SEQUENCE ARCHITECTURE IN A TIDE-DOMINATED INCISED VALLEY SYSTEM: AN EXAMPLE FROM THE OLIGOCENE SANDSTONE RESERVOIR, EASTERN LLANOS BASIN, COLOMBIA

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ABSTRACT

The Eastern Llanos Basin (ELB) represents the richest oil-producing region in Colombia. With most of its potential for structural traps already exploited, stratigraphical and combined traps are becoming the main exploration target in the Basin, both for the Cretaceous and Cenozoic sequences. In the South-Central ELB, the Late Paleocene Unconformity is represented by a complex network of incised valleys that were eventually filled-up by a thick (up to 400ft) section of Oligocene tide-dominated paralic transgressive deposits. Despite the excellent production and reservoir properties, this Oligocene reservoir revealed complex compartmentalization and an intricate distribution of fluid contacts and pressure regimes. This cannot be explained by structural traps or simple stratigraphic correlations. Based on seismic interpretation, sequence stratigraphy and facies analysis of cores, cuttings and well logs, it was possible to delineate a predictable model for internal sedimentary architecture. Two main depositional cycles separated by a regional flooding event were identified. The older cycle represents the initial infill of an incised valley network with fluvial-tidal influence. The younger cycle consists of estuarine-deltaic deposits with strong tidal control. Each cycle exhibits very distinct depositional geometries and correlation surfaces when observed in the seismic data. At well log scale, an internal architecture involving natural fluid boundaries was interpreted, responsible for the multiple fluid contacts and pressure regimes. This case-study can be applied to similar exploration and production scenarios and regarded as a methodology to evaluate the internal complexity of such stratigraphic/combined traps.

RESUMEN

La Cuenca de Llanos Orientales (ELB) es la región petrolífera más prolífica de Colombia. Con la mayoría de los recursos exploratorios en trampas estructurales ya conocida, las trampas estratigráficas y combinadas se convierten en el principal objetivo exploratorio de la cuenca, para las

secuencias Cretácicas y Cenozoicas. En el sector centro-sur del ELB, la discordancia del Paleoceno tardío se manifiesta como una compleja red de valles, finalmente colmatados por una espesa (400 ft) secuencia Oligocena, fluvio-estuarina dominada por mareas. A pesar de sus excelentes propiedades petrofísicas y producción, este reservorio Oligoceno reveló una compleja compartimentalización y una intricada distribución de contactos de fluidos y regímenes de presión. Esto no puede ser explicado como una simple trampa estructural o mediante correlaciones estratigráficas simples. Basados en interpretación sísmica, estratigrafía secuencial y análisis de facies de núcleos, recortes y perfiles eléctricos, fue posible delinear un modelo predictivo para la arquitectura sedimentaria interna. Se identificaron dos ciclos deposicionales principales, separados por un evento regional de inundación. El ciclo más antiguo representa una red de valles colmatada por depósitos fluviales con influencia mareal. El más joven, consiste en depósitos estuario-deltaicos con un fuerte control mareal. Cada ciclo exhibe geometrías deposicionales y superficies de correlación claves al ser interpretadas en sísmica. En escala de pozo, se interpretó una arquitectura interna que involucra barreras naturales de fluidos responsables de múltiples contactos y regímenes de presiones. Este estudio se puede aplicar a escenarios similares de exploración y producción, considerándolo como metodología para evaluar la complejidad interna de trampas combinadas a estratigráficas.

INTRODUCTION AND SCOPE

The Eastern Llanos Basin (ELB) is the most prolific oil producing province in Colombia (75 % of the yearly production, ANH 2015). One of the main reservoirs in the Central-Southern ELB (particularly in the East AOI, Fig. 1) is represented by the Oligocene Sandstones (Fig. 2). Despite their excellent production history (13 MMBbls cumm. in 5 years from only one block), the distribution of hydrocarbons within this Oligocene reservoir has not yet been fully understood. Even though the main trapping mechanism was assumed to be structural, hydro-

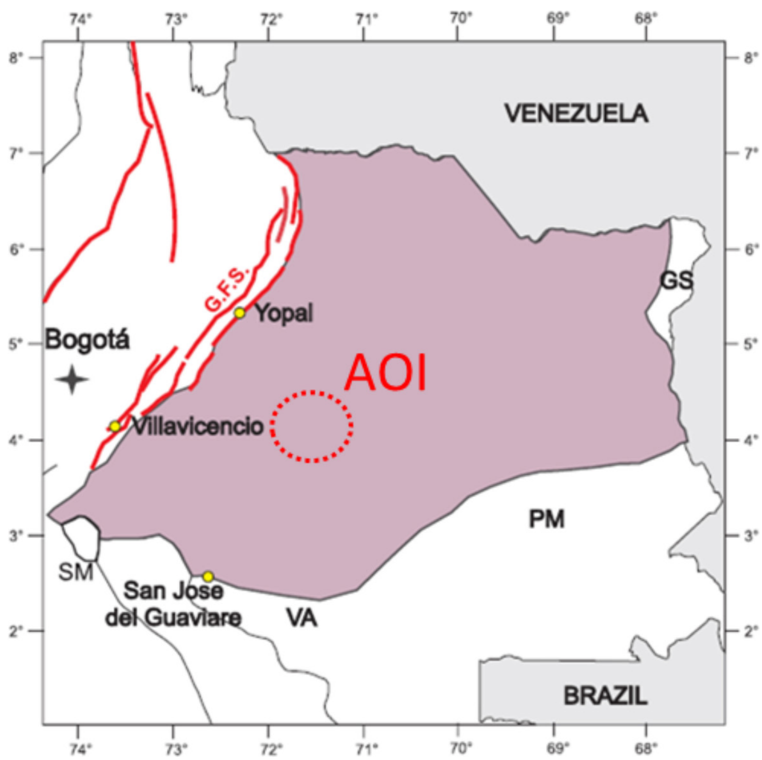

Figure 1. Llanos Basin location map, from Cooper *et al.* (1995). AOI: Area of Interest

carbon accumulations do not follow structural contours (Fig. 3). Therefore, a stratigraphic component turned out to be crucial to describe accumulation variations within the trap. According to multiple oil-water contacts and pressure regimes, the reservoir shows a highly compartmentalized fluid distribution. Originally, a set of arbitrary boundaries were used to explain this reservoir behavior. Furthermore, history matching analysis was unattainable during dynamic simulation, when applying this type of geologically unsupported boundaries.

Thus, a new integrated approach was carried out to optimize development plans based on three scales of investigation: 3D seismic, well logs and cored intervals. This study is focused on the Central-Southern region of the ELB (Fig. 1, AOI). However, its methodology and conclusions may result useful when analyzing similar reservoirs, potentially driving exploration and development success.

REGIONAL GEOLOGY

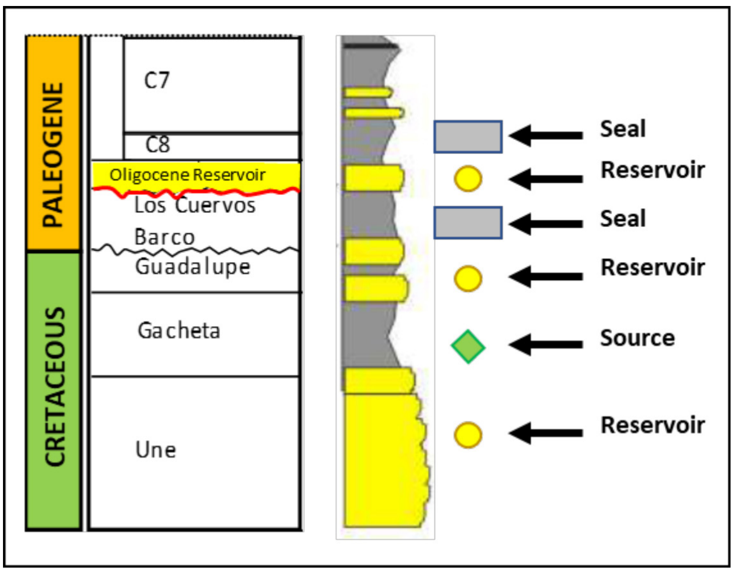

Figure 2. Partial stratigraphic column of the Eastern Llanos Basin showing the main petroleum systems elements (modified from Barrero *et al.* 2007).

The ELB is bounded to the west by the Eastern Cordillera Mountain range, to the east by the Guyana Shield, and to the south by the Macarena Range and the Vaupes basement arch (Cediel *et al.* 2011; Moreno-López and Escalona 2015). The basin continues northeast into Venezuela as the Apure and Barinas Basins, which have been separated from the ELB since the Early Cenozoic by the Arauca arch (Fig. 1). The ELB is a retro-arc foreland basin represented by an asymmetrical sedimentary wedge that rests upon Proterozoic to Paleozoic rocks and thickens westwards onto the Eastern Cordillera, reaching up to 10 km in thickness (Fig. 3). The sedimentary infill wedges out to the east onto the Guyana Shield.

Since the Early Cretaceous, sediments were sourced from the Guyana Shield, with later contributions from the uplifted Central Cordillera until the Middle Miocene when the Eastern Cordillera was uplifted and started to provide sediments to the ELB (Cooper *et al.* 1995; Gomez *et al.* 2005).

The sediment infill in ELB started with a syn-extensional episode during the Latest Jurassic to Early Cretaceous (Fig. 3, 4 and 5). This was followed by a back-arc post-extensional regime which spanned throughout the Late Cretaceous (Cenomanian to Maastrichtian), when thermal subsidence dominated in the ELB. This episode involved a eustatic sea-level rise that resulted in a regional transgression and the establishment of a shallow epicontinental seaway with restricted, anoxic, and sediment-starved conditions. It was during this episode when the principal source rock in the ELB was deposited (the Gacheta Fm., equivalent to the La Luna Formation in other Colombian basins). The rest of the Cretaceous is characterized by falls in relative sea level (Guadalupe Fm) alternating with minor transgressions.

