TECTONO-STRATIGRAPHIC CONTEXT FOR THE CRETACEOUS-TERTIARY BOUNDARY IN THE PUTUMAYO FORELAND BASIN, COLOMBIA

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Keywords: Putumayo Foreland Basin, N-Sandstone, Tectono-stratigraphy, Tidal Deposits, Stratigraphic Trap, Cretaceous-Tertiary Boundary

RESUMEN

La cuenca del Putumayo (PFB) se localiza en el sector norte de la mega-cuenca de Marañon-Oriente-Putumayo (MOP). Sin embargo, la cuenca del Putumayo representa tan solo la cuarta región en producción para Colombia. Cohembí, el campo de mayor producción (intervalo Cretácico-Terciario), es un ejemplo del potencial reservado de la cuenca. Este intervalo Cretácico-Terciario presenta una sección arenosa de 40ft conocida como la Arena-N, depositada en un ambiente estuarino influenciado por mareas. Estratigráficamente, la Arena-N yace discordantemente sobre lodolitas carbonáticas de plataforma, sin la presencia de los ambientes de depósito intermedios, marcando una pérdida abrupta del espacio de acomodación en la plataforma. A pesar de su amplio desarrollo en gran parte de la cuenca, este intervalo no tiene una distribución uniforme: está fuertemente restringido a bajos topográficos controlados por procesos de deformación activos al momento de la depositación. Un episodio puntual de inversión durante el Cretácico Tardío, asociado al levantamiento de la proto-Cordillera Central, fraccionó la cuenca en altos y bajos topográficos de bajo relieve, pero sin conexión lateral. En términos de la interpretación sísmica, los depósitos de la Arena-N están caracterizados por un reflector de baja impedancia que genera anomalías relativas de baja amplitud. Los reservorios asociados a estos depósitos fluvio-estuarinos son clave para el futuro de la exploración en el PFB, la caracterización sísmica, estratigráfica-sedimentológica y tectónica es fundamental para encontrar trampas estratigráficas sutiles. Este estudio puede además servir como guía para futuros trabajos que busquen disminuir riesgos exploratorios en la región del MOP.

ABSTRACT

The Putumayo Foreland Basin (PFB) constitutes the Northern end of the prolific Marañon-Oriente-Putumayo Megabasin (MOP). However, the Colombian sector (Putumayo) of the MOP

represents only the fourth oil producing region in country. Despite some significant discoveries made since the 90´s, this basin remains underexplored. The highest producing Cohembí Field (Cretaceous-Tertiary interval) is an example of this untapped potential. This interval is represented by a 40ft thick sandstone (N-Sandstone), deposited in a tidally influenced environment. Stratigraphically, the N-Sandstone lies unconformably above carbonaceous mudstones, without the occurrence of the intermediate depositional systems, indicating an abrupt loss in accommodation space. Despite its basin wide extension, this interval does not have a uniform spatial distribution along the basin: it is entirely restricted to topographic lows which were substantially controlled by the tectonic regime. An early episode of inversion during the Late Cretaceous, associated to the onset of the Cordillera Central uplift, segmented the basin into areas of subtle topographical highs and lows. In terms of the seismic point of view, the Cretaceous-Tertiary deposits are characterized by low impedance reflectors which generate a relative low amplitude anomaly. Petroleum

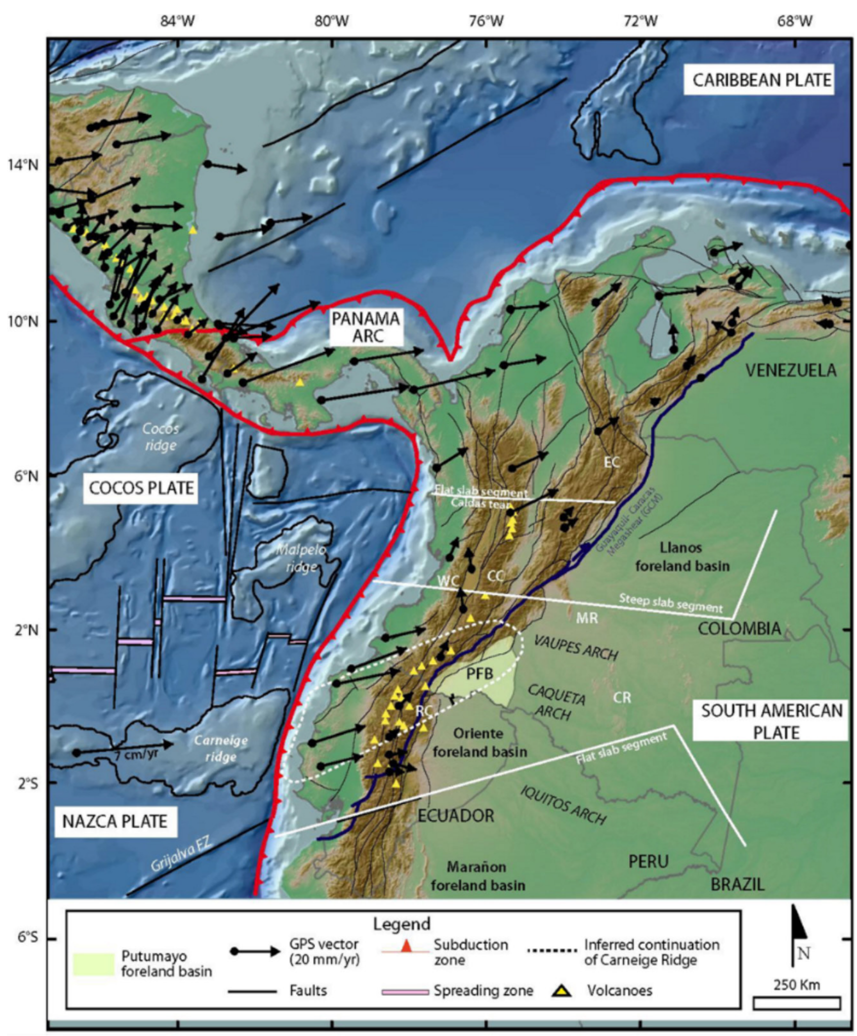

Figure 1. Location Map with GPS plate motion vectors and dominant tectonic features for northern South America (modified from Pachón-Parra 2020; Trenkamp *et al*., 2002).

reservoirs associated to fluvial-tidal transition are key for future exploration targets in the PFB, the stratigraphic characterization and its relationship with the tectonic regime constitute the main elements to unravel the location of stratigraphic and subtle traps. Therefore, the case presented in this study may bring new lights to mitigate future risks when exploring new opportunities in the PFB and the rest of the MOP.

INTRODUCTION

The Putumayo Foreland Basin (PFB) is the northern termination of the Marañón-Oriente-Putumayo (MOP) sub-Andean foreland basin system, which extends from northern Peru to southern Colombia (Fig.1). The MOP Basin is the result of multiple tectonic episodes in the overall context of continent-oceanic plate interactions (Vallejo et la., 2021, Baby *et al.*, 1999). The Oriente Basin is a highly productive hydrocarbon province. There is no geological feature separating the Putumayo and Oriente Basins, the boundary is purely political at the border of Colombia and Ecuador. However, production from the PFB remains comparatively low, with a very limited exploration history (Fig. 2). Therefore, efforts are being made in compensating the lack of exploration on the Colombia (Putumayo) side of the MOP.

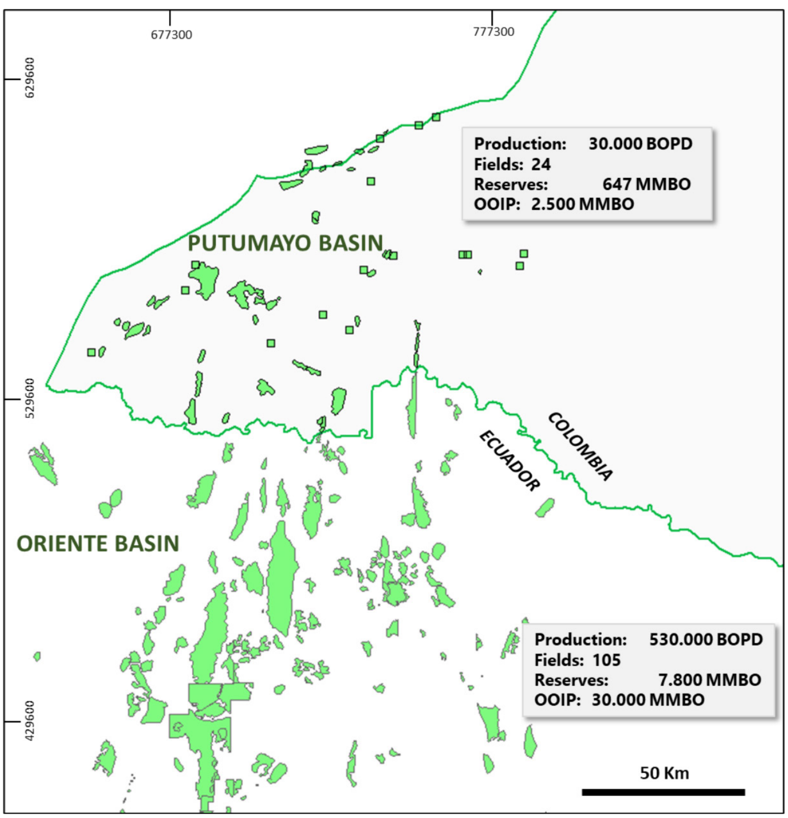

Figure 2. Hydrocarbon fields of the Putumayo Basin (Colombia) compared to the Oriente Basin (Ecuador).

