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Abstract

The Llanos basin, located in the eastern region of Colombia, South America, is a foreland basin between the Eastern Cordillera (Colombian Andes) and the Guyana Precambrian shield. This Andean foreland basin is the latest stage of a complex Paleozoic- recent multiphase evolution of eastern Colombia, where previous tectonic phases have been overprinted but still can be identified in the southern part of the Llanos basin.

Using ~5000 km of 2D seismic data and 19 exploratory wells in the southern Llanos basin, the tectono- stratigraphic evolution was analyzed in order to better understand the different structural styles and timing of deformation of the pre-foreland structures that can define new trends in exploration.

Four main tectono-sequences divided by regional unconformities were identified: a)Lower Paleozoic, b) Upper Paleozoic and c) Upper Cretaceous and d) Cenozoic.

a) The fold and thrust belt of Neo- proterozoic rocks and Paleozoic triangular zones are the result of a compressional event during the Lower Paleozoic; b) Upper Paleozoic sediments were deposited in piggy back basin at top of the thrusting. The rocks are mainly black graptholitic shales (Upper Paleozoic). This sequence has high potential as source rock and hydrocarbon generation.

A major sequence boundary is interpreted between folded Paleozoic rocks and overlying Upper Cretaceous-Paleocene wedge. c) Upper Cretaceous –Paleocene consists of shallow marine sediments deposited in the distal area of the Cretaceous foreland basin; and d) Cenozoic sequence dominated by fluvial-deltaic sedimentary rocks that were deposited in Llanos foreland basin. The basin was formed during uplift of the Eastern Cordillera from Late Paleogene to Recent.

As result, several types of traps were developed, which include: Cenozoic thrusts related with the uplift of the Eastern Cordillera, normal faults on the foredeep hinge areas, Cretaceous stratigraphic traps and Piggy-back basins formed by the the reactivation of the Lower Paleozoic/Neoproterozoic? fold and thrust belt.

Paleozoic piggy back basins represent a new exploration target that have been poorly explored in comparison to the better understood and explored plays in the Eastern Cordillera foothills and the flexural normal faults in the present-day foredeep area.

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1. Introduction

Colombia is located in the South- America northwestern region. The Figure 1.1 shows the major geographic features of the region, with the Andean mountain range as its most important relief. The Andes trends northeast and is divided into three: Western, Central and Eastern Cordillera. The Llanos foreland basin is developed in the central-eastern region of Colombia between the Eastern Cordillera, the Macarena range (Colombian Andes) and Precambrian basement outcrops of Guyana shield (Figure 1.1). The foreland basin extends north into the Barinas basin of Venezuela.

In terms of hydrocarbon prospectivity, the Llanos basin is the most petroliferous basin in Colombia (ANH, 2007). It has 4 giant oil fields (Rubiales, Cano Limon, Cusiana and Cupiagua fields) and a considerable number of oil/gas fields related with the Cenozoic foreland basin phase (Figure 1.2). The total cumulative production of the Llanos basin is 1,500 MBOE (million barrels of oil equivalent) with estimated remaining reserves of more than 3,050 MBOE (Vargas-Jimenez, 2009).

These important accumulations make Llanos basin one of the most detailed and well studied basins of Colombia. Oil exploration activity is mainly focused in the maximum tectonic flexure structures and reservoir rocks associated with the Cenozoic phase (Campos, 2011). This oil exploration trend has been unsuccessful in the southern area, with total of 4 small heavy oil fields (Manacacias, Camoa, Voragine and Valdivia fields) within the area of study (Figure 1.2).

A growing interest for heavy oil resources, unconventional resources and main hydrocarbon discoveries in the eastern part of the foreland area (Rubiales field) is pointing out positive relationships between gravity- define basin structures and major-oil fields (Pratsch,1994).
The Figure 1.3 shows the Bouguer total anomaly map for Llanos basin and surroundings. Positive anomalies are located mainly towards the south of the basin and are associated with crystalline basement highs, due to its high density compared with the low values of Paleozoic sedimentary rocks filling contiguous basins and the thick sedimentary column of the Eastern Cordillera towards the west(Pratsch,1994).