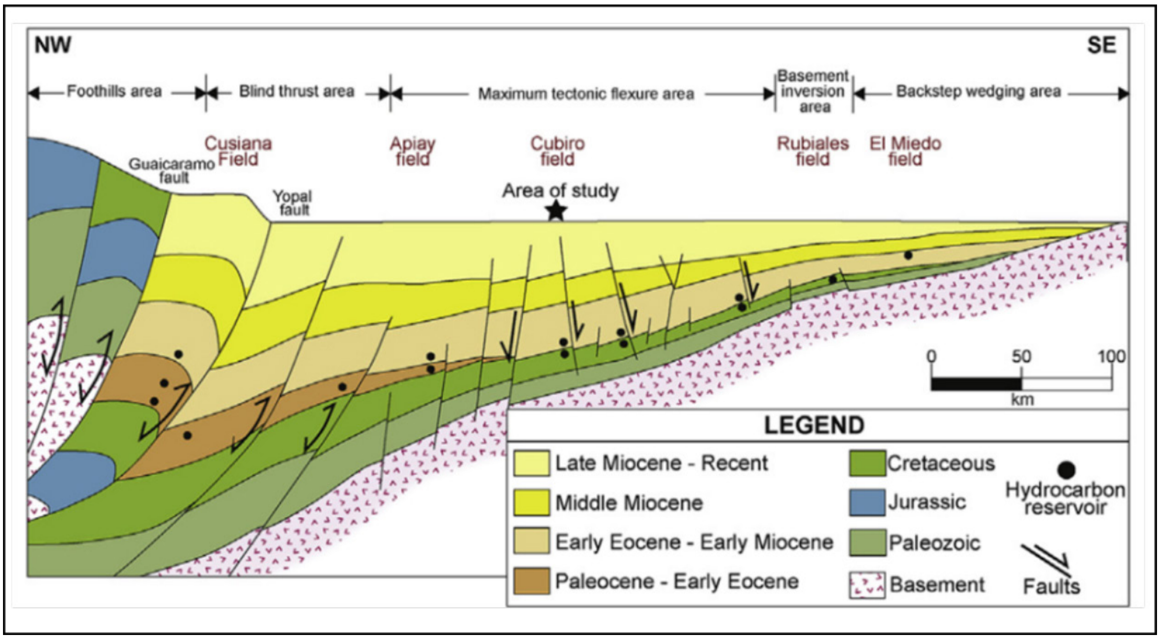

Figure 3. Schematic cross-section ELB (modified from Torrado *et al.* 2020).

Afterwards, at the end of the Cretaceous, the ELB was inverted into a foreland basin (Bayona *et al.* 2007) as the Central Cordillera underwent a new pulse of tectonic uplift and became an important sediment source for the ELB. This new tectonic regime was responsible for an abrupt end of the previous shallow marine system and the establishment of Paleocene coastal-estuarine environments on the Western Sector (Barco and Los Cuervos Fms) and a non-marine realm on the easternmost ELB (Bayona 2018). This shift in sedimentary environments is evidenced by a regional unconformity at the base of the Barco Fm (K-T boundary).

The Early and Middle Eocene brought different scenarios on the Western (Llanos Foothills) and Eastern regions of the ELB. The former is represented by a thick succession (up to 600ft, Cediel *et al.* 2011) of amalgamated sandstones and conglomerates of a braided fluvial system (Mirador Fm). The latter, is characterized by no net sediment accumulation, involving in turn, processes of bypass and erosion that shaped the previous topography into a discrete network

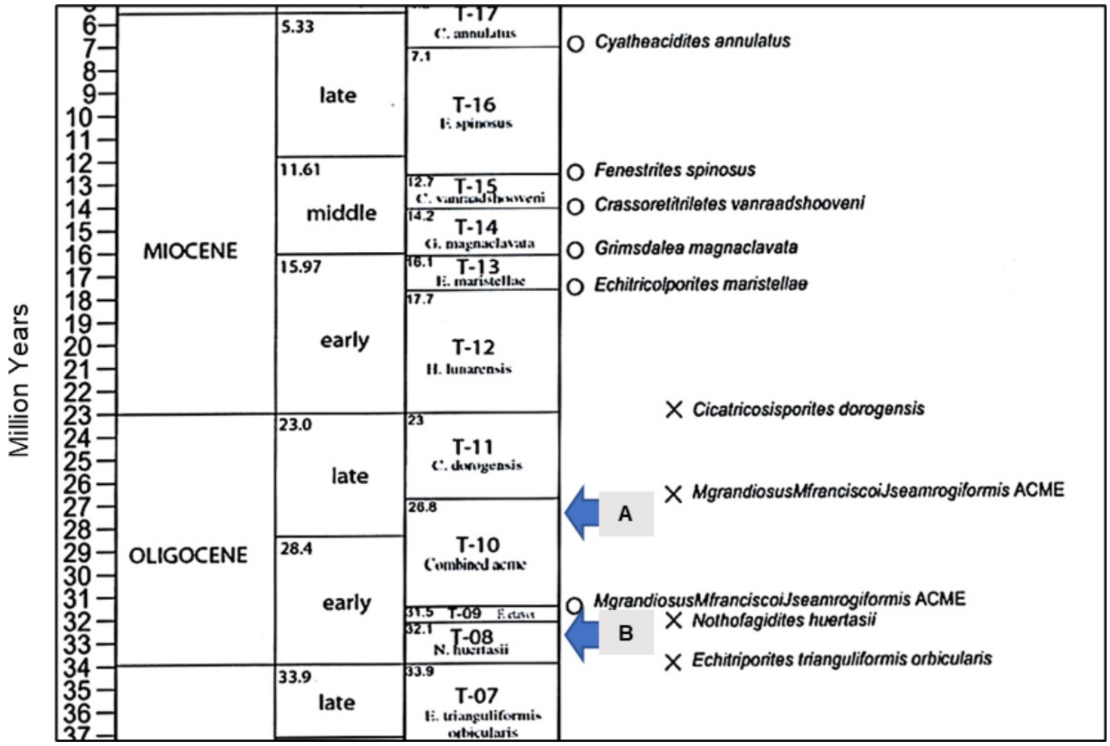

Figure 4. Current biozone zonation for the basal Paleogene in the study area. A and B well samples confirm the Oligocene section (biozone T08) on top of the Paleocene (T04a-T03) (Jaramillo *et al*. 2011).

of incised valleys (up to 200 ft). This re-shaped topography produced a high impact regional unconformity that played a major role in most of the traps of the Eastern Llanos Basin, a hiatus spanning from biozone T04 to T07 (Late Paleocene to Early Oligocene, Bayona *et al.* 2008). This gap is referred to as the Paleocene Unconformity in this study. The infill of the Paleocene unconformity corresponds to biozones T08 to T10 of the Oligocene (Fig. 4).

The pre-Andean Foreland episode in ELB started with the rapid drowning of the incised valleys due to an increase in relative sea level driven by a combination of tectonics and eustasy. Thus, marginal marine conditions prevailed during the Early Oligocene (Hoorn *et al.* 2010) resulting in the accumulation of a diverse series of sandstones packages alternating with mudstone intervals. The work presented in this paper is strictly focused on the basal unit of this infill cycle. In order to avoid possible conflicts with the classical lithostratigraphic nomenclature (cause of several pitfalls), the authors will refer to this unit in terms of its age – Oligocene Sandstone, independently from the existing lithostratigraphic nomenclature variants it may associated with. For further information of the evolution of the Llanos Basin, the following articles are suggested: Duque-Caro (1979); Pindell *et al* (1998); Villamil (1999); Moreno- Sanchez and Pardo-Trujillo (2003); Escalona and Mann (2011).

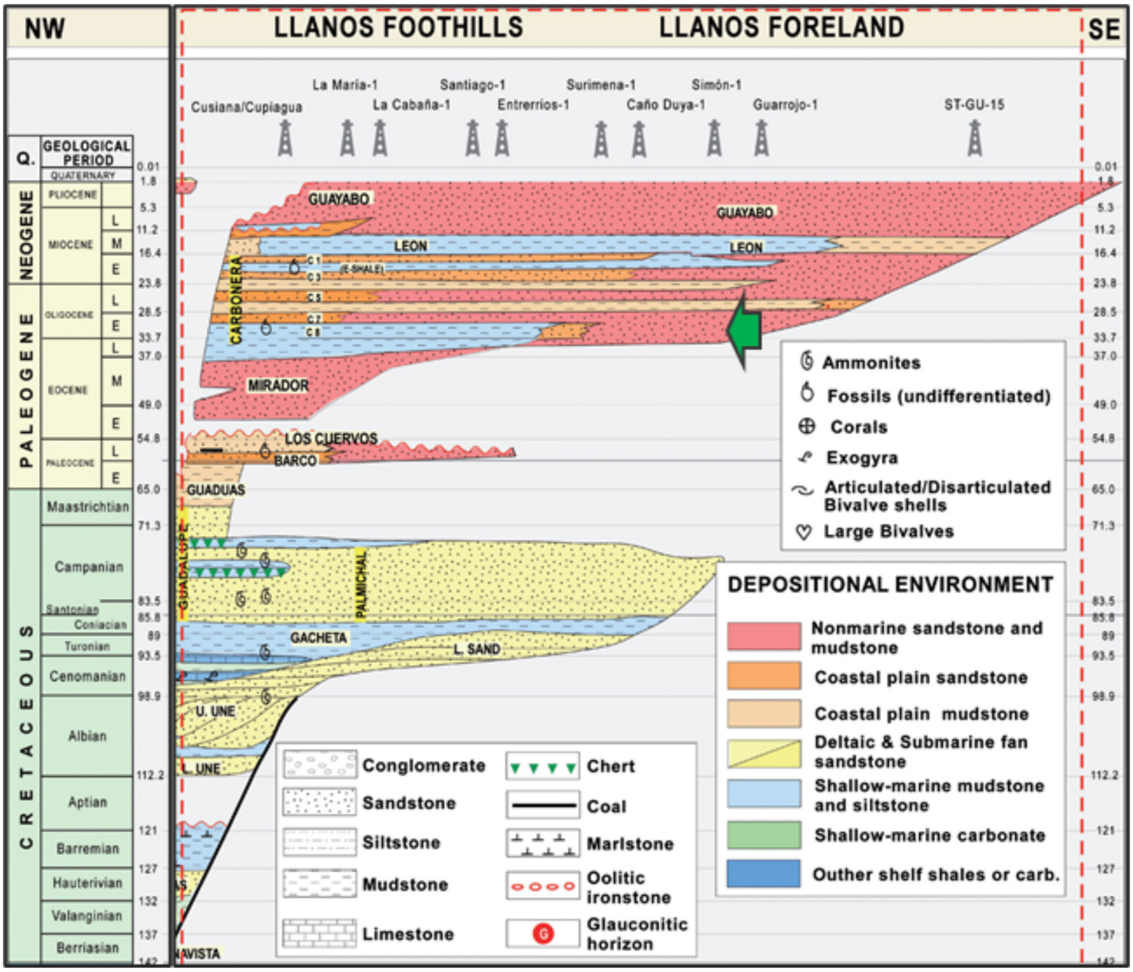

Figure 5. Llanos Basin Chronostratigraphic Chart, modified from ANH 2011. Green arrow indicates the stratigraphic interval of interest (Early Oligocene).