Recent acquisition of 3D seismic data in the central foreland sector of the Putumayo Basin (area of interest for this study, Fig. 3) has provided the basis for further understanding its tectono-stratigraphic evolution, with a direct application to the exploration of hydrocarbon accumulation in this profoundly under-explored basin. More specifically, this study focuses on the tectono-stratigraphic context of the Cretaceous-Tertiary boundary, an interval with high potential in terms of hydrocarbon accumulations. Fields discovered to this sequence have revealed a strong stratigraphical component controlling the trap configuration. The Cohembí Field, with an average production at 5800 BOPD (ANH 2021) from the Cretaceous-Tertiary interval, is an example of this untapped potential.

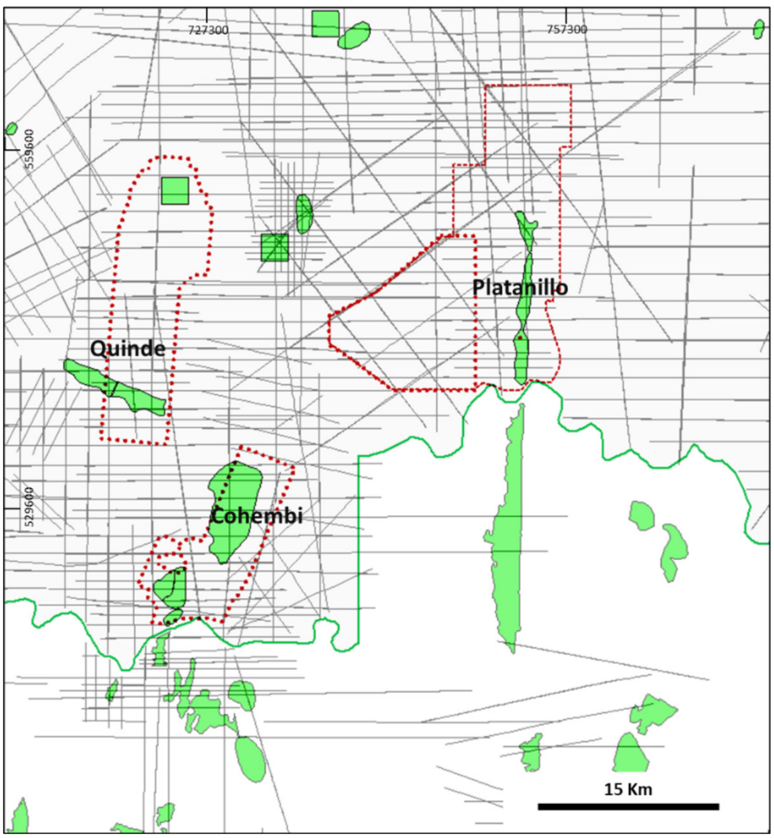

Figure 3. Area of Interest, showing the existing fields and the 2D and 3D seismic coverage available.

GEOLOGICAL SETTING

The PFB belongs to a large-scale sub-Andean Foreland Basin system that extends from northern Peru to northern Colombia and Venezuela, developed between the Guyana Shield to the East and the Andes Cordillera to the West (Fig.1). This system formed as a result of an ocean vs continent plate convergence that started during the Late Triassic. Prior to the inversion of the

Eastern Cordillera during the Miocene, the PFB was connected to the Upper Magdalena Valley Basin (Pachón-Parra *et al.*, 2020). The PFB in its present-day configuration is limited to the West by the Eastern Cordillera and the Neo-Proterozoic Garzón and Quetame Massifs; to the North by the Macarena Arch, to the East by the Florencia Arch, but continues to the South as the Oriente Basin (Fig.4).

The PFB is a retro-arc foreland basin assembled as an asymmetrical sedimentary wedge of a Late Jurassic to Cenozoic sedimentary column that rests upon Proterozoic to Paleozoic rocks and thickens westwards onto the Eastern Cordillera, achieving a 5 km thick column (Fig. 5). The sedimentary infill (particularly the Cretaceous to Eocene sequences) wedges out to the east onto a forebulge feature identified as the Florencia Arch (Fig. 6).

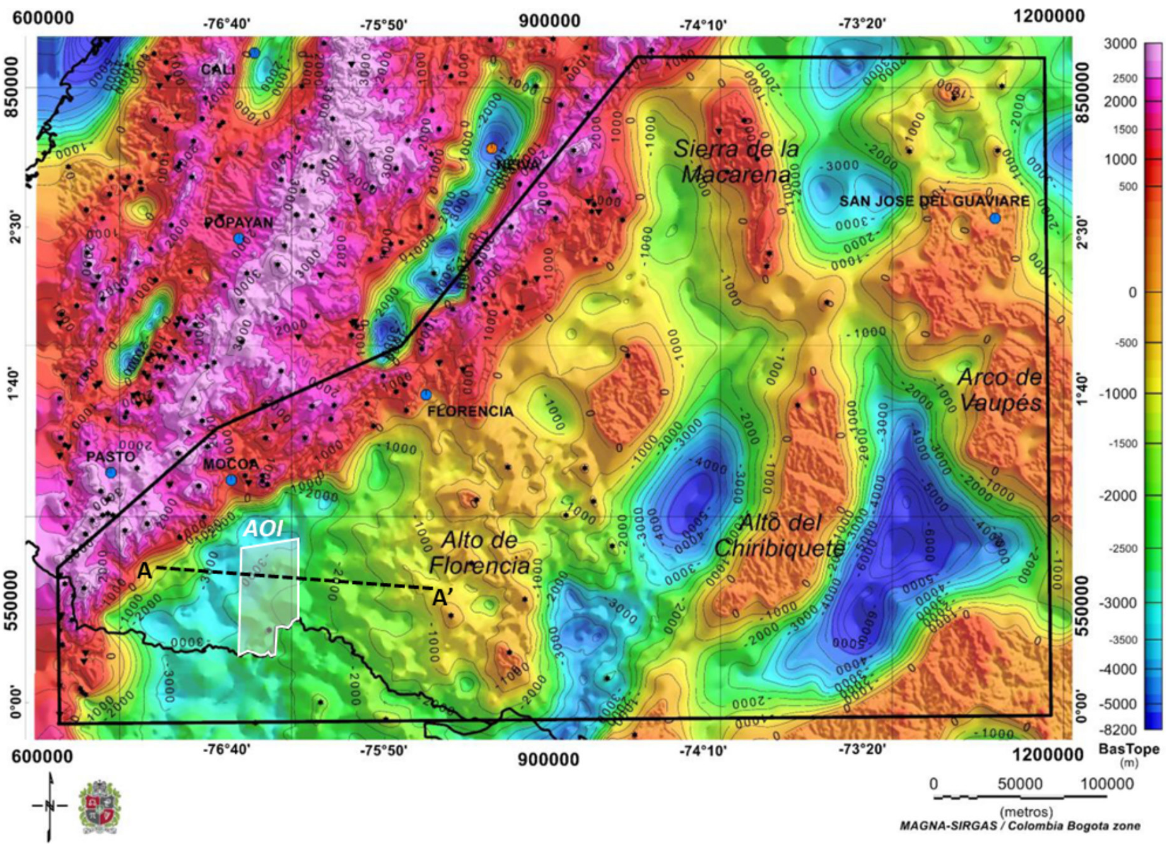

Figure 4. Top Basement Map for the PFB: 3D Gravimetric inversion for the controlled residual (Vargas 2020).