The Eastern Cordillera relief has a SW-NE orientation while the regional positive anomalies in the southern Llanos basin are trending NNE-SSW; which is parallel to the positive relief of the Macarena range (Figure 1.3). The orientation difference between these two trends shows

evidence of previous events in the southern Llanos basin. This implies reactivation of older events earlier to the Andean deformation controlling the present-day foreland basin. Moreover, the basin configuration is the combination between Mesozoic and Cenozoic structures, reactivated Paleozoic- basement structures and preservation of buried pre-foreland structures.

This alternative interpretation has implications for hydrocarbon exploration and represents new trapping mechanism that has been poorly explored in comparison to the better understood and explored Cenozoic traps in the fold and thrust belt of the Eastern Cordillera foothills and the flexural normal faults in the foredeep area.

1.1 Previous work

Most of the published studies are focus on outcrop studies in the axial zone Eastern Cordillera and in the Llanos foothills segments. (Hubach, 1957; Burgl, 1967; Irving, 1975; Colletta et al., 1990; Cooper et al., 1995; Branquet et al., 2002; Gomez, 2005; Sarmiento-Rojas, 2006; Bayona et al., 2008; Parra et al., 2010). These studies have been described in detail the evolution of the northern Andes and they are the base information to understand Llanos basin evolution.

Analysis and integration of seismic and well data has been done in previous studies (Duenas, 2006; Bayona et al., 2007; Moretti and Mora, 2009; Mora et al., 2010; Campos, 2011). However these studies include mainly the latest evolutionary stages of the basin, related with the Upper Cretaceous and Cenozoic foreland basin.

Recent works, (Duenas, 2006; Mora et al., 2010; Gonzalez, 2011) agree in the importance to understand pre-Cenozoic stages, mainly since Early Paleozoic. Ideas of a prospective Paleozoic (Duenas, 2006) and the role of basement structures as important hydrocarbons migration barriers from Eastern Cordillera, during the Oligocene (Mora et al., 2010) has been develop as isolated studies. This information needs to be integrated into a coherent summary of geological evolution from earlier stages.

The southern area of the Llanos basin is a key area to recognize some pre-foreland events. Early interpretations have proposed inversion, transpressional and compressional as the main structural styles. Figure 1.4 shows three previous models applied for southern Llanos basin. a) Rift inversion has been interpreted for the Eastern Cordillera (Sarmiento, 2001 and Branquet et al., 2002) and the Apaporis inverted graben in the Amazonian basin (Ceron, 1998). It shows basement structural highs as a horst.b) transpressional deformation style with main dextral-strike-slip faults (Cediel, 1982), where the high may be explained as a positive flower structure and c) reverse faulting with detachment in the basement that originates a fold propagation fault (Gonzalez, 2011).

The variety of interpretations is related with the poor understanding of the Pre-foreland structures role, including Macarena mountain range, in terms of timing, relative age of events and their influence in later evolution stages.

1.2 Objectives

The purpose of this study is to provide an overview of southern Llanos basin tectono- stratigraphy evolution on 2D seismic interpretation in order to understand and show evidences of deformation styles and timing of structures.