THE OLIGOCENE FIELD: CONTEXT

This case-study field is defined as a three-way dip closure (3WDC) bounded by a normal fault system that runs in a NE-SW direction, where petroleum occurs in the downthrown block. The fault throw is generally enough to juxtapose the Oligocene reservoir rocks with sealing lithologies. The downthrown side of the fault system involves a large structural nose that climbs upwards to the south without showing any structural closure (Fig. 6).

Many wells have been drilled in the Oligocene field finding oil accumulations distributed in a set of compartments that bear different oil-water contact (OWC) and pressure regimes. When modeling the reservoir, arbitrary lateral limits had to be located between these compartments, since neighboring wells showed different fluid columns at the same structural position (Fig. 7 and 8). With these arbitrary model compartment limits history matching could not be fully achieved.

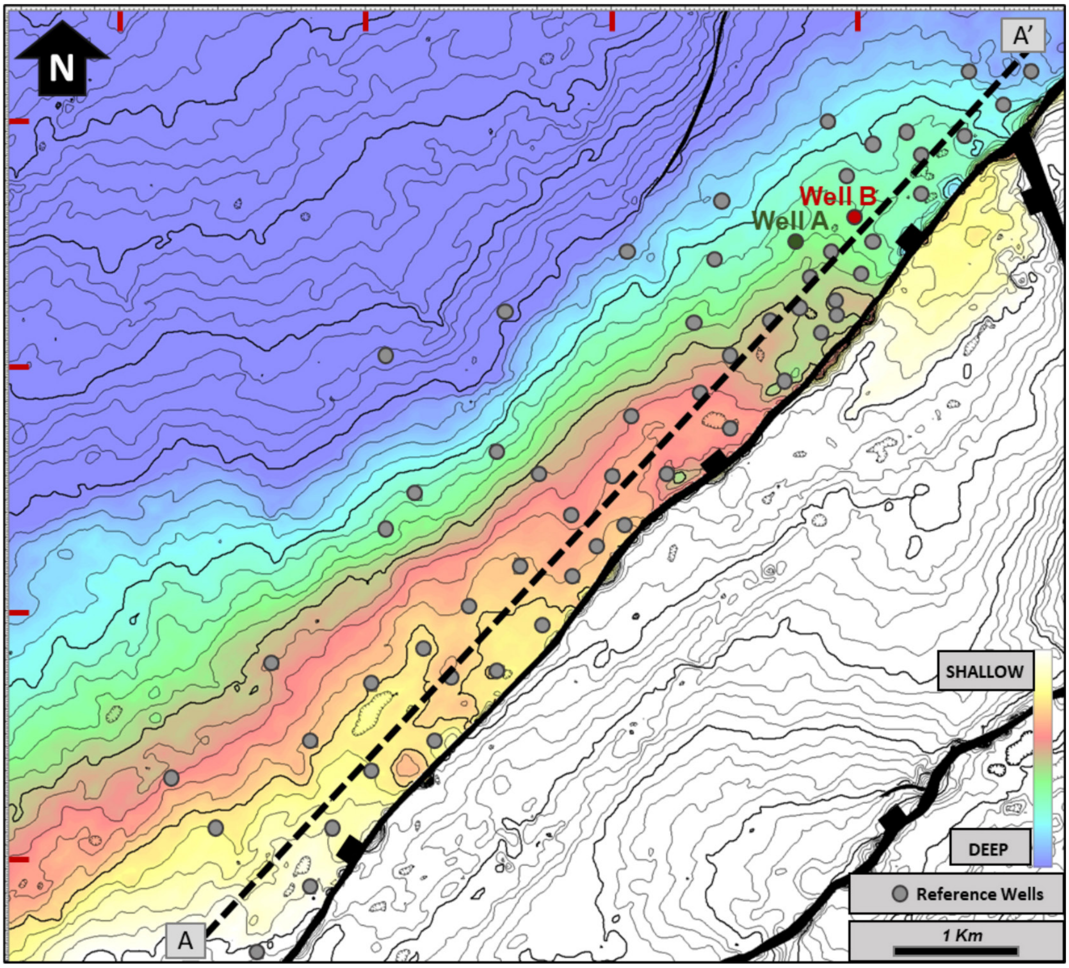

Figure 6. Structural Depth Map to the Top of the Oligocene Field. The oil accumulation is concentrated in the downthrown side of a normal fault NE-SW orientation. The structure opens out towards the south, with no structural closure providing trap. Contouring interval: 20ft.

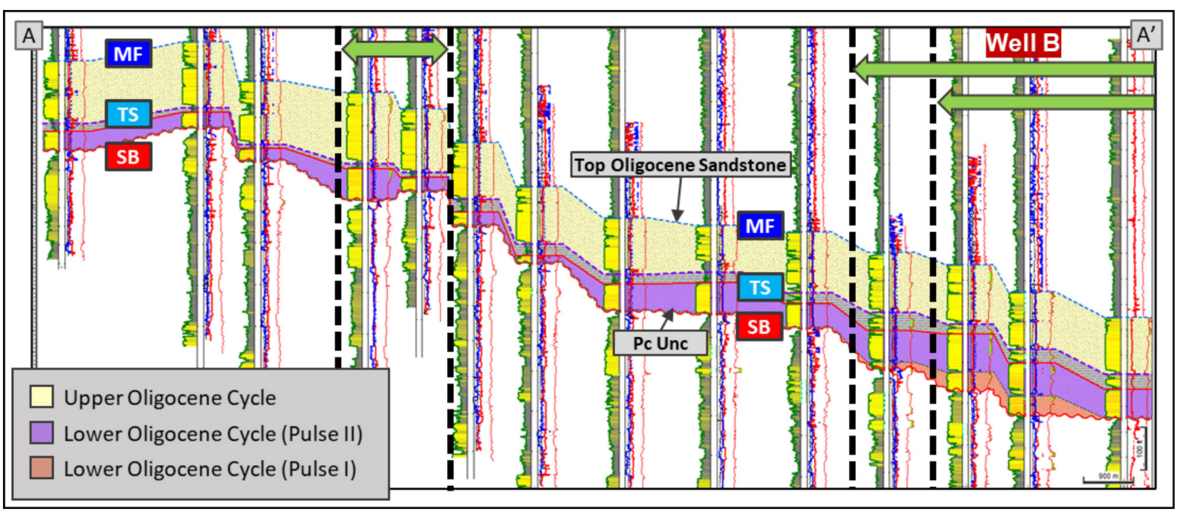

Figure 7. Hydrocarbon accumulations do not have unique OWC with no structural control. Arrows indicate accumulation limits within the same structure and black dashed lines: vertical arbitrary boundaries. Figure 6 illustrates cross-section and well location.

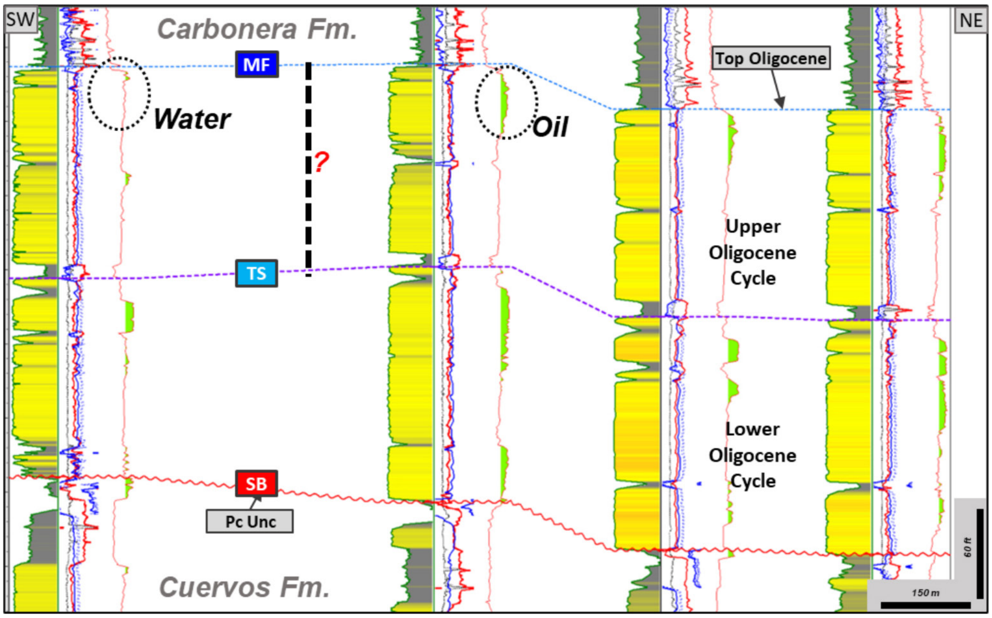

Figure 8. Structural correlation along strike exhibiting wells with different oil columns, interpreted from resistivity and supported by production. Wells are in a similar structural level. From left to right, curves: Green GR, blue-red Neutron-Density, thin red Deep Resistivity.