Deposition in the PFB begins during a stage of retro-arc subduction-related extension during the Late Jurassic with the Saldaña and Motema formations of a volcano-clastic origin. This Pre-cretaceous sequence is deposited within a horst-graben back-arc basin. The Lower Cretaceous (Pre-Albian) is represented by a regional unconformity, driven by a compressional event (Vallejo *et al.*, 2021, Litherland *et al.*, 1994, Ruiz, 2002).

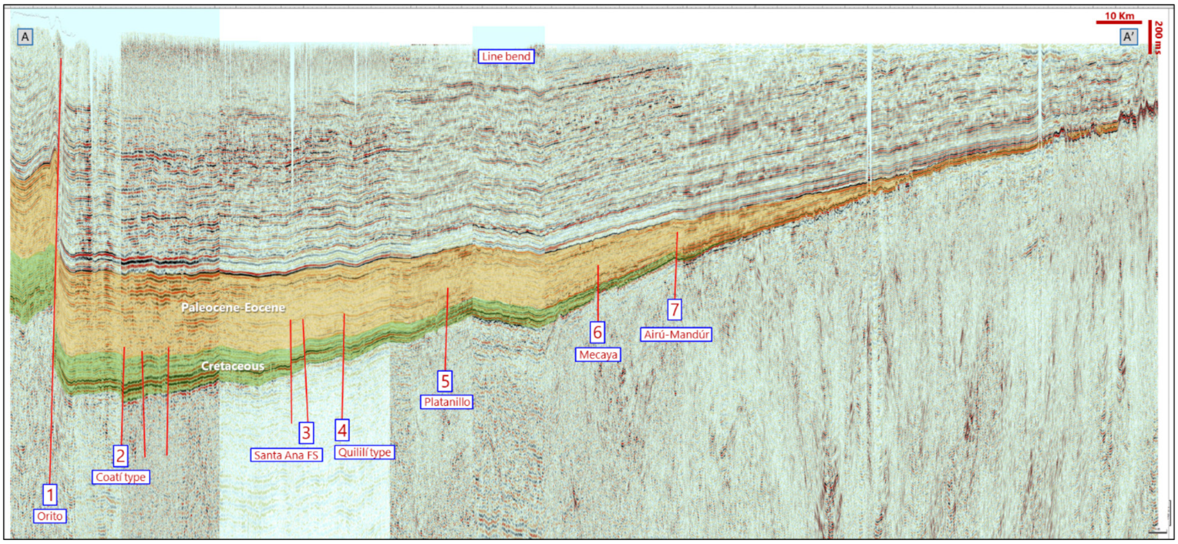

Figure 5. West-East Regional cross-section on 2D seismic lines throughout the PFB, see figure 4 for location.

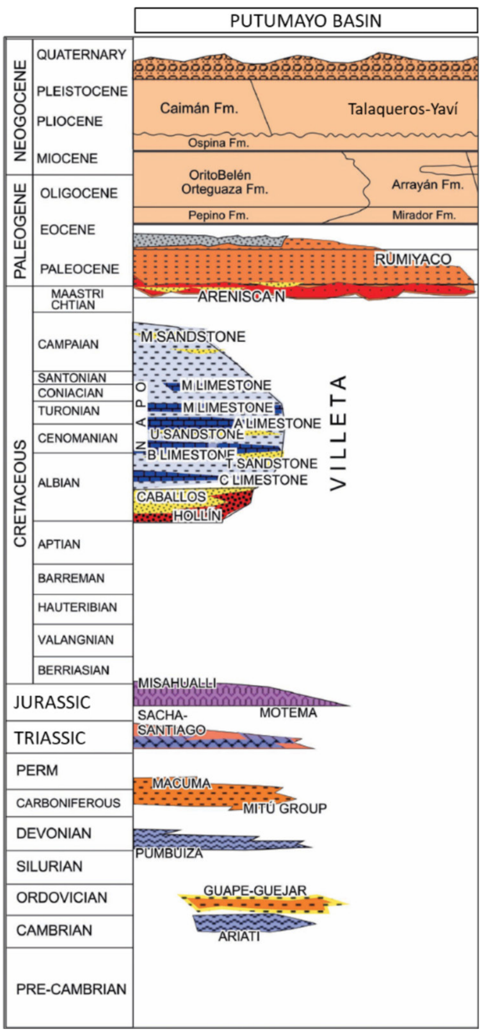

Figure 6. PFB Chronostratigraphic chart. Modified from Montenegro and Barragán ANH 2011.

The Upper Cretaceous Sequence, is represented by the Caballos (Aptian to Albian) and Villeta (Late Albian to Late Campanian) Formations deposited in a wide epicontinental seaway, controlled by eustatic sea level fluctuations and the onset of pre-Andean uplifts to the west (Central Cordillera). Active back-arc extension ceased, and subsidence was triggered by thermal processes (Vallejo *et al.*, 2021).

Early Albian times represented the deposition of fluvial to paralic sandstones that shifted towards an estuarine marine system in the Late Albian during a regional transgression (Shanmugam *et al.*, 2000). Sediments were derived mainly from the east (Guyana Shield) with important local contributions from the western pre-Andean uplifts, particularly within the Oriente Basin (Vallejo *et al.*, 2021). Transport was driven by broad braided river systems that evolved downwards into estuarine coastlines.

The Late Albian transgression initiated the deposition of the Villeta Formation (Napo Formation in Oriente). From Late Albian to Cenomanian times the PFB was characterized by cycles of short-lived transgressions alternating with rapid sea-level drops (second to third order sequences). These cycles backstep and wedge-out against the Florencia arch, a forebulge feature initiated during the latest Cretaceous with the loading of the proto-Central Cordillera (Vallejo *et al.*, 2021).

Low sedimentation rates prevailed throughout the Cretaceous, in a basin with a low gradient topography (<1°). The last pulse of sedimentation for the Villeta Formation occurred during the Campanian, in an inversion-dominated tectonic regime (Luzieux *et al.*, 2006, Vallejo *et al.*, 2021).

Uplift and compressional pulses characterized the Latest Cretaceous, producing a basin-wide unconformity that spanned from Late Campanian to Late Maastrichtian (Baby *et al.*, 2013, Montenegro and Barragan 2011, Vallejo *et al.*, 2021). Most of the structural hydrocarbon traps in the MOP system were formed during this inversion stage. This marks the transition into a flexural foreland basin. Deposition was re-established during the Maastrichtian when the depositional environments shifted from dominantly marine-transitional conditions to continental (Rumiyaco Formation in Putumayo or Tena Formation in Oriente).

This study focuses on the depositional setting that occurred immediately after the Campanian-Maastrichtian Unconformity, known as Basal Tena in the Oriente Basin of a fluvial origin (Vallejo *et al.*, 2021) and a time equivalent paralic-estuarine N-Sandstone in the Putumayo Basin (Corredor *et al.* 2018).

The final foreland phase continued to evolve during the Paleogene to Neogene, with the deposition of fluvial to alluvial sediments of the Pepino (Eocene), Orteguaza (Oligocene), Orito-Belen (Miocene), and Caimán (Plio-Pleistocene) Formations. The PFB was fully disconnected from the Upper Magdalena Basin during the Miocene with the uplift of the Easter Cordillera (Anderson *et al.*, 2016).

THE MAASTRICHTIAN N-SANDSTONES: PREVIOUS WORK

The N-Sandstone of the PFB has been the focus of scattered exploration efforts since the early 1990's with the discovery of the prolific Cohembí field. This reservoir has consistently demonstrated a stratigraphical control on trapping, with a fundamental role played by the depositional paleo-topography of the Maastrichtian-Campanian Unconformity. In order to fully understand the depositional setting of the N-Sandstone, it is crucial to appropriately locate it within the basin´s chronostratigraphy. This problem has been approached by works such as Mora *et al.*, 1998, Jailard *et al.*, 1997, Baby *et al.*, 2014. Equally important is to describe the tectonic setting, deformational styles, and structural configuration of the basin during the Cretaceous-Tertiary boundary, synthesized in the works of Fechi 2015, Pachon-Parra *et al.*, 2021, Corredor *et al.*, 2018, and Vallejo *et al.*, 2021: The N-Sandstone of the PFB is a Maastrichtian to Earliest Paleocene paralic to fluvial section deposited during active deformation. Its distribution depends highly on the syn-depositional growth of structures throughout the basin (Corredor *et al.*, 2018). This study aims to expand on this model for one of the most important and underexplored reservoirs in the PFB.

