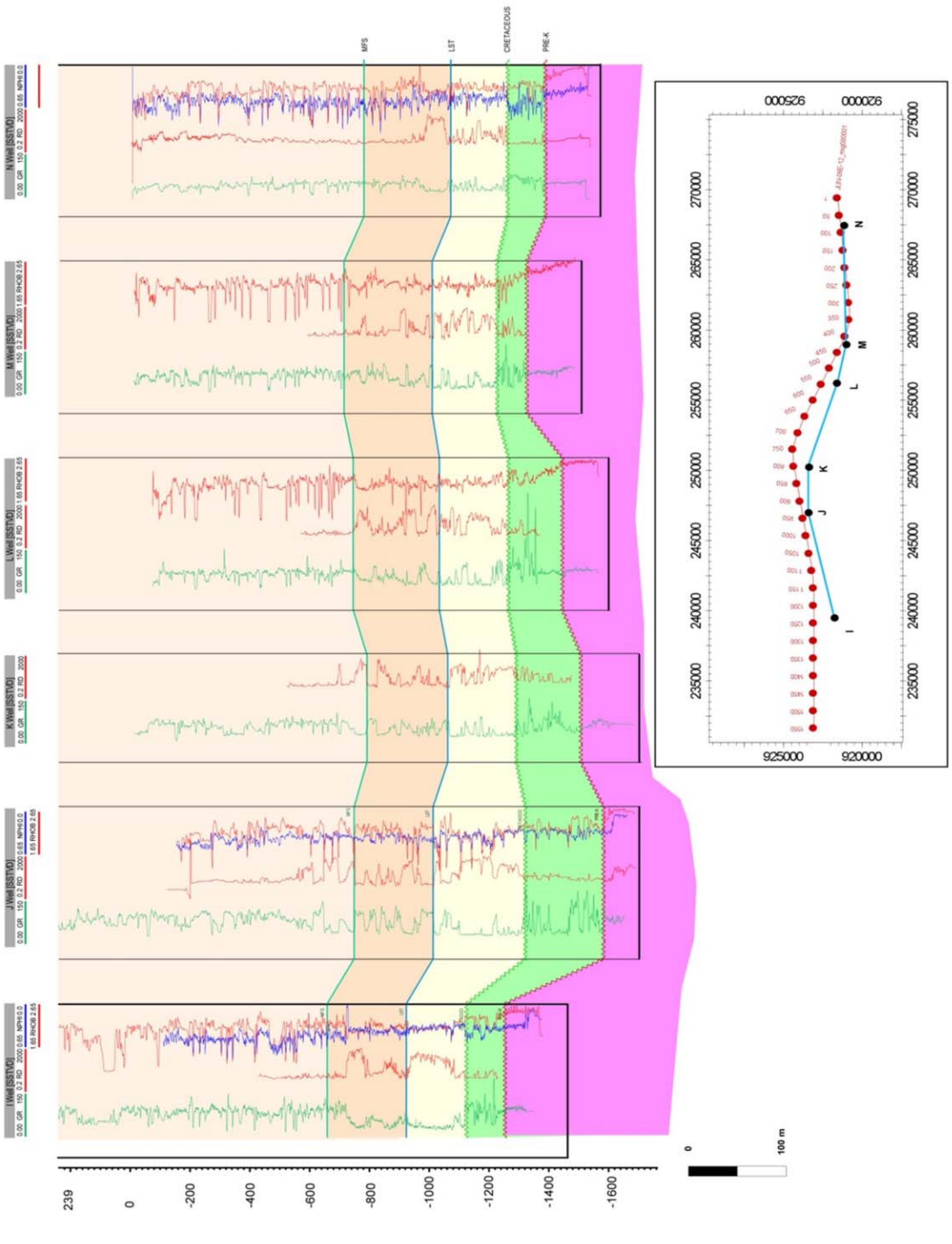
APPENDIX II

List of cores studied

WELL NAME	NORTH (m)	EAST (m)	DEPTH (m)	Comments
A	231354	915905	295.6-398.6	Good preservation
B	227189	948506	337.7-349.3, 376.4-383.1, 420.6-441.9, 476.4-570.8, 619.6-628.4, 631.8-633.0, 714.1-721.1, 723.2-732.4	Good preservation
C	175133	930645	481.2-504.1, 506.2-541.3, 543.4-553.8, 555.95-561.4, 564.4-570.8, 572.1-619.0	Good preservation
D	169918	938642	545.5-548.3, 551.0-554.7, 556.5-558.3, 562.0-565.0, 569.0-576.0, 576.6-594.6, 598.3-663.54	Good preservation
E	217459	933331	426.7-433.7, 438.9-440.4, 447.5-490.7, 496.5-499.2, 505.6-510.5, 514.8-537.9	Good preservation
F	261686.54	934472	494.6-588.5	Poor preservation
G	169918	938642	629.4-796.1	Good preservation
H	241413.4	958635.75	518.1-708.35	Good preservation

APPENDIX III

Cross section W-E showing correlation and valley parallel to the seismic line in Appendix IV



APPENDIX IV

Seismic line showing incise valley