METHODOLOGY AND DATA SET

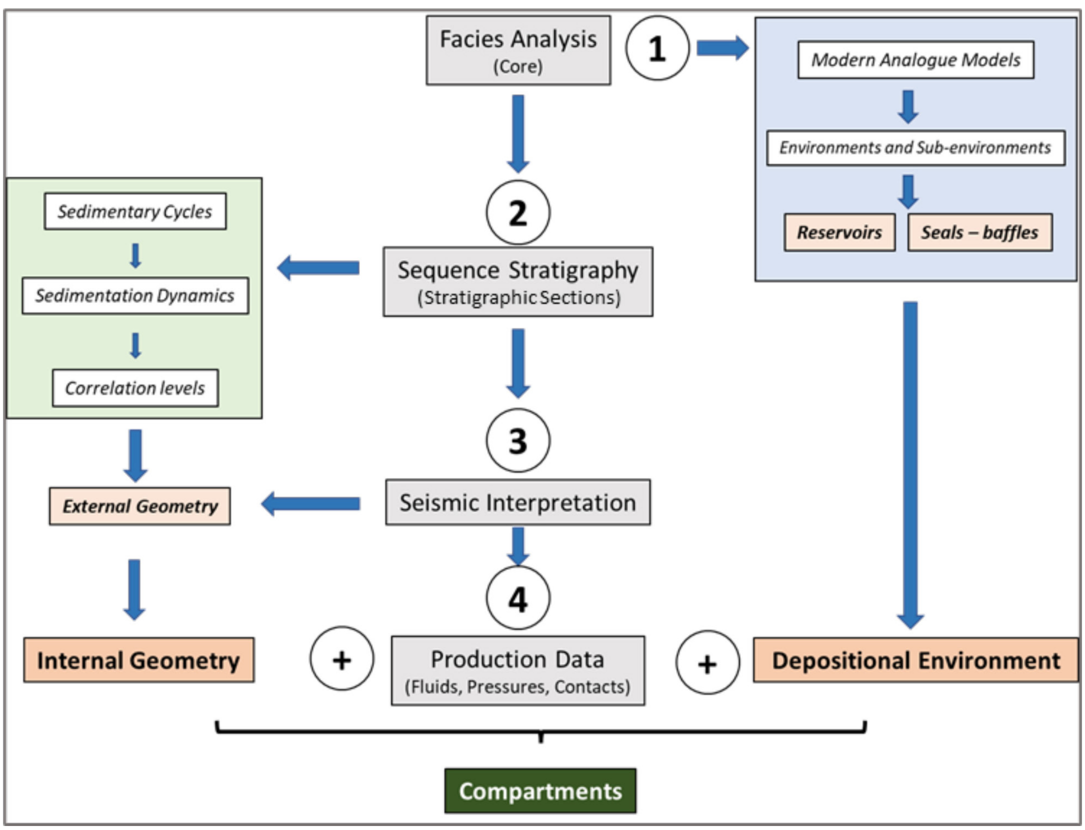

Figure 9. Methodology workflow.

Three scales of investigation were used to approach the understanding of the Oligocene reservoir. First, a sedimentological analysis was performed on the available core data. This provided the basis for a paleo-environmental interpretation and triggered the search for modern analogues that would eventually indicate the diverse sub-environments that may have coexisted during deposition. Simultaneously, a seismic-stratigraphic framework was constructed based on seismic interpretation and well log correlation panels. As a result, sedimentation cycles, dynamics and key correlations levels were obtained, which allowed the decoding of external and internal geometries of the deposit. Finally, the integration of the interpreted depositional environment, external and internal geometries, and production data (Fig. 9), provided the basis to propose a new model that honors geologically supported boundaries, oil water contacts, pressure regimes and fluid dynamics.

An exhaustive dataset was collected to accomplish this workflow, which included approximately 800 km^2 of 3D seismic data, well logs of more than 200 wells and 410 ft of cored intervals.

SEDIMENTOLOGY

The following section describes and shows the interpretation of each of the facies and facies associations that were identified in the available cored intervals of the Early Oligocene Sandstones. Each facies is the result of integrating textures, grain size distributions, ichnology, and sedimentary structures. The particular spatial and vertical arrangement of the facies indicate fluctuating energy regimes and therefore the overall depositional environment. Facies are presented in a descending order from coarse to fine-grained (Table 1 and 2). Most of the sandy facies present abundant oil stains.

F1: Massive Conglomerate Facies

Corresponds to reddish orange, granules to small pebbles; this facies exhibits massive to faint planar cross-lamination in sets of a centimetric scale. Bases are erosive and irregular. They are interpreted to be deposited by episodic unidirectional tractive currents within an overall low energy environment, possibly associated to highly diluted hyper-concentrated flows (Fig. 10a).

F1 Gmm	Massive Conglomerate Facies
F2 Sgt; St	Gravel Conglomerates with cross-stratification
F3 Sm; Smi	Massive Sandstones Facies
F4 Stcr; Spcr	Cross-Stratified Sandstone Facies
F5 Sb; Sbi; Scr; Scr-oph; Scr-sk	Intensely Bioturbated Sandstone Facies
F6 FSib; rizoliths and coal	Bioturbated Coaly Mudstones
F7 Fb; Fm	Laminated to Massive Mudstones with scarce bioturbation

Table 1. Facies Classification Summary.

F2: Conglomerates with cross-stratification

This facies is composed of granules of a light brownish red color. Sediments are arranged into planar cross-stratified sets of a centimetric scale. Bases are irregular to slightly erosive. The dominant texture is generally massive, with faint low-angle cross-stratification. Sorting is predominantly poor; a sandy matrix is present and there are no fossils or ichnofacies. These sediments were deposited by unidirectional tractive currents, likely to involve hyper-concentrated flows. Faint cross-stratification and occasionally massive textures could suggest the onset of a core bar formation (Fig. 10b).

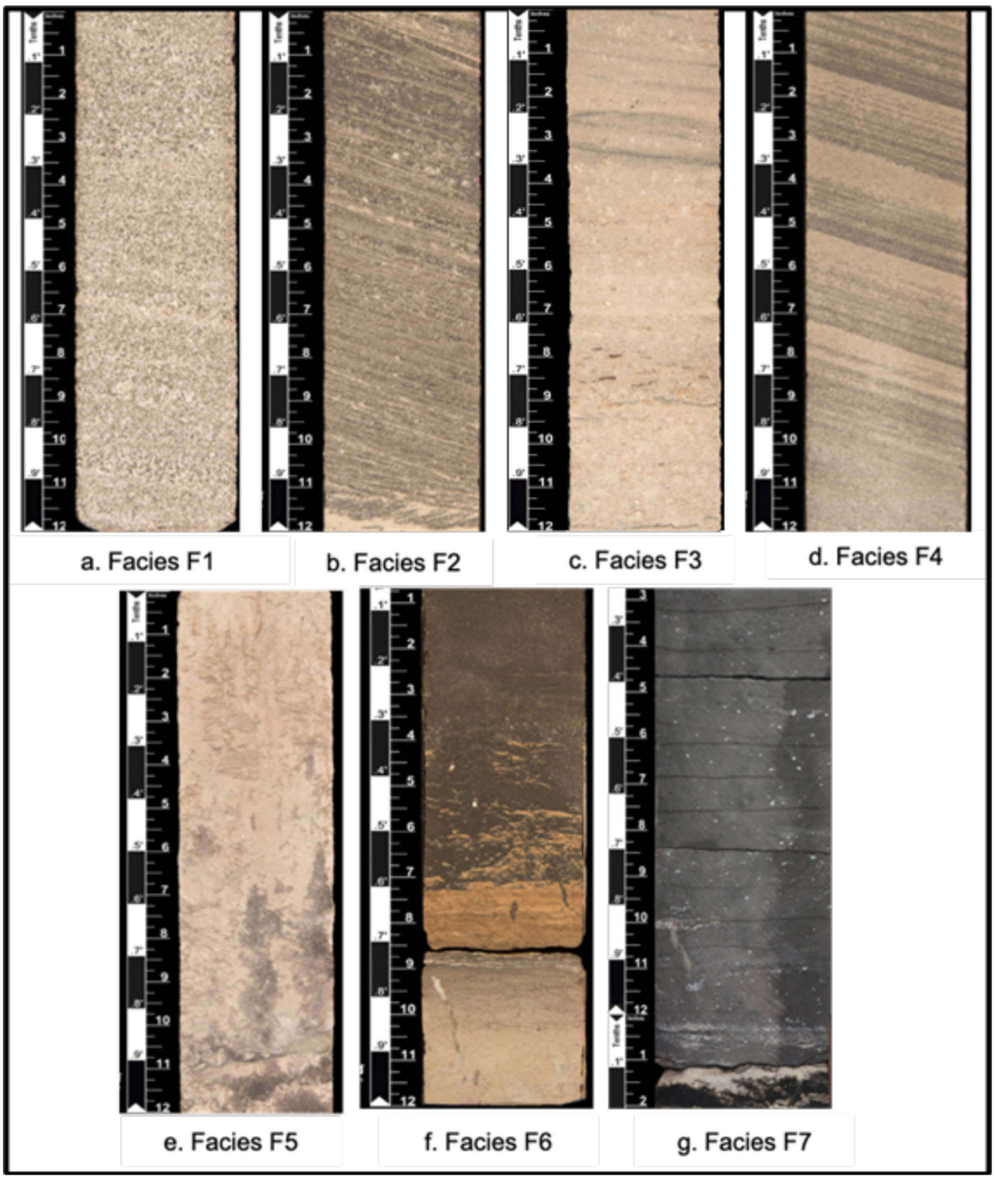

Figure 10. Facies of the Oligocene Reservoir.

F3: Massive Sandstones Facies

The F3 comprises light yellowish to brownish orange fine to medium grained sandstones. Identified sets fall within a centimetric scale. Bases range from irregular to planar. No internal sedimentary structures or bioturbation traces are observed. Sorting is poor and matrix support is observed. This facies is interpreted to be associated to ephemeral-episodic currents, possibly hyper-concentrated, corresponding to single-event type deposition. It also may be associated to fluvial-influenced flows with low sorting capacity (Fig. 10c).

F4: Cross-Stratified Sandstone Facies

F4 facies represents fine to medium sandstones with a light brownish yellow color. Sets range within a centimetric to decimetric scale. Bases are erosive to planar, exhibiting numerous reactivation surfaces. Internally, these units present medium angle cross-stratification, with noticeable changes in sedimentation transport polarity and a marked rhythmical bimodal grain size. Additionally, it is common to observe pre-existing sedimentary structures locally modified by cryptobioturbation. In terms of sedimentary processes and environment, this unit is interpreted to represent a low velocity tractive flow recording the migration of 2D dunes with evident changes in transport direction. Mud crinkles, flaser bedding and fine-grained layers, occasionally observed, are indicative of pauses in tractive sedimentation, suggesting tidal influence (Fig. 10d). This facies shows the most intense and abundant oil stains.

F5: Intensely Bioturbated Sandstone Facies

This facies is described as fine to medium grained sandstones with a brownish red color, grouped into sets of centimetric to decimetric scale. Bases are irregular to net planar, with internal sedimentary structures that have been completely obliterated by pervasive bioturbation (cryptobioturbation with some traces of Ophiomorpha and Skolithos). Internal stratification is therefore masked by biogenic activity. On few occasions it is possible to distinguish thin wavy lamination towards the top. This facies was deposited by low energy flows with manifest changes in transport polarity. The presence of bioturbation in varying intensities is indicative of fluctuating energy regimes that remain low enough to allow the colonization of organisms (Fig. 10e).

F6: Bioturbated Coaly Mudstones

Mudstones of a light brownish grey color have been classified into this F6 category. This facies is generally grouped into intervals of a centimetric scale interbedded with coal horizons and fossilized plant debris. Occasionally fossilized rootlets (rhizoliths) can be observed. This facies correspond to fallout processes occurring in extremely low energy subaqueous to supra-tidal environments, involving punctuated episodes of subaerial exposure (as interpreted from the presence of plant material, coaly intervals and fossilized rootlets, Fig. 10f).