METHODOLOGY AND DATASET

This study was carried out on an abundant well and seismic dataset over the Putumayo-Oriente Foreland Basin. Over 100 wells were included when constructing the sequence-stratigraphic framework that supported this interpretation of the Maastrichtian-Paleocene Sequence, alongside approximately 1200km of 2D seismic and 530km2 of 3D seismic data within the PFB internal foreland area of interest. The sedimentological observations and subsequent depositional environment interpretation were based on a cored interval within the Cretaceous-Paleocene boundary at the Cohembí-2 well.

In order to construct a depositional model that may ultimately guide the interpretation of reservoir facies fairways for the N-sandstone, a methodology based on sedimentological observations, sequence and seismic stratigraphy, and analogue analysis was established. This multi-scale investigation produced a set of criteria that can be consistently applied throughout the basin when determining the distribution of the N-Sandstone and its reservoir facies.

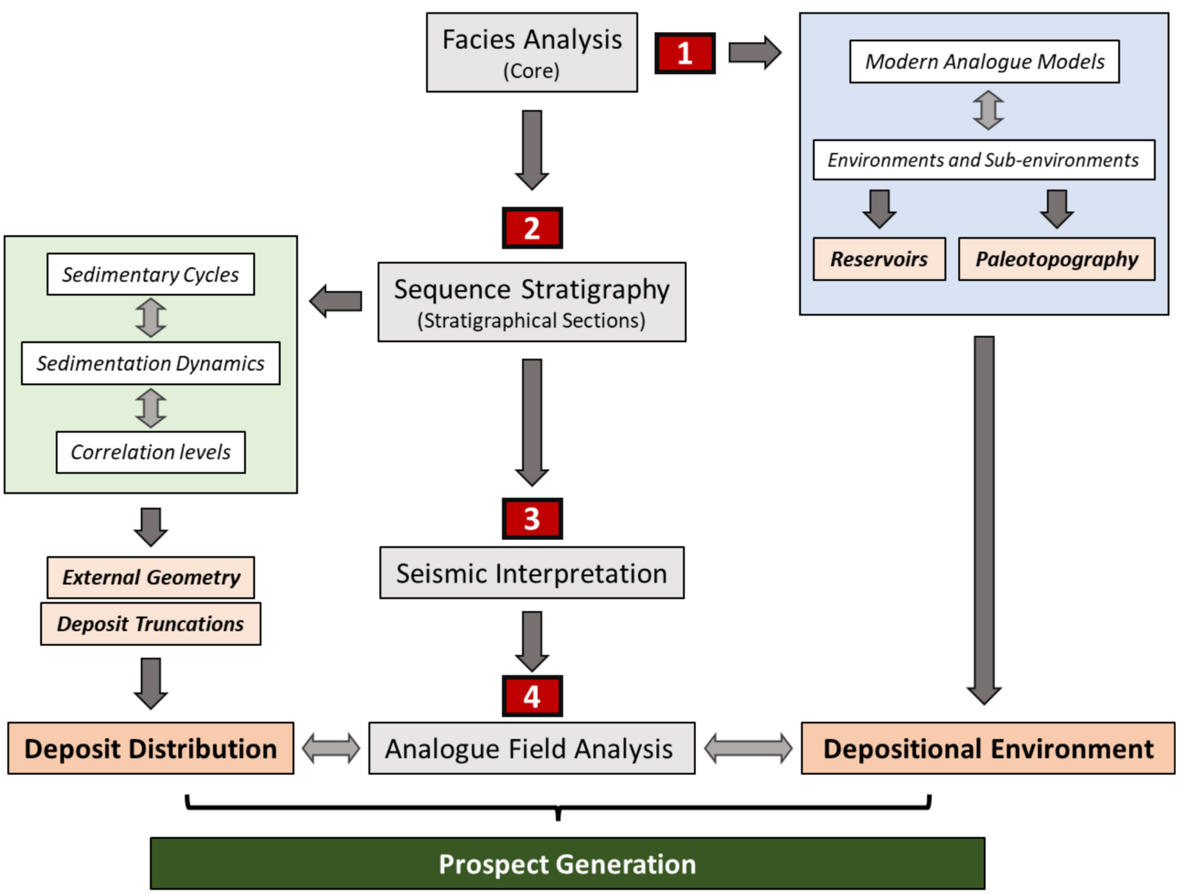

Figure 7. Methodology Workflow for the identification of prospects for the N-Sandstone in the PFB (modified from Rossi *et al*., 2022).

SEDIMENTOLOGY AND STRATIGRAPHY

Cohembí is one of the best producing fields in the PFB. It produces exclusively from the N-Sandstone unit, in what has been interpreted as a stratigraphical trap with a strong structural (syn-depositional) control. Several wells in the field have extracted core sections from the Cretaceous to Paleocene sequence. In this case study core, from Cohembí-2 has been analyzed to determine lithologies, sedimentary structures, and ichnofacies as the basis for facies, facies associations and depositional system interpretation.

Facies

Lithology for the N-Sandstone is dominated by fine to medium grained cross-laminated (planar, low angle) quartz-rich sandstones with frequent double mud layers, convoluted mud lamination and crinkles, and wavy to flaser type bedding. The shallowest section of the cored interval transitions into massive grey mudstones, mottled with occasional organic debris. Sedimentary structures of the N-Sandstone are predominantly tractive.

In terms of sandstone-dominated facies, it is possible to classify units as (A) Massive Sandstones, (B) Cross-laminates Sandstone with double mud layers and mud crinkles, and (C) trough cross-laminated sandstones with wavy to ripple type lamination. Cross-lamination occurs at decimeter dune-scale, defined by sharp grain size variations. The cored interval is intensely oil-stained in most of its extension, a condition that heavily masks sedimentary structures and limits interpretation. Thin mudstone layers are scarce and trace fossil intervals include Planolites, Skolithos and Rhizocorlium.

At the base of the N-Sandstone, massive to cross-laminated sandstone facies dominate with bed-sets that are arranged into fining-upwards cycles of up to 5cm. This interval exhibits the coarsest grain size in an aggradational cycle that is abruptly capped by a heterolithic horizon of mud crinkles and flaser lamination. No bioturbation is observed within this basal interval.

The mid-section of the unit comprises a fining upwards cycle of finer sand-grained sediments with a stronger presence of mud layers and wavy type lamination in an overall cross-laminated sandstone with high porosity-permeability values. Bioturbation and trace fossils are also absent in this mid-section. As the sandstone transition into silty to shaly and ultimately into siltstones, sedimentary structures switch from cross-stratification to mud crinkles and flaser to wavy lamination. The siltstone that caps the cycle is characterized by soft sediment deformation in the form of crinkles and collapsed laminae, with no evidence of bioturbation.

The next cycle in the N-Sandstone cored interval comprises trough cross-laminated sandstones with wavy to ripple type lamination facies, with an erosional base onto the siltstone horizon that caps the previous cycle. Some horizons of massive sandstones and scarce flaser laminae can be observed. This cycle has an aggradational character, similar to that of the basal section, with fine to medium sand-grained sediments distributed vertically into bed-sets of a 5cm scale. The cycle is capped abruptly by massive mudstone facies.

The massive mudstone facies constitutes a 60cm thick layer towards the top of the N-Sandstone cycle, capping the intensely hydrocarbon-stained sandstones. Contact with the underlying sandstones is net and planar. It consists of predominantly massive mudstones, occasionally laminated, with a mottled texture and an overall pale grey color. Trace fossils are absent and organic matter content is low, with scant organic debris.

The cored N-sandstone in Cohembí-2 ends with a section of medium sand-grained massive sandstone facies with no bioturbation and lower oil-staining. Convoluted mudstone laminae can be identified occasionally and the base against the underlying mudstone interval is apparently planar. According to well log interpretation, this unit marks the end of the N-Sandstone section and is overlain by continental reddish-brown of the Paleocene Rumiyaco Formation.

Facies Association and Depositional Environment

The N-Sandstone described in this sedimentological core analysis is composed of three fining upwards cycles marked by (1) a coarser-grained generally massive sandstone base, (2) a middle section dominated by cross-laminated sandstones (fine to medium grained) with frequent double mud layers, mud crinkles and flaser type lamination, and (3) a top section of heterolithic shaly-siltstones dominated by soft sediment deformation, flaser to wavy lamination. The sequence is completed at the very top of the N-Sandstone by a mottled massive mudstone overlain by another single massive sandstone episode, in its turn overlain by continental reddish-brown mudstones. Some intervals reveal the presence of faint ichnofacies of the Skolithos-Cruziana classification, particularly within the finer sandstone intervals.