The main objectives are:

- Establish the relative timing of deposition and deformation of the different tectono-sequences from Paleozoic to Cenozoic.
- Correlate local structures into a regional framework.
- Understand the continuity of Pre-foreland structures and how it affects the Mezosoic-Cenozoic evolution.
- Identify structures that may control hydrocarbon accumulations in the southern Llanos basin

2. Geological setting

The present-day tectonic configuration of Colombia is a combined result between the subduction of the Caribbean Plate and Nazca Plate beneath the South American Plate and the Panama Arc-indentor (Figure 2.1A). This framework can be divided in six inland tectonic provinces, from west to east: a) the Western Cordillera, which consists of oceanic accreted terrains; b) the Central Cordillera, identified as a active continental magmatic arc and a pre-Oligocene eastern boundary for sub- Andean basins (Cooper et al., 1995); c) Cretaceous foreland basin Upper located in Magdalena/Llanos area(Gomez et al., 2005); d) the Eastern Cordillera double vergent fold and thrust belt related with the Cenozoic inversion of Mesozoic rifting structures; e) Llanos Cenozoic foreland basin located parallel to the fold and thrust belt (Bayona et al., 2008); and f) Precambrian rocks of Guyana shield. (Figure 2.1B)

This geometrical configuration is the latest resulting stage of a complex Paleozoic to Recent multiphase evolution of the northwestern corner of South America. The events are associated with previous tectonic phases, that have been overprinted in most of the areas. Such events can still identified based on subsurface data in relatively stable regions, as for example, the main study area of this project, the southern region of Llanos basin.

Llanos basin has a sedimentary record from Paleozoic until Recent sediments, overlaying an igneous-metamorphic basement (Forero- Suarez, 1990). There are 3 main sequences: Paleozoic, Mesozoic and Cenozoic with regionally significant unconformities dividing them.

Lithological units and petroleum systems have been well described for Cenozoic and Cretaceous sequences. The reservoir rocks are Paleogene and Upper Cretaceous silicilastic sediments of shallow marine environments. The source rock is related with Cretaceous and Paleogene organic shales with generation during the Miocene peak of the Eastern Cordillera uplift (Mora, 2010) (Figure 2.2).

Valuable geological information, together with structural features and rock properties, from surroundings areas has been extrapolated in order to understand older sequences than the Cenozoic sediments outcropping in the area. Figure 2.3 indicates the location of these areas, which include:

a) **Eastern Cordillera**: double vergent thrust belt placing Cretaceous and Paleogene rocks over a thick Cenozoic sucession; Paleozoic and Neo- proterozoic basement rocks exposed in its axial part (Bayona et al., 2008).

b) **Macarena range:** eroded anticline trending NNW of possible Neo- proterozoic? igneous and metamorphic rocks exposed in the central and southern areas (Gomez et al., 2007), while sedimentary rocks from Cambrian and Upper Cretaceous located in the flanks. The first report of the area is Trumpy (1943); who described the Macarena range basement rocks as gneisses and amphibolites overlaid by undeformed Cambrian-Ordovician sediments.

c) **Guyana shield**: igneous and metamorphic complex with Paleo- Proterozoic ages. Based on geochronological information it is related with the Rio- Negro Jurena terrain (Cordani et al., 2010). It outcrops towards the west and in the vicinity of the Orinoco River.

d) **Adjacent basins:** Upper Magdalena basin, Amazonas basin, Putumayo basin and Venezuelan Llanos (Barinas basin) have similar age for the sedimentary record.

The general geology of the study area and its surroundings have grouped by chrono- stratigraphic units. The oldest rocks are located towards the west in the Guyana shield, Paleozoic and Mesozoic rocks are mainly reported in the Macarena range and the Eastern Cordillera, while Cenozoic is widely exposed in the study area (Figure 2.3).

2.1 Tectono- stratigraphic evolution

The following descriptions are based on the stratigraphy and tectonic evolution for Four megasequences: Precambrian (Figure 2.4A), Paleozoic (Figure 2.4B and Figure 2.5), Cretaceous (Figure 2.6A and Figure 2.7A) and Cenozoic (Figure 2.6B and Figure 2.7B). Figures 2.3 and Figure 2.6 shows a geological map based on Gomez et al., (2007). They contain: a) rock units from each mega-sequence; b) relevant absolute chronological data taken from Maya, (2001), Mann et al., (2010) and Ibanez-Mejia, (2010) and c) recompilations, main stratigraphic relations and interpretations from previous papers that are applicable to understand the tectono-stratigraphy of the southern Llanos basin. Figure 2.5 and Figure 2.6 shows regional tectonic reconstructions of South America form each interval based on Williams (1995) and Mann et al., (2010).