F7: Laminated to Massive Mudstones with scarce bioturbation

This facies is composed of dark grey to black mudstones, generally grouped into intervals of a centimetric to decimetric scale. The dominant sedimentary structure is fine lamination to occasionally massive. Trace fossils can be found slightly modifying the original texture. These fall-out sediments were deposited in a quiet subaqueous sub-tidal environment at a moderate distance from shoreline and below the storm-wave base, possibly in a realm of scarce and undistinguishable organism activity (Fig. 10g).

FACIES ASSOCIATIONS

A. Meandering Fluvial Channels with Tidal Influence

Comprises facies F1, F2, F4 & F6. This stacking of finning upwards sequences, with erosive bases, conglomeratic lags, and rip-up clasts, is interpreted as the infill of fluvio-estuarine channels near the proximal section of an estuary. The basal lags represent the initial phase of erosion under high water discharge and sediment concentration. The conglomeratic sandstones represent the migration of 2D and possibly 3D subaqueous dunes.

The fine-grained sandstones, also with thinner sets, are representative of the uppermost part of this association. They are related to the final stages when flow velocity and energy diminish. The presence of mud drapes and alternating laminae of bimodal grain size suggests tidal influence (Shanmugam *et al.* 2000). The poor diversity of ichnofacies of this association reflects the relative high energy of flows and increased salinity, as both conditions inhibit the development of organisms. However, this setting promotes the development of cryptobioturbation, which can heavily modify sedimentary structures.

B. Tidal Channels

This association is composed of facies F4 and F5 and comprises medium to thick beds with net contacts, composed of fine (locally medium to coarse) criptobioturbated sandstones with some remnants of cross bedding. This crossbedding is composed of laminae of marked bimodality, regularly alternating fine and medium to coarse sands grains. Bedsets are in the order of 10 to 40 cm, with an average of 20 cm. The presence of mud drapes and discontinuous coal laminae is common. Also common are elongated and angular mud intraclasts and reactivation surfaces. To the bottom of this association Ophimorpha is frequently observed in horizontal caving, as far as the core interval reveals.

This association is interpreted as being deposited in tidal channels. The dominant sandy facies with cross stratification result from the migration of subaqueous dunes and represent the active infill of the channels. The alternation of two different grain sizes with two opposing directions indicates tidal influence. The low diversity of fossil traces and the occurrence of criptobioturbation produced by opportunistic biogenic communities suggest a saline-brackish water environment (Pemberton and Wightman 1992).

Minor tidal channels can also be distinguished, composed of medium to coarse sandstones (locally conglomeratic), criptobiotutbated with remnants of low-angle cross-stratification, occasionally massive. This type of channel is characterized by medium beds with erosive bases and rip-up clasts. These sediments are thus interpreted as being deposited by the active infill of minor channels (tidal creeks) formed during high-low tide cycles. They are developed in intertidal zones, cutting through the tidal plains, stretching out to supratidal zones. Criptobioturbation with faint cross-stratification and the lack of ichnoforms evidence high-sedimentation rates and the development of meiofauna.

C. Tidal and Subtidal Bars.

This facies association is composed of F3 and F4 and can be observed at the basal section of the Oligocene sequence, above an erosive contact. The vertical and lateral stacking of subaqueous 2D dunes (predominance of cross-lamination) is interpreted as the consequence of tidal bar accretion which occur at shallow tidal to subtidal sub-environments within the estuary (Shanmugam *et al.* 2000). Fine-grained facies and their associated sedimentary structures drape over dune foresets during slack water stages. The observed cryptobioturbated intervals formed within facies of cross-laminated sandy sediments.

Subtidal bars and estuary mouth bars can also be distinguished. These bars comprise fine- to medium-grained sands with abundant bioturbation, predominantly in the form of cryptobioturbation. Some intervals have completely lost their sedimentary structures due to the degree of bioturbation, however, other sets exhibit cross-stratification, interpreted as trough-type. This facies association presents the interlamination of fine-grained bioturbated sands with relicts of mud-silt wavy laminations that have been affected by feeding trace fossils (fodinichnia). In this type of bar, some intervals affected by Skolithos and Ophiomorpha were identified, predominantly towards the top of the association.

The Upper Cycle of the Oligocene Sandstone is dominated by these bar stacking associations, distinguished by coarsening-upwards sequences that begin with bioturbated fine-grained sand with remnant wavey lamination and end with fully bioturbated (Ophiomorpha zone) fine to medium sands. Subtidal to tidal bar stacking occurs in the external realm of the estuary mouth, generally associated to transgressive cycles and the final stages of estuarine infill.

D. Tidal Flats

This association involves facies F5 and F6. These sediments were deposited in intertidal flats of a sandy nature located in the internal to external (coastal sandy intertidal flats) realm of the estuarine system. This type of tidal flats is dominated by unconfined traction currents that were able to transport the sandy fraction. At this marginal-protected position, the intensity of tidal currents was relatively low, which allowed prolific bioturbation that ultimately obliterated pre-existing sedimentary structures. The low energy levels in this protected estuarine sub-environment, combined with episodical exposure to subaerial conditions resulted in a high diversity of biological activity of indistinguishable feeding burrows and ichnofacies including Thalassinoides, Teichichnus, Asterosoma, and Planolites (Buatois and Mángano, 2011).

The external coastal sandy flats involved traction currents with a higher energy regime when compared to the internal (estuarine) tidal flats. These high energy currents fluctuated occasionally, alternating episodes of high velocities and high sedimentation rates (restricting biogenic activity to Skolithos and Fugichnia) and episodes of lower energy and low sedimentation rates in which bioturbation conditions were established for longer periods of time, with abundant feeding burrows. During slack water stages, mudstone-siltstone laminae and mud drapes were deposited.

The presence of rhizoliths indicates plant colonization, possibly associated to progradation of the coastline in the context of bar stacking and accretion, or, alternatively, associated to plant colonization of the saline intertidal realm.

E. Interior Seaway

This association comprises facies F7 and occurs above F5. The finer grained facies association corresponds to an Interior Seaway setting, exposed to open shallow marine conditions. This association can be found towards the middle section of the sedimentary column of the Oligocene Sandstone, marking the boundary between two distinct stratigraphical cycles (discussed in the next section). This association comprises predominantly thick (50 cm) beds of bioturbated mudstones mottled with indistinct burrows that are locally sub-parallel to bedding, also including scarce fossil plant debris. Additional subordinate facies observed are fine to medium beds of bioturbated with Fodichnia and Thalassinoides trace fossils.

An interior seaway refers to a body of water of a regional extension with a connection to the ocean (in this case the Atlanitc) that developed in the Llanos Basin during the Mesozoic and Early Cenozoic, extending from northern Peru to northern Colombia and Venezuela (Jaramillo et. al. 2017; Louterbach *et al.* 2014; Boonstra *et al.* 2015). The dominant sediment deposition mechanism was suspension settling and fallout of mud size material at very low sedimentation rates, conditions that allowed the colonization and proliferation of biogenic activity. However, diversity remained low, probably due to salinity levels in the water column related to the highly restricted conditions of the interior seaway. The presence of plant debris suggests proximity to the coastline. Episodically, traction currents intervened in the system, transporting silt to very fine sandy sediments.

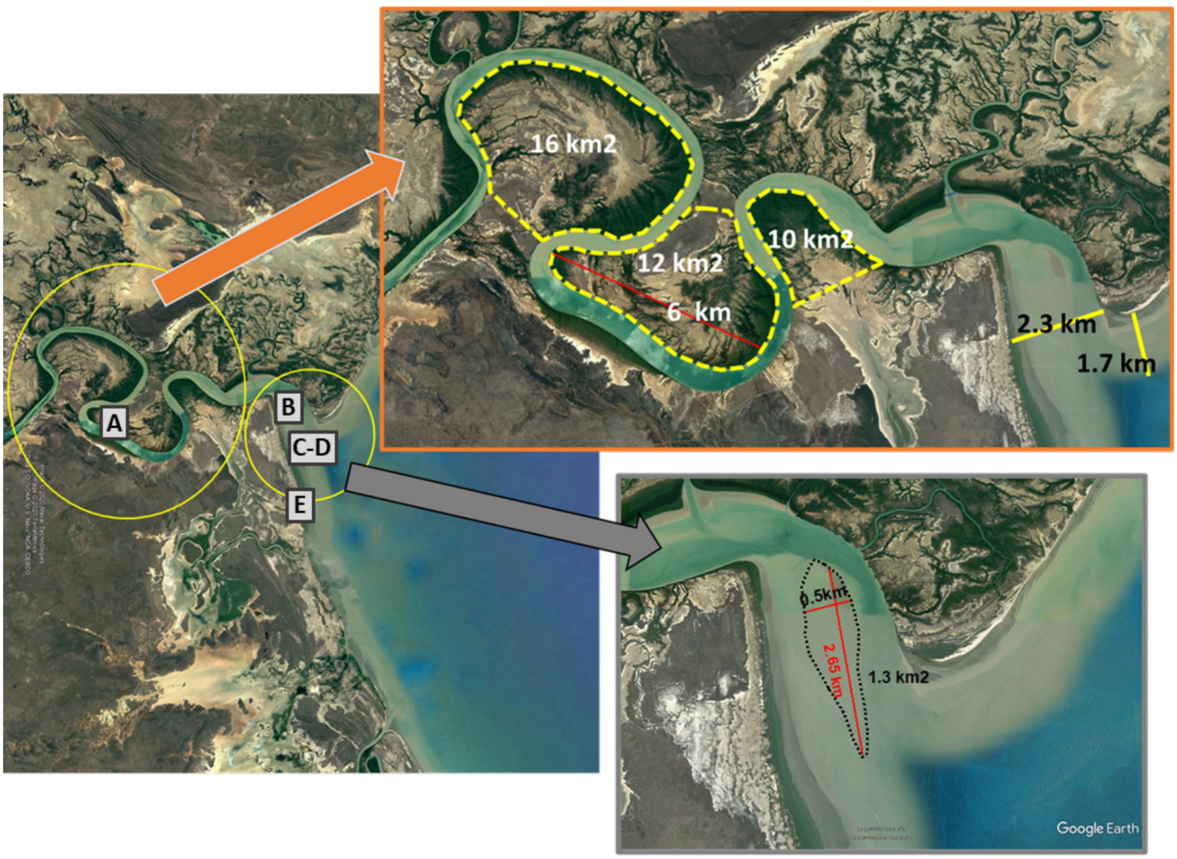

Figure 11. Modern Analogues, macroforms; point bars (A), mouth bars (B), subtidal to supratidal bars (C-D), muddy to sandy tidal flats (E). Roper river estuary, Northern Territory, Australia (Ashworth *et al.* 2015).