This rhythmic arrangement of fining-upward sets together with the high net-to-gross relationship and the presence of fine-grained sedimentary structures such as double mud layers, mud crinkles and flaser-wavy lamination point towards a transitional (paralic) tidal-influenced system dominated by traction with waning episodes (cyclicity, Shanmugam *et al.*, 2000). The basal massive to cross-laminated section of each set is interpreted as the infill of a tidal channel with fluvial influence, the transition to heterolithic cross-laminated finer grained bed-sets with mud crinkles and couplets represent positions within tidal sand bars. The massive grey silty-mudstone (mottling) dominated horizon can be associated to subtidal mud flats, episodically exposed to meteoric (sub-aerial) conditions.

Furthermore, even though the ichnofacies record is faint and scarce, providing a weak interpretation framework, the identified ichnofacies are associated to this realm within the fluvial to marine transition. The scarcity in the ichnofacies record could be attributed to stressful conditions

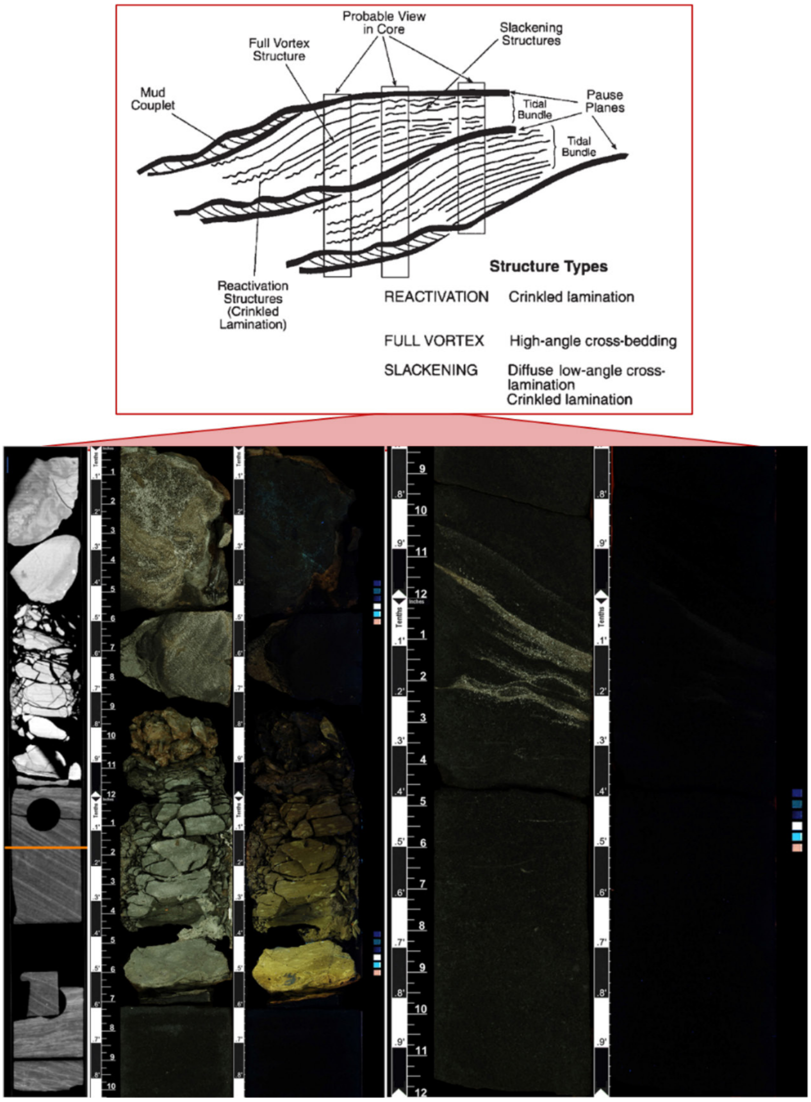

Figure 8. Examples from the Cohembí-2 N-Sandstone Core. Photograph quality compromised by very intense oil staining.

for biogenic activity due to either salinity levels or the current energy. However, despite the weak ichnofacies support, sedimentary structures clearly indicate a transitional realm influenced by both fluvial and tidal processes (Shanmugam *et al.*, 2000). Deposition during waning-to-flow events, tidally influenced, in the fluvial to marine transition of an estuarine coastline. Channelized, confined environment within the estuary.

Sequence Stratigraphy

The Albian to Campanian stage of the basin (pre-N-Sandstone deposition) was triggered by a second order transgressive cycle (controlled by eustasy), with the establishment of a vast epicontinental sea that flooded a great area of northwestern South America. The Cretaceous infill is therefore arranged in an asymmetrical wedge geometry, thickening to the Eastern Cordillera and Garzon-Quetame Massifs, backstepping and wedging-out onto the Florencia Forebulge (Vallejo *et al.*, 2021, Montenegro and Barragán 2011).

During the end of the Campanian a regional tectonic uplift drastically disrupted the evolution of the Cretaceous cycle. This accelerated uplift of the incipient Andes Orogen (Pindell and Kennan 2009, Luzieux *et al.*, 2006, Vallejo *et al.*, 2006). This geotectonic control resulted in an irregular topography of highs and lows that continued to be active throughout the Early Paleocene and eventually controlled deposition and erosion.

Above this unconformity surface, deposition reinitiated during the Maastrichtian with a new transgression pulse of South American Seaway which flooded the late Campanian paleo-topography in a tectonically active basin. This syn-deformational deposition occurred within a transitional marine-continental system within an estuarine-type coastline.

During the late Maastrichtian to Paleocene, flexure and uplift of the basin continued with the evolution of the Andean Orogeny resulting in a rapid shift to non-marine conditions and the establishment of alluvial to braided river systems that deposited the red mudstone dominated Rumiyaco Formation.

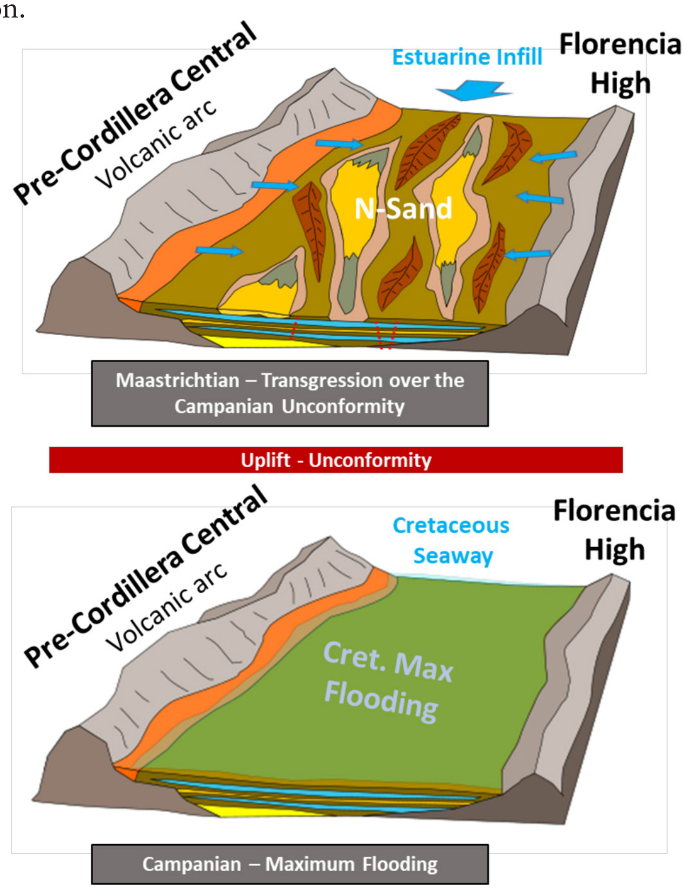

Figure 9. Conceptual representation of the sequence stratigraphy scenario from Campanian to Maastrichtian.

STRUCTURAL FRAMEWORK AND TIMING OF DEFORMATION

Overview

In terms of its structural framework, the basin can be subdivided in different structural domains (Pachon-Parra *et al.*, 2021) that include, from West to East, the piedmont sector, the western and central foreland sector, and the eastern forebulge domain. Each domain accommodates the deformation generated by the oblique subduction zone to the West differently, with a strong influence of pre-existing basement structures. The focus of this study is to describe the tectono-stratigraphic context during the transition from the post-Extension phase of the PFB to its Syn-Inversion compressional phase at the Maastrichtian to Paleocene boundary (Fechi 2015) within the central foreland region.