2.1.1 Precambrian

Basement rocks of Llanos basin has been defined in most geological publications as an extension of the outcropping Guyana shield (Figure 2.4A). Geochemical data correlates the Guyana shield with the Rio Negro-Jurena orogeny (~1.55-1.8 G.a) (Cordani et al., 2010). The analysis of isolated exposures of basement inliniers in the Eastern Cordillera; in particular the Garzon complex (Jimenez –Mejia, et al., 2006), the Macarena Range, the Santander Massif, and the Merida Andean Range in Venezuela show a Neo- proterozoic age (~0.99 G.a) related with the Grenville-age orogenic belt (Cordani et al., 2010). Furthermore, recent geo- chronological data in well samples shows evidences of Neo- proterozoic rocks buried beneath the Putumayo basin and Llanos basin (Ibanez-Mejia, 2011a) instead of the typical correlation with the Guyana shield rocks. (Figure 2.4A).

2.1.2 Paleozoic

Sedimentary rocks from Paleozoic are mainly identified based on stratigraphic relations and fossil identification in: Eastern Cordillera (Campbell and Burgl, 1965), Macarena range (Trumpy, 1943), Amazonic basin (Herrera and Rodriguez, 1996), Llanos basin (Duenas, 2006) and west Venezuela (Feo-Codecido et al., 1984). Geological information is extrapolated from these regions into the area of study in order to have an approximation to the lithological and structural features of the sequence (Figure 2.4B). Base on this, two main sequences can be identified:

a) **Lower Paleozoic**: It is characterized by a Paleozoic igneous- metamorphic belt next to a main Cambro- Ordovician undeformed basin (Feo-Codecido et al., 1984). The rocks from the Paleozoic orogenic belt are exposed in Venezuela at the Perija range and the Baul arch (Viscarret et al., 2009); and in Colombia at the Eastern Cordillera (Quetame and Silgara complex) (Restrepo-Pace et al., 1997). They consist of granites and metamorphic rocks with sedimentary protolith.

Unmetamorphosed Cambrian- Ordovician sediments are mainly continental and shallow marine deposits. They are exposed at: a) the Amazonas basin with siliciclastic sediments related with beach deposits of the Araracuara formation dated with brachiopods (Herrera and Rodriguez, 1996) and trilobites (Thery et.al, 1986); b) the Macarena range which consists of graptolitic shale with banks of quartzitic sandstones of the Guejar formation (Trumpy, 1943); a) the Llanos basin, shallow marine deposits that includes from base to top: black-shales, calcareous sandstones, shales and quartz sandstones of the Negritos formation. Its last member has been interpreted as a result of an active tectonic event during the Upper- Ordovician (Ulloa and Perez, 1982). Silurian sequence in Colombian Andes is limited. Forero-Suarez (1986) and Grosser (1991) suggests paleontological evidence of Ludlovian stage for the eastern Cordillera (Quetame group).

b) **Upper Paleozoic:** It is a sedimentary sequence composed of marginal marine mudstones and sandstones. They are exposed at: a) the Eastern Cordillera with mudstones of Floresta and Cuche formations, which yields a rich marine fauna; b) The Llanos basin with marine shales. Duenas, (2006) reported palinological assamblages in well samples from Devonian- Lower Carboniferous age and high grade of affinity with the Appalachian fauna.

General disagreement surrounds timing and geological models to explain Paleozoic metamorphism, pre-andean deformation and other geological features in the northern Andes described above. Models includes: non collision (Pindell and Dewey, 1982), arc collisional (Restrepo-Pace, 1992) and continental orogenesis (Dalziel et al., 1994).