SEDIMENTARY ENVIRONMENT: MODERN ANALOGUES & CONCEPTUAL MODEL

Once the facies, facies associations and paleoenvironment were determined, a comparison with modern analogue settings was carried out to grasp the potential sub-environments and their lateral interactions. Many similar modern analogues were analyzed, including the Bahía Blanca estuary (Argentina) and the Ropper River estuary in Norther Australia (thoroughly studied by Ashworth *et al.* 2015). The purpose was to determine not only lateral relationships within the Oligocene estuary, but also to have an idea of the size and areal extent of the main components of the system (Fig. 11). This was crucial when stablishing feasible correlations by means of having an idea of, for example, how long one may correlate one single bed with another. Such knowledge allowed to discover, among other issues, that many of the stratal relationships that were already stablished in the pre-existing model (which included correlations of relatively thin beds of sandstones for almost 10 km without interruptions) were impossible to find in similar and modern depositional scenarios and thus, making it unrealistic.

The conceptual sedimentary model for the Upper Cycle of the Oligocene sequence is depicted in Fig. 13. The observation of modern analogs was important in terms of defining the possible dimensions of the different macroforms and morphologies that may be found in similar depositional settings. In Fig. 11 it is possible to appreciate the size of the subtidal bars, the width of the fluvial meandering channels (major and minor) and the importance of point bar deposits in the order of 10 to 16 km2. This also points out to the value of modern depositional areas when considering potential stratigraphic/combined traps.

Sequence Stratigraphy

A sudden decrease in the accommodation space in the eastern zone of the platform occurred during the Late Paleocene. Therefore, incisions over the Cretaceous-Paleocene deposits were produced, locally creating incisions in the order of 100 ft (this work). The surface of the resulting topography was exposed during the entire Eocene in a context of tropical, humid climates. This pervasively weathered surface constitutes a basin-wide horizon of an aluminum-rich kaolinitic mudstone, which represents a key element in the petroleum system of the Cretaceous-Paleocene reservoirs, since it acts as an excellent regional top-lateral seal above the Late Paleocene Unconformity.

Net sedimentation restarted during the Early Oligocene with the onset of a transgressive episode that flooded the preexisting incised valley topography. This means that deposition occurred ca. 20 myrs after erosion. Consequently, erosion and accumulation processes should not be considered as a single simultaneous event.

During the final stages of infill, when the accommodation potential started to gradually decline, deposition progressively shifted in a basin-ward direction, consequently promoting the stacking (progradation and lateral accretion) of sandy macroforms.

According to Zaitlin *et al.* (1994), incised valleys may be classified into piedmont and coastal plain systems. While the former have their headwaters in a mountainous hinterland and are characterized by longer fluvial reaches, the latter are confined to low-gradient coastal plains that do not cross "fall line". Also, piedmont systems more commonly contain coarse-grained immature fluvially derived sediments, whereas coastal plain systems are usually filled by finer-grained more matured deposits, recycled by coastal plain processes (Fig. 12a).

Furthermore, the infill of any incised-valley system may be classed as either simple or compound depending on the absence or presence, respectively, of multiple, internal sequence boundaries (Fig. 12b). If the valley is filled completely during a single Low Stand (LST)-Transgressive (TST)-High Stand (HST) sequence, the fill is classified as a "simple fill". A compound fill records multiple cycles of incision and deposition resulting from fluctuations in base level and is therefore punctuated by one or more sequence boundaries in addition to the main sequence boundary at the base of the incised valley. Matching Zaitlin *et al.* (1994) criteria, in terms of physiographical context and infill complexity, the incised valley analyzed in this paper, corresponds to a coastal (low gradient coastline, not associated to fault scarps or mountain range) type setting with a simple infill.

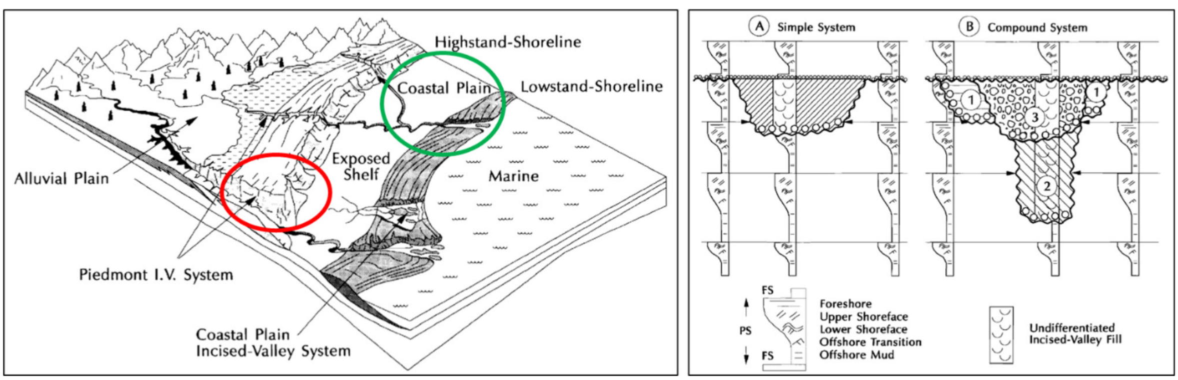

Figure 12. (a) Incised valley type – Coastal (blue circle) vs Piedmont (red circle), (b) Simple vs Compound infill. Modified from Zaitlin *et al.* (1994).

Internal Subdivision

The Early Oligocene infill spans approximately 7 myrs, comprising biozones T08 to T10 (Jaramillo *et al.* 2011) Therefore, it corresponds to a third order tecto-eustatic cycle according to Kerans and Tinker (1997). This single lowstand, transgressive and highstand system tracts (LST-TST-HST) infill may be grouped into: lower and upper depositional cycles, which will be described in the following sections.

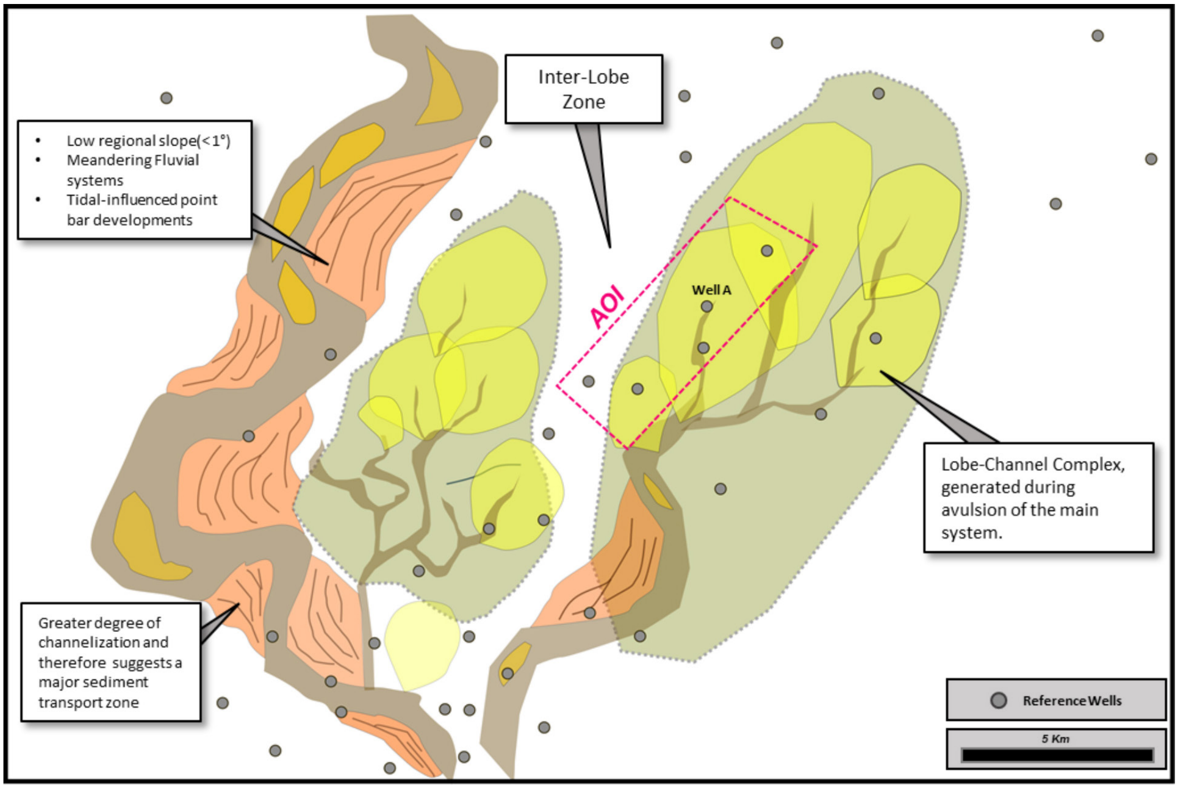

Figure 13. Conceptual Sedimentary Model, Upper Oligocene Cycle.

Lower Depositional Cycle

First stage of net accumulation of sediments started after the rate of eustatic sea-level drop reached its minimum and slowly began to rise (Fig. 14). Thus, the accommodation potential in the platform started to gradually increase. In this context, the basal deposits of the Oligocene reservoir overlay the underlying sequences only causing minor erosion. This is evident from the regional preservation of the aluminum-rich kaolinitic mudstone underlying this unit. When sea level rose and drowned the incised valley network, the transitional low energy paralic environments of the lower depositional cycle were established, associated with estuarine deposits with fluvial-tidal influence.

The main sub-environments involved are (Fig. 11 and 13): (1) tide influenced point bars, (2) fluvial flood plains, (3) bay-head deltas, (4) tidal bars, (5) tidal flats, (6) tidal channels, (7) inter-tidal flats, and (8) beach line zone (low energy). A regional TST episode marks the end of the Lower Depositional Cycle, in which a 10-20 ft mudstone layer was deposited as a consequence of a basin-wide flooding event. The depositional environment associated to this internal flooding event is interpreted as an outer shelf system. This mudstone behaves as a regional seal between the hydrocarbon accumulations of the Lower and Upper Depositional Cycles. The deposition of a basin-wide flooding event is interpreted as an allocyclic event triggered by out-of-the-system changes and thus represents the most horizontal surface to use as a datum (flattening reference) in cross-sections, acting as a key correlation level (Bayona *et al.* 2006).