The central foreland of the PFB is dominated by steep-angle reverse faults trending generally on a North Northwest-South Southeast strike, with vergence both to the East and West (Corredor *et al.*, 2018). The main planes of these fault systems root from the pre-cretaceous sequence and crystalline basement and are generally restrained up to the Paleocene section in which vertical propagation of the fault system is expressed in the form of folding. These faults have an extensional expression deep within the basement (Mesozoic extension) and are then reactivated during tectonic inversion for the Cretaceous-Paleocene, compressively deforming the sequence (Late Cretaceous-Tertiary foreland phase). The Eocene and younger sequences are virtually undeformed. The pre-Cretaceous system is therefore arranged into half-graben structures, while the Cretaceous and Cenozoic presents positive relief compressional structures. The pre-Cretaceous depocenters and structures have a general N-S strike, oblique with respect to the Andean front and subduction trench: these features are truncated by the Andes (Pachon-Parra *et al.*, 2021).

The driving mechanism for the formation of the PFB structural framework is the oblique subduction of oceanic plates on the northwestern margin of South America. This oblique subduction generates a transpressional deformation regime, however, the strike-slip component in the faults of the PFB has been accommodated completely by the piedmont fold-and-thrust belt (Pachon-Parra *et al.*, 2021, Corredor *et al.*, 2018, Fechi 2015). Therefore, the central foreland inversion is characterized predominantly by pure reverse fault-slip (Corredor *et al.*, 2018).

Timing

In the central foreland domain of the PFB, the steeply dipping normal faults that trend N-NE to S-SW were formed during the Mesozoic syn-extensional phase. During the post-extensional phase and before the transition into the flexural foreland phase, the basin experienced a period of quiescence with low subsidence rates controlled by thermal sag (early Villeta Formation). In this study area, this Mesozoic-inherited structural configuration is represented by the Santa Ana, Puerto Asís and Platanillo fault systems.

Subtle thickness variations observed within the Villeta Formation suggest that deformation reinitiated during the Latest Cretaceous defining the end of the post-extensional sag phase and the transition into the flexural foreland phase. This tectonic setting generated basin-scale uplift and a hiatus in sedimentation, creating the Campanian-Maastrichtian unconformity: a dynamic topography with actively growing anticlines and subtle flanking synclines (Corredor *et al.*, 2018). This flexural-compressional deformation controlled the subsequent deposition of paralic fluvial-estuarine systems referred to as the N-Sandstone (Vallejo *et al.*, 2021).

Work carried out by Corredor *et al.*, 2018 demonstrated the truncation of the N-sandstone against the Puerto Asís fault. Also, a similar relationship is observed towards the Platanillo Fault System. This reversed fault zone created a local paleo-high of no Maastrichtian deposition (i.e., N-Sandstone) and associated topographical depressions at the flanks that were the loci of deposition. The uplift rates of the fault system inversion at the K-T boundary were therefore higher than the sedimentation rates, preventing accumulation at the highs. Structural interpretation of the area also reveals the presence of relay ramps that interrupt the continuity of these fault systems. During the Maastrichtian-early Paleocene these active ramps routed sediment transport through the active topography.

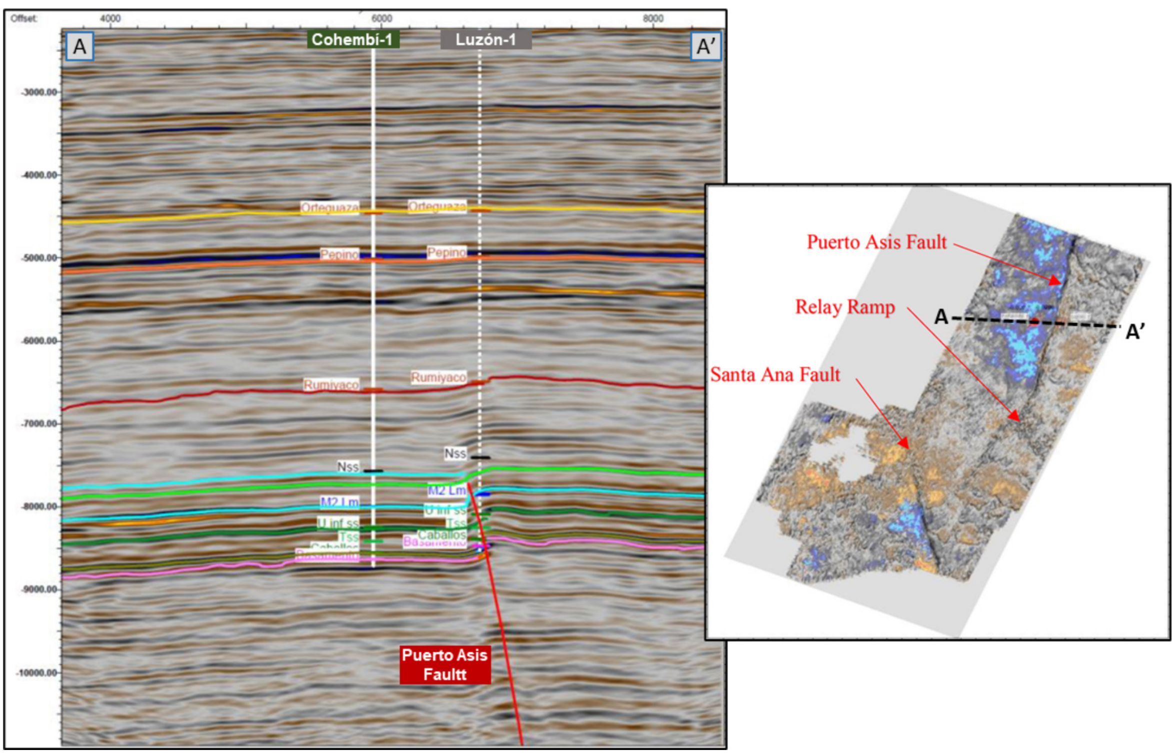

Figure 10. Seismic section between the Cohembí-1 and Luzón-1 wells, showing the loss of the N-Sandstone reflector across the Puerto Asís Fault. On the right, a blended amplitude-similarity stratal slice for the N-Sandstone showing the distribution of the reservoir (strong blue colors), modified from Corredor *et al.*, 2018.

N-SANDSTONE DEPOSITIONAL MODEL AND SEISMIC INTERPRETATION

As in the case of the Santa Ana and Puerto Asís fault systems of the central foreland domain, the Platanillo Fault System was also active during the Maastrichtian to Early Paleocene, and most likely inverted since late Cretaceous (Campanian) times. During the initiation of the foreland phase, the Platanillo fault system became a topographical high on which no sediment deposition occurred but instead focused N-sandstone deposits on its flanks, particularly on the western down-to-the-basin side.

2D seismic lines connect the 3D seismic cubes that cover the Cohembí and Platanillo areas. Seismic-well ties in the Cohembí field confirm that the N-sandstone is expressed as a high amplitude discontinuous negative reflector. This reflector can be seen on the footwall block of the Puerto Asís fault but not on the hanging-wall anticline (confirmed by the Luzon-1 exploration well), as per the syn-deformation depositional model. However, when interpreting across 3D and 2D seismic data further eastwards in the direction of Platanillo, a strong discontinuous negative amplitude reflector is once again observed truncating downwards against the underlying Campanian-Maastrichtian unconformity. This event has been interpreted as the N-Sandstone beyond the Puerto Asís paleo-high on a different local depocenter created within the subtle syncline that existed on the western flank of the Platanillo paleo-high during the Maastrichtian. This N-sandstone reflector is then lost once more, eastwards against the unconformity as the Platanillo high gains relief.