Timing of these episodes also varies. It has been proposed for: Cambrian (Cardona et al., 2006; Chew, et al., 2008), Ordovician–Silurian (Irving, 1975; Boinet et al., 1985; Cediel et al., 2003; Chew, et al., 2007), Late Silurian–Devonian (Campbell and Burgl, 1965; Forero- Suarez, 1990; Restrepo- Pace, 1992; Ordoñez- Carmona et al., 2006), and Permian–Triassic (Irving, 1975; McCourt et al., 1984; Cardona et al., 2006; Vinasco et al., 2006)

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Paleozoic reconstructions for northern South America support Ordovician and Permian as key periods of deformation. The Figure 2.6 shows South-America located near the south- pole during the Ordovician. It has some glacial deposits towards the west which correlates with the east margin of Africa and form Gondwana. Llanos basin is interpreted as a barc-arc basin in a marine shelf environment, as result of a subduction zone towards the west with an east high land related with the stable Guyana shield and a volcanic arc in northern South- America (Williams, 1995).

The Figure 2.6B shows a Permian reconstruction, in which it has been identified a volcanic arc due to the continental collision of North America and South America during the assemblage of Pangea in Late Permian (Ruiz et al, 1999 and Malone et al, 2002).This constitute one of the evidences to corralate the Oachita- Marathon adjacent to Colombia during this continental collision. The geographic and geological relationships and evidences between terrains for these epochs however are not enough and tectonic reconstructions are still controversial**.**

2.1.3   Mesozoic

This sequence started with Jurassic-Triassic continental red beds and igneous rocks reported in the Eastern Cordillera outcrops (Giron formation- La Quinta formaiton) and in northern Llanos basin area. They are isolated and limited areal distribution and have been interpreted as terrestrial syn- rift Mezosoic sediments (Cooper et al., 1995). There is no evidence of Triassic-Jurassic rocks in southern Llanos basin (Cooper et al., 1995), indicating that most of the basin was sub-aerially exposed.

The Early Cretaceous time has been interpreted as a back-arc setting. The sediments are alluvial, deltaic, and basal transgressive sandstones with interbedded shales. The Cretaceous rocks are identified in the Eastern Cordillera as three main formations: the central Gacheta formation shale enclosed by a transgressive sand of the Une Formation and a regressive sand of the Guadalupe formation (Cooper et al., 1995). The equivalent units located in the fordeep of the present-day foreland Llanos basin comprise the main source rock of the area. The uplift of the central Cordillera during the Late Cretaceous-Paleocene time results in the first stage of a foreland basin, affecting what is known as the Upper Magdalena and Llanos basin (Gomez et al., 2005) (Figure 2.6A)

2.1.4   Cenozoic

The Upper Cretaceous- Cenozoic sequence is related with the foreland basin stage due to the uplift of the Eastern Cordillera. It has been deeply studied in the Llanos foothills outcrops by Hubach (1957), Colleta (1990), Forero (1990), Cooper, et al. (1995), Hoorn (1995), Villamil (1999) Gomez, et al., (2005), Martinez (2005), Duenas (2006), y Parra et al., (2010) and others. (Figure 2.6B)

Caribbean paleogeographic reconstructions (Mann et al., 2010) shows two main collisions as one of the causes of the uplift of the Central Cordillera, for Upper Cretaceous- Paleocene (Figure 2.A) and the tectonic peak of Eastern Cordillera uplift (Figure 2.7B). The upltift of the Eastern Cordillera controlled the basin sedimentation changing the depositional environment from shallow marine to transitional- continental (Cooper et al., 1995).

The Cenozoic sequence starts in the Llanos basin with Paleocene sediments of estuarine basal sandstones overlain by a shale sequence with few sandstone intercalations (Barco and Los Cuervos Formations). These units are overlied unconformably by massive coarse to medium grained sandstones of the Mirador formation (Villegas et al., 1994). This unit constitutes the main reservoir rocks of the Llanos basin.