Upper Depositional Cycle

The final stage of net accumulation of sediments started after the TST episode. In this context, the rate of eustatic sea level rise began to decrease until reaching a minimum. This triggered a gradual decrease in accommodation space in the platform. Consequently, sand bodies prograded towards the interior of the basin. Thus, the first deposits of the Upper Cycle found a relatively flattened relief to prograde onto, in contrast to the case of the Lower Cycle which was deposited in an irregular topography. The deposits of this HST are characterized by bodies accumulated in transitional environments but with a marked progradational trend.

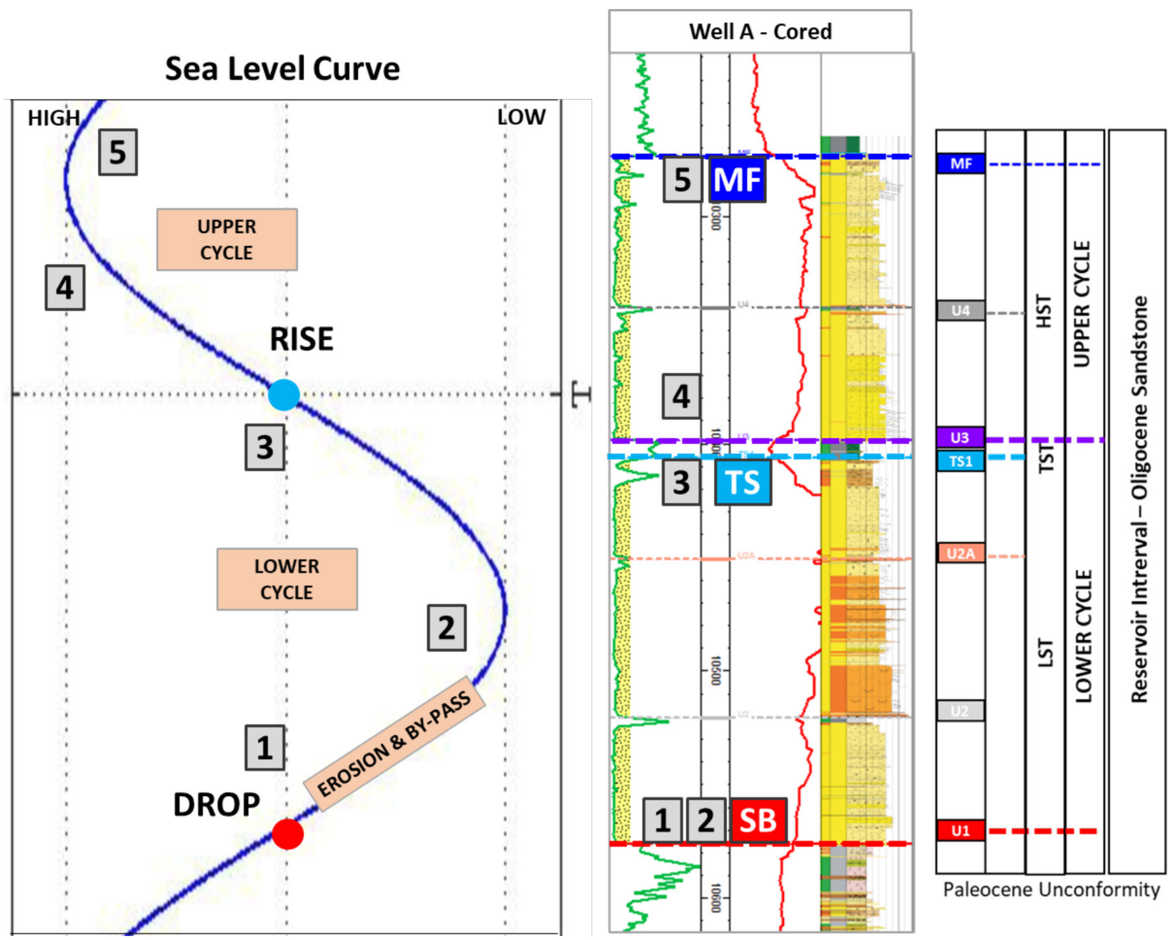

Figure 14. Oligocene sequence subdivision according to fluctuations in accommodation potential. Type well & main depositional cycles.

GEOLOGICAL RESERVOIR MODEL

External Geometry

The Oligocene sequence exhibits areas of variable thickness, not associated to structural reasons. In order to define the internal architecture of this deposit, it is fundamental to begin by defining the external geometry. Unfortunately, preparing isochron maps of the Oligocene sequence alone (seismic or well derived) is not enough to determine the overall external geometry of the interval: they cannot discriminate whether the unit increase its thickness either by the base or by the top.

To unravel this important stratigraphic element, 3D seismic data played an important role. Two isochrons maps where elaborated: (A) of the Oligocene sequence itself and (B) of a "reference" isopach between the top of the Oligocene sequence and the closest continuous reflector above it. These isopach maps were then placed on top of each other and the following conclusions were made: (1) the places where the Oligocene sequence thickens but the reference isopach map shows

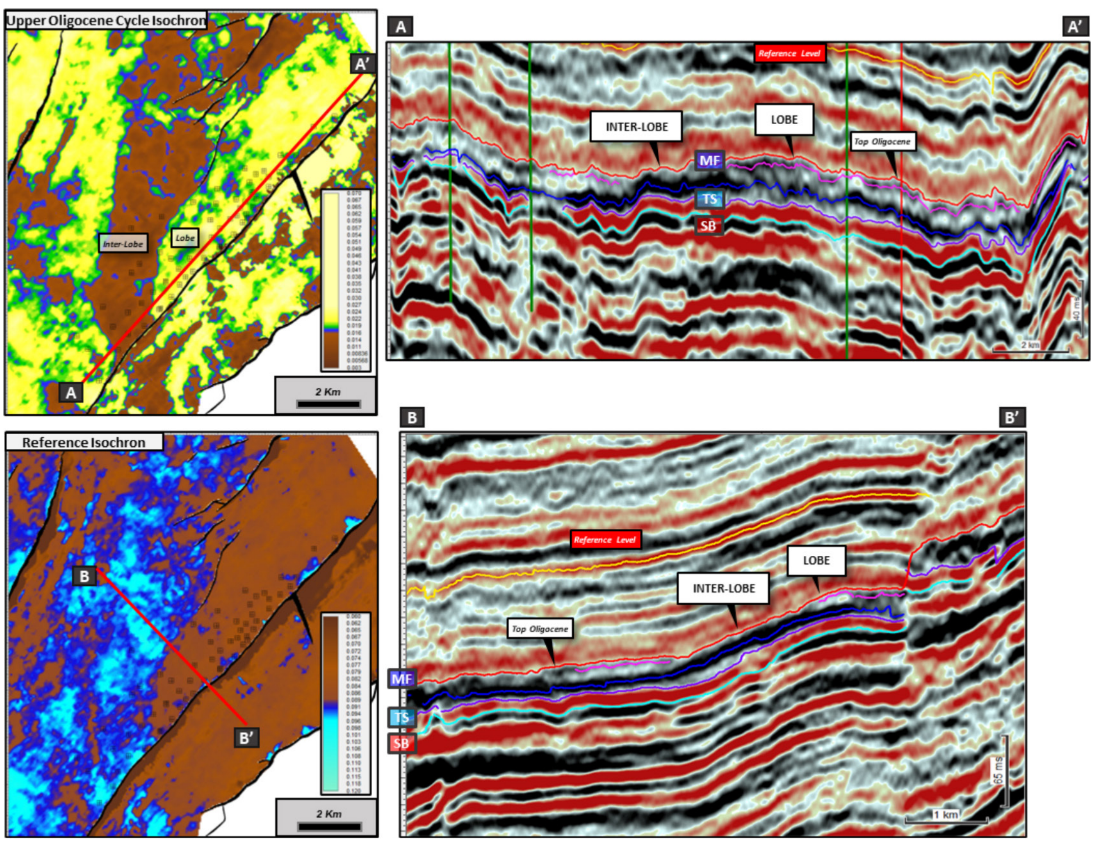

Figure 15. External geometry interpreted from seismic data. Top left: Upper Oligocene isochron - yellow represents higher (time) thickness. Bottom left: Reference isochron - blue represents higher (time) thickness. In both sections a lobate surface can be clearly defined at the top of the Oligocene reservoir, delineating lobe and inter-lobe sectors (note that structure was not removed in seismic sections shown).

a reduction in thickness indicates that the Oligocene reservoir increases by the top, (2) when the Oligocene sequence isopach shows an increase in thickness but the reference isopach shows either constant or increasing thickness, the Oligocene sequence is interpreted to grow by the base.

This thickness increase by the top can be clearly appreciated in certain seismic sections as a lobate surface on the top of the Oligocene sequence (Fig. 15 and 16). Isochron maps allow the removal of the structural component on the Oligocene, enhancing the structurally unaffected external depositional geometries.

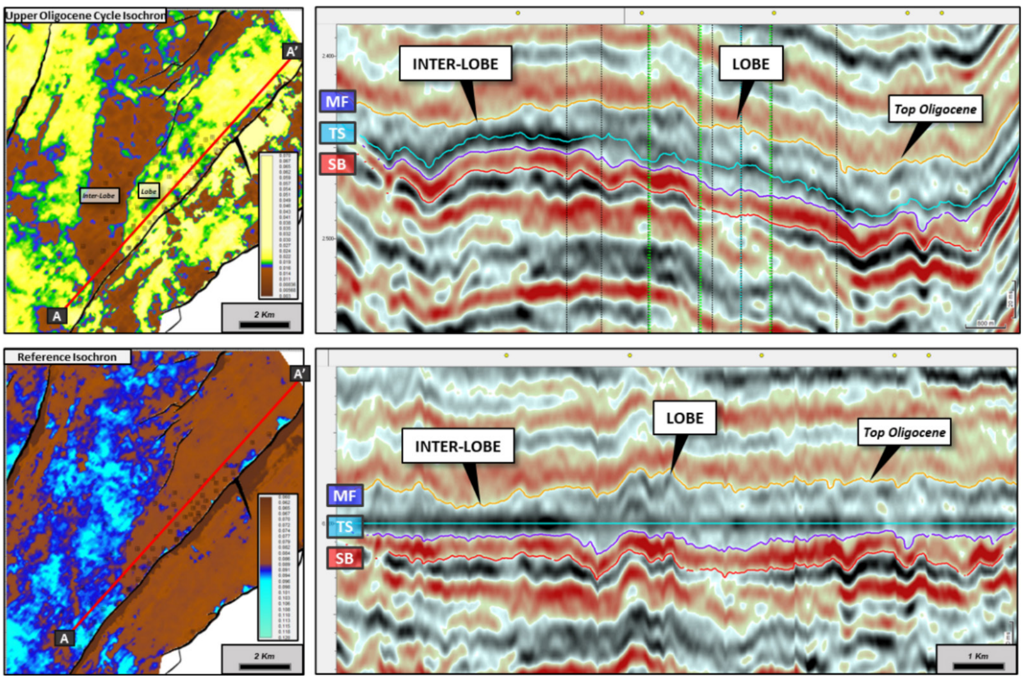

Figure 16. Top left: Upper Oligocene isochron - yellow represents higher (time) thickness. Bottom left: Reference isochron - blue represents higher (time) thickness. Structural (top right) and flattened (bottom right) seismic section revealing the lobular geometry observed for the Upper Oligocene Cycle, when removing structure.