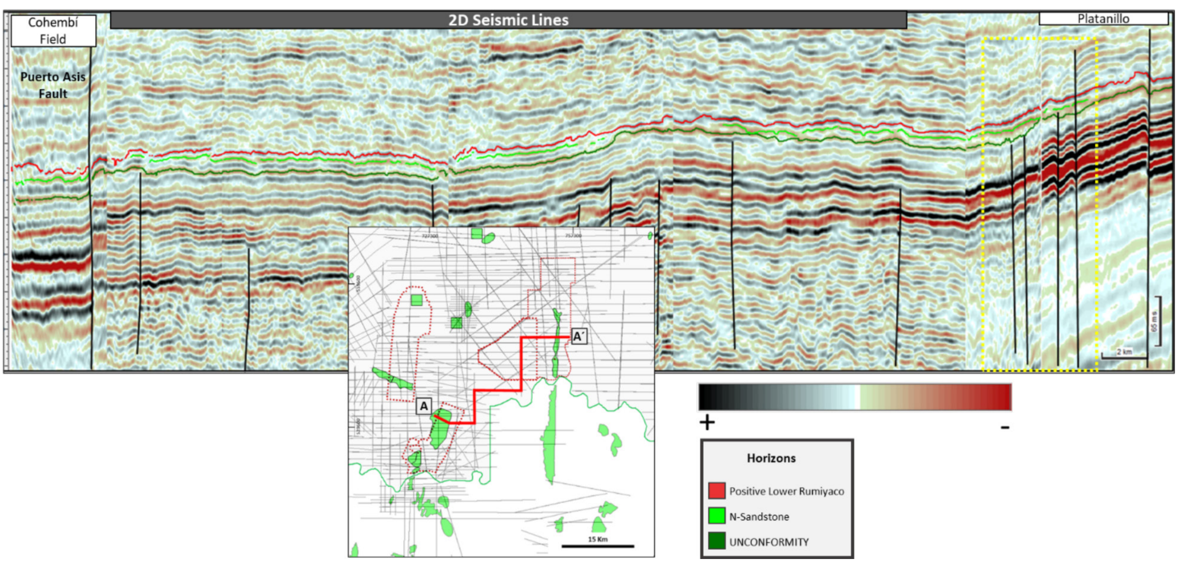

Figure 11. Composite line connecting the Cohembí area with the Platanillo High. The N-Sandstone of the Cohembí Field can be continued towards the east where it truncates against a paleo-high (Platanillo).

After identifying the reflector expression of the N-sandstone and the seismic-stratigraphic context, three parallel interpretation methods were used to understand the distribution of this event towards the Platanillo sector: (1) isochron maps, (2) stratal slices referred to a key reflector within the Rumiyaco Formation, and (3) instantaneous amplitude extraction on the N-Sandstone reflector.

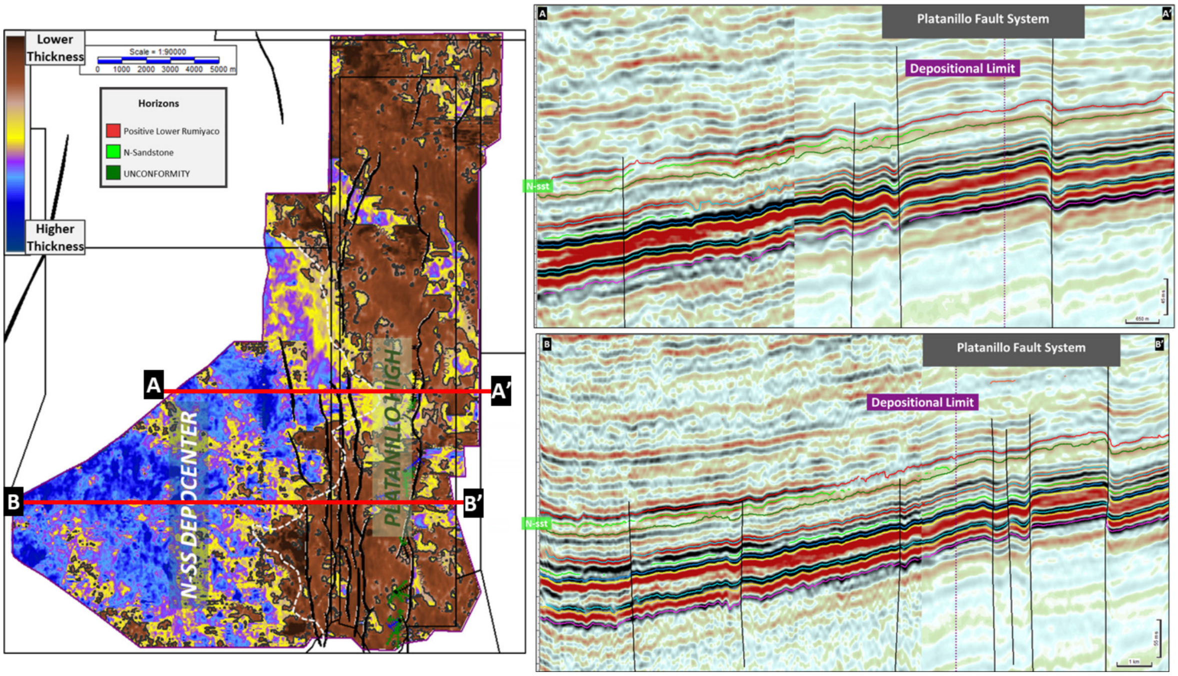

Figure 12. (Left) N-Sandstone isochron map. (Right) Representative seismic sections showing the stratigraphic relationship between the N-Sandstone, the Lower Rumiyaco Formation, and the Platanillo High.

Approach 1 – Isochron Map

An isochron map was constructed between the Maastrichtian-Campanian unconformity and the first continuous high amplitude positive event at the base of the Rumiyaco Formation (key reflector). The resulting map was used as a proxy for paleo-topography during the Maastrichtian. Areas of lower to no thickness of the N-sandstones were associated to the structural highs and areas of higher thickness were interpreted as local depressions that hosted the reservoir facies of these fluvio-estuarine sandstones. The resulting geometries reveal a series of NW-SE trending lobate macro-forms.

These lobate macroforms correlate with channel-shaped bodies towards the Platanillo High in the SE, where a depositional boundary for the N-Sandstone is to be expected. Bearing in mind the sedimentological-stratigraphical nature of these deposits, their geometries have been associated to sub-aqueous mouth bars and feeding channels developed within an overall fluvial-estuarine system (Fig. 13).

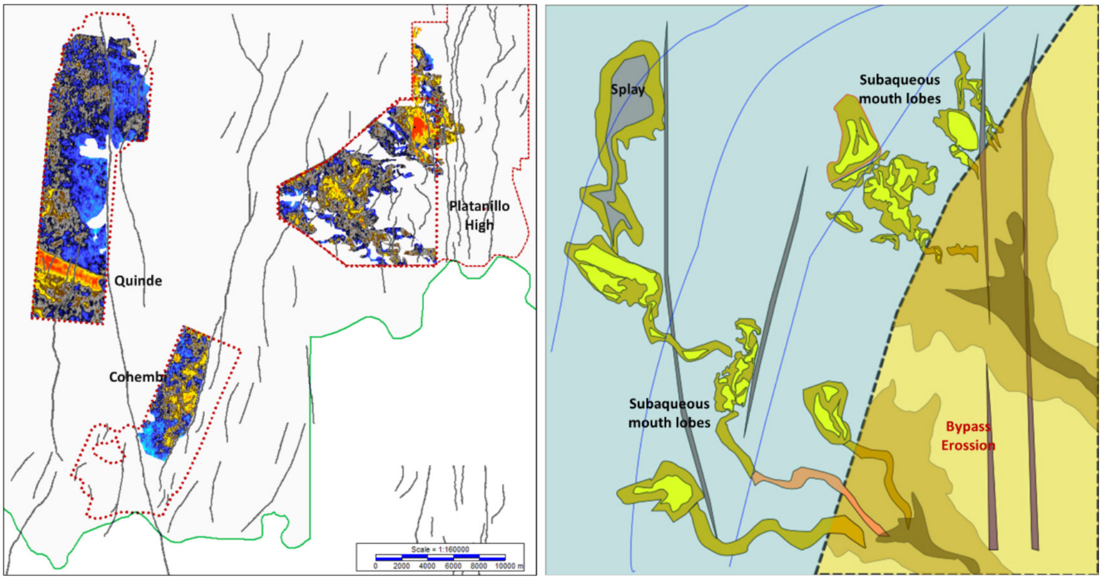

Figure 13. (Left) N-Sandstones instantaneous amplitudes. (Right) Paleo-environmental interpretation for the N-Sandstone.