The Oligocene- Lower Miocene section comprises a thick sequence of four main interbedded regressive sand units (C1, C3, C5, and C7 members) and transgressive shale units (C2, C4, C6, and C8 members). The Figure 2.5B shows the Guyana shield as a positive relief towards the east, it is interpreted as the main feature for sediment supply, as result Cooper et al., (1995) suggested that Oligocene sequences increase their percentage of sand towards the East and onlap eastward.

Conformably overlying the Carbonera formation, the shaly Leon formation was deposited over a wide area of the Llanos basin by meandering and braided channels that facilitated sedimentation caused by the Eastern Cordillera uplift (Parra et al., 2010). The Leon formation is considered the regional seal in the basin.

The last sequence in the Cenozoic is Late Miocene- Pleistocene. It consists of a thick sequence of continental sediments (Guayabo formation) as a result of the second stage of the foreland basin evolution due to a main uplift pulse of the Eastern Cordillera. This unit is part of the overburden rocks (Figure 2.6B).

3. Data and methodology

This study is primarily based on the tectono- stratigraphic analysis of ~2000 km of available 2D seismic reflection data and 19 exploratory wells covering an area of 25.000 km^2 in the southern area of the basin[1]. Our results comprise the first academic study that integrates wells, seismic data and potential data to explain evolution since the Paleozoic of south Llanos basin, Colombia, South America and its implication in oil exploration**.**

Figure 2.1 shows the study area with the selected dataset and four transects used to explain the main tectono-sequences.

3.1 Seismic data

The seismic grid was selected from a larger database to obtain a regional coverage of the study area. The quality of the data varies, due to differences in acquisition parameters, sampling time, coordinates system, seismic processing and target between seismic surveys. The dataset compromises information from the National Hydrocarbons Agency of Colombia (ANH) public database acquired with different fold, between 1969 and 2000. It was necessary to build a database that uniforms all the seismic information. This includes reprojection of coordinates, datum correction by shift (between 0 and 300 ms) and resampling to 4 ms.

3.2 Well data

Well information from exploration wells in the area; close to the 2D seismic lines have been used for reference under the seismic interpretation. In total 18 wells with Paleozoic/basement report were selected to be tied to the seismic data.

A variable suite of logs (gamma ray, resistivity and sonic logs); geological information (formation tops and rock description) together with geophysical information (checkshot and velocity seismic profile VSP) were used to constrain the synthetic seismogram and determine geophysical properties of keys reflectors and to correlate the logs with the seismic character.

3.3 Potential field data

Regional bouguer anomaly gravity maps are taken from published maps by ANH, 2009 (Figure 1.2). It has contour each 20 m gal and a general R= 2.67 g cm^3. A gravimetric profile was made in *Oasis,* at the same location of Transect A. This profile is the first approach to define the location and approximate depth of high density rocks and sedimentary sequence.

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[1] Provided for academic purposes by GEMS S.A and CBTH

3.4 Methodology

Conventional interpretation of 2-D seismic data was carried out using *Landmark's OpenWorks™* interpretation software package and then migrated to *Decision Space* for map creation. Regionally continuous seismic reflections were picked as chrono- stratigraphically surfaces for this study. Time structure maps of significant seismic surfaces and isopach maps of seismic sequences were developed to highlight structural and depositional trends. Furthermore, change of keys subsurface intervals thickness is useful to define timing of deformation.

Also, to describe and analyze well data methodology and terminology in Escalona and Mann, 2006 was fallowed. Stacking patterns from well data was build to understand if the sequences have been eroded (disrupted cycles) or if basement structures are paleo- geographic barriers (complete cycles). A structural well correlation in the north was made to understand the Cretaceous arrengment and a stratigraphic well corralation in the south for the Cenozoic. In this last step main erosional surfaces are identified as boundaries and related with tectonic activity.

A challenging assumption for the well correlation is that the sedimentation supply is the unique regime variable that can be taking in account because the continental nature of the Llanos basin