Internal Architecture and Boundaries

Considering the physical features inferred from the facies analysis and from the modern analogues, this lobate morphology appreciated in seismic sections can be interpreted as the result of macroform (tidal bars) migration and stacking to the north and west. Lateral accretion of bars was not only the cause of the lobate morphology of the Oligocene sequence top, but also the cause of a series of low angle dipping bounding surfaces. This natural boundaries between the accreting bars exhibit downward changes in lithology that eventually constitute hydraulic barriers between reservoir sand bodies. Therefore, the reservoir architecture involves both reservoir sandy compartments and the internal seals that disconnect them, producing different OWC and pressure regimes, from one bar set to another. These bounding surfaces are not exclusively composed of fine sediments but may involve highly bioturbated sediments or even cemented levels affected by early siliciclastic diagenesis.

The stratigraphic correlation and outlining of the different reservoir bodies was direct by following criteria: (1) knowing the depositional environment (based on core study), (2) the associated macroforms (shape, size, degree of interconnectedness, etc.) developed in such environments (deduced from modern analogues), and (3) honoring the different OWC and pressure regimes.

The need of a new way of interpreting boundaries between reservoir compartments arose when comparing two nearby wells in terms of fluid type, API gravity distributions, and pressure regimes. The extreme case showed two adjacent wells (spaced 300 m), at the same structural level, one water bearing and the other fully saturated with oil.

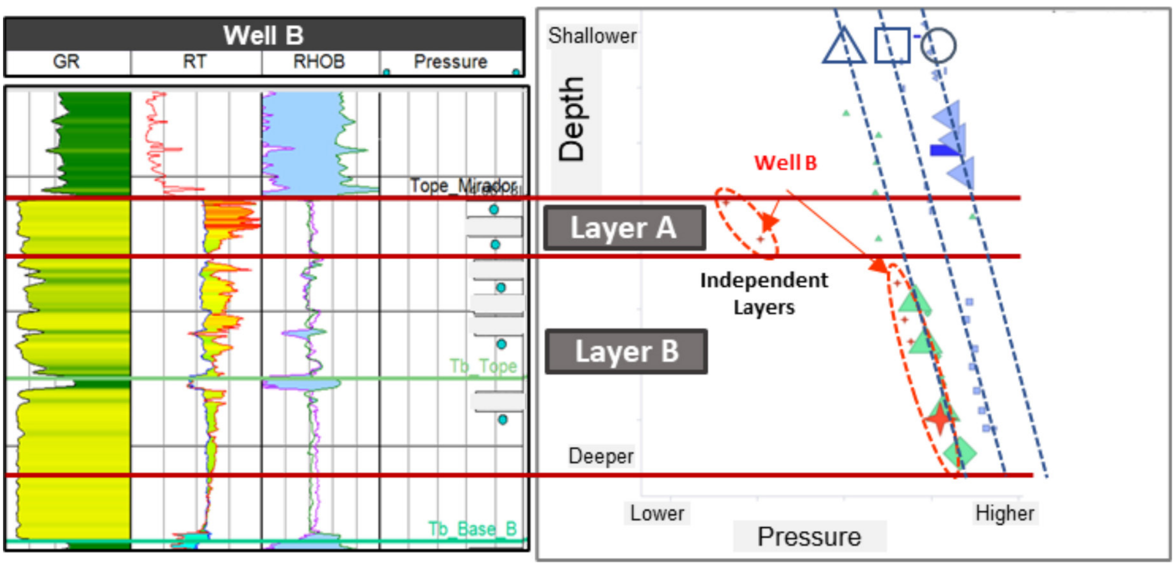

Figure 17. Different pressure regimes for an apparent homogeneous sandstone body, evidencing effective disconnections that explain different fluid contacts and depletion histories (Layer A vs Layer B). Each gradient (dotted blue lines) represents different reservoir pressure regimes within different compartments.

Modular dynamic tester (MDT) pressure data (Fig. 17) carried throughout the most recent wells in the field for the Oligocene reservoir reveal clear pressure compartments at positions in which electric logs do not indicate limits or sealing lithologies. This pressure data points-out to: (1) different pressure compartments in both vertical and lateral directions within an otherwise apparently homogenous sand sequence and (2) different depletions histories for each of the sand bodies that compose the internal sedimentary architecture.

The resulting model proposes a complex lower cycle composed of channels, bars and supratidal sandflats. Internally, seismic resolution is not enough to depict each architectural element. However, such elements could be inferred from well correlation panels that honor both sedimentological (core facies analysis) and stratigraphical derived from this work.

For the Upper Cycle, nine different vertical accreting bars were recognized (Fig. 18). The younger 7 and northern bars are oil bearing (with different contacts and regimes) and are located at the lower structural position. The two oldest and southern bars, in turn, are fully water bearing and are located at the crest of the structure. This situation indicates the dominance of a stratigraphic control in the distribution and accumulation of the hydrocarbons.

Lastly, a static model was elaborated based on interpretation framework and underwent an initial stage of dynamic simulation with promising results that will continue to be refined and feed back into this new sedimentary model.

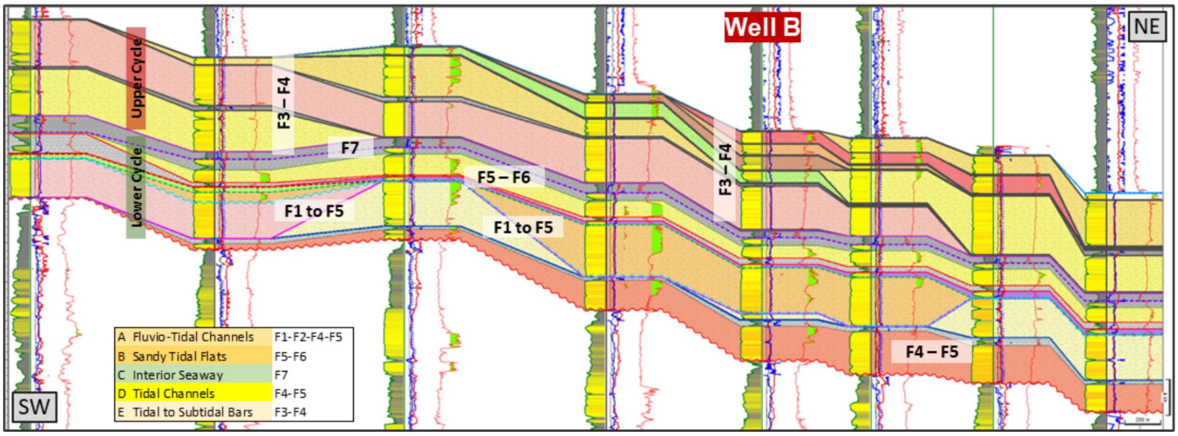

Figure 18. Well correlation and sedimentary architecture for the Oligocene upper cycle in the Oligocene field. Figure 6 illustrates cross-section and well location. Well B: cored interval.

SUMMARY AND CONCLUSIONS

The study of reservoirs and their behaviors is crucial for the definition of an effective development plan. Reservoirs are composed of rocks deposited in various depositional environments which bear specific characteristics in terms of facies and internal architecture. The presence of different macroforms with diverse morphologies, sizes, connectivity makes that each reservoir should be assessed uniquely. Therefore, to evaluate a reservoir comprehensively, these internal complexities must be understood and considered when making stratigraphic/ sedimentological correlations.

The methodology proposed in this paper is the result of numerous iterations and feedback from reservoir engineering data. The initial approach to interpret the ELB Oligocene reservoir was to establish correlations without considering the internal sedimentary architecture. Instead, correlations were guided by the misleading concept of assuming that similar electro-facies meant time equivalent bodies. This resulted in 10km wide layer-cake bodies that were unable to explain the complex fluid distribution and limits along the field.

A better way to approach the understanding of a particular reservoir is to consider the morphology, size, interconnectedness, and natural boundaries of the macroforms that developed within the depositional environment of the reservoir. The natural boundaries between these macroforms may act as hydraulic barriers, eventually dividing the reservoir into discrete compartments that will define the field development plan.

Bearing this consideration, it was possible to delineate a predictable model for the internal sedimentary architecture and production behavior for the Oligocene Field. According to the palynological data, the Oligocene sequence extended for approximately 7 myrs, thus corresponding to a 3rd order depositional sequence (Kerans and Tinker 1997). Due to the fluctuation of accommodation space through time, two main depositional cycles (LST-HST), separated by a regional flooding event (TST), were identified. The older cycle (LST-TST) represents the initial transgressive infill of the incised valley network within a tidal setting possibly influenced by fluvial processes. The younger cycle (HST) comprises deposits accumulated in an estuarine to low-energy marginal marine scenario with strong tidal control.

Each cycle exhibits very distinct depositional morphologies and correlation surfaces when observed in seismic data. At well log scale, surfaces that constitute natural fluid boundaries were identified (e.g., Fig. 17), responsible for the non-unique fluid contacts and pressure regimes within field.

In contrast to the pre-existing layer-cake model, this new approach allowed the correlation of sand bodies based on the depositional morphologies of the architectural elements within the paleoenvironment. These correlations resulted in the definition of reservoir compartments bounded by natural surfaces between macroforms. The static model derived from this interpretation (tested by dynamic simulation) helped to largely explain the complex distribution of fluids and pressures in the reservoir.

This case-study may offer an alternative approach that can be applied to evaluate the internal complexity of such stratigraphic/combined traps in similar exploration and production scenarios.

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