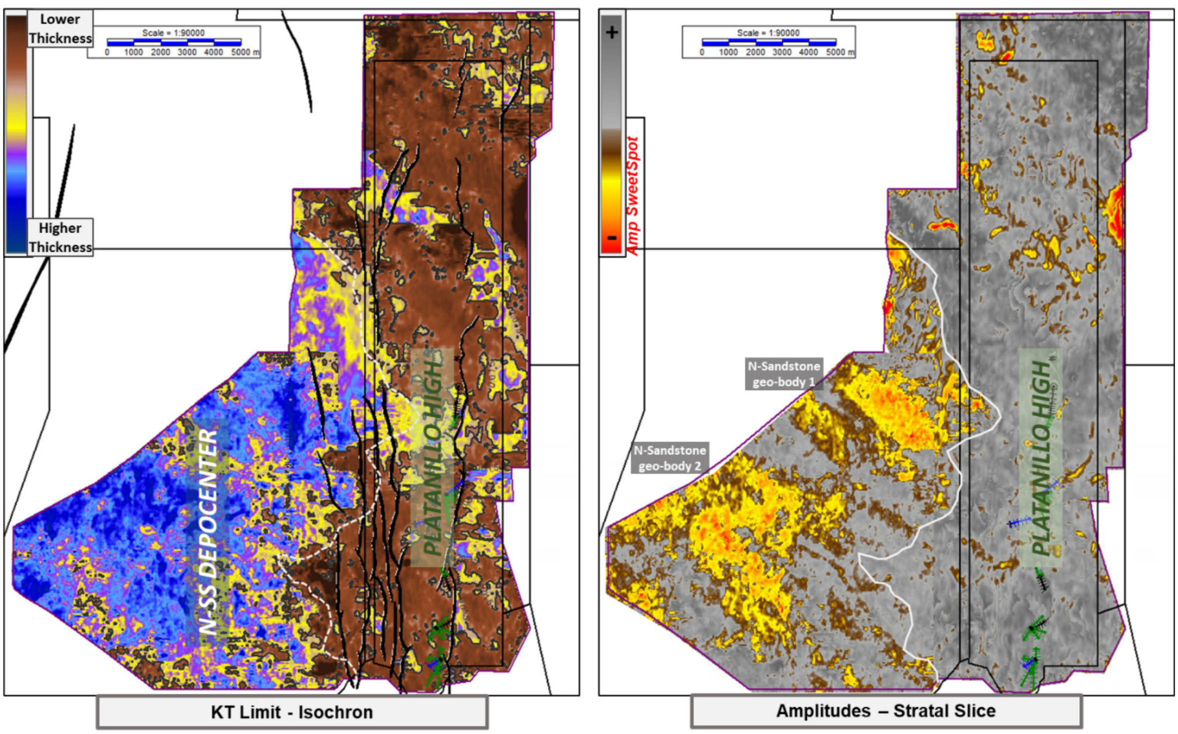

Figure 14. (Left) Isochron map and (Right) Stratal Slice for the N-Sandstone interval in the available 3D seismic coverage.

Approach 2 – Stratal Slice

A stratal slice within the N-sandstone, interval was extracted 6 msecs below the Rumiyaco key reflector (Lower Paleocene). This amplitude slice showed the same geometries observed in the thickness map (approach 1), but now with the additional contribution of revealing the amplitude content within the N-Sandstone (Fig. 14). This approach indicates that the areas associated to thicker N-sandstone intervals bear stronger negative amplitudes, a situation that has been associated to the existence of good reservoir facies in the neighboring Quinde and Cohembí fields.

Approach 3 – Instantaneous Amplitude Extraction

Later, the pre-existing interpretation of the Cohembí N-Sandstone reflector was continued to the east across the Puerto Asís High. Thus, the interpretation of the N-Sandstone towards the western flank of the Platanillo High was finally completed. The resulting map revealed the complex depositional geometries with greater detail and showed a clearer delineation of the truncation limits onto the Platanillo high (Fig. 15). An instantaneous amplitude extraction was carried out on the mapped reflector (N-Sandstone), further strengthening the interpretation of macro-forms, paleo-environment, pinch-outs, and the direct relationship between thickness-accommodation space and negative amplitude response (observed in approaches 1 and 2).

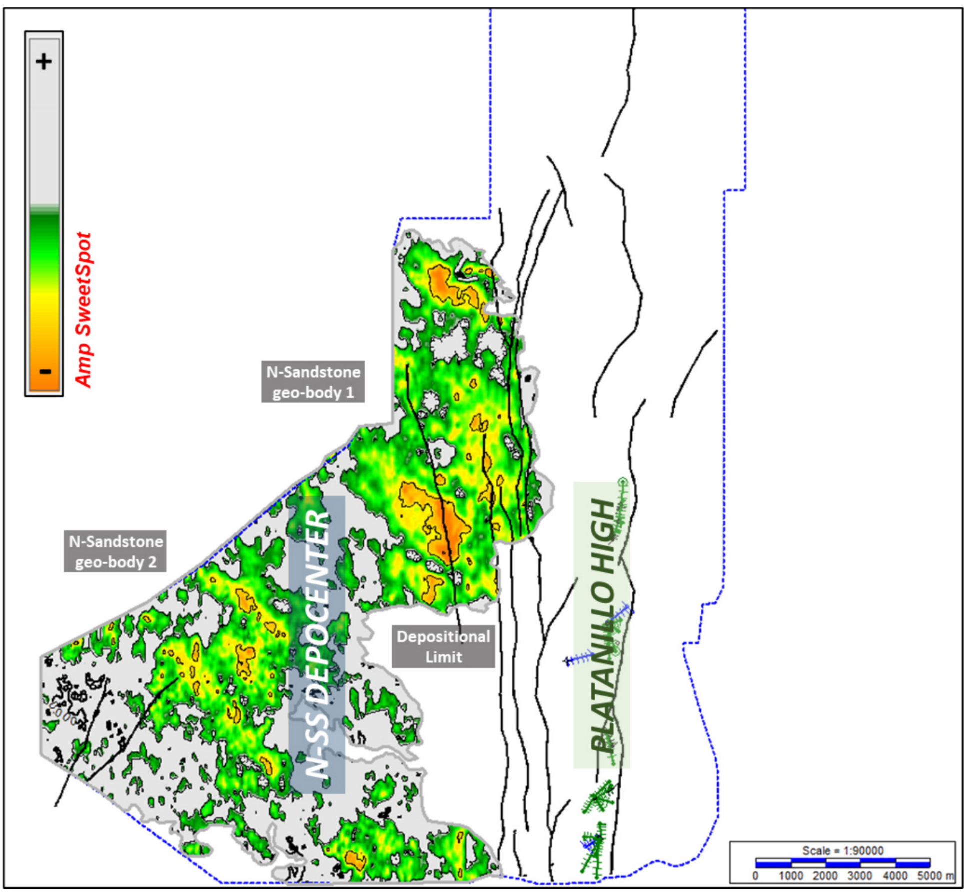

Figure 15. N-Sandstone instantaneous amplitude extraction. Depositional limits and local depocenters.

CONCLUSIONS AND DISCUSSION

The N-Sandstone is a syn-deformational deposit associated to a fundamental change in basin dynamics during Campanian-Maastrichtian times. Inversion tectonics produced uplift and consequently a basin-wide regional unconformity. The associated anticlines created positive relief in the form of subtle paleo-highs on which the Maastrichtian N-Sandstone was not deposited (Platanillo and Puerto Asís Highs). The deposition of the transgressive fluvial-estuarine sandstone was therefore limited to the flanks of these actively growing paleo-highs that had uplift rates greater than the existing sedimentation rates at the time.

This tectono-stratigraphic context of the Cretaceous-Tertiary boundary allowed the establishment of stratigraphical traps for the N-Sandstone (estuarine bars and channels pinch-outs against Paleo-highs). The Cohembí and Quinde fields (and other recent discoveries) are clear evidence of this. The interpretation presented in this paper has allowed the extrapolation of the stratigraphical-sedimentological concept of these fields to new equivalent prospective areas located on western flank of the Platanillo High as it represents the easternmost boundary of the N-sandstone depositional system.

The paleo-topography proxy reconstruction, the interpretation of the N-sandstone reflector and the instantaneous amplitude extraction to this event has strengthen the prospectivity of this area for commercial accumulation of hydrocarbons. Accommodation space existed on the subtle depression of the western Platanillo flank allowing the deposition of sand bodies that eventually truncate up-dip against the Platanillo high creating promising stratigraphical traps. Lateral sealing is provided by marine carbonaceous mudstones of the upper Villeta Formation while top sealing is given by the regionally extensive red mudstones of the lower Rumiyaco Formation.

This interpretation and derived depositional model may be extrapolated throughout the Oriente-Putumayo basin in order to identify areas of potential N-sandstone deposits within good reservoir facies belts.

ACKNOWLEDGEMENTS

We would like to thank GeoPark for providing the Putumayo Basin dataset used in the development of this study and for encouraging its publication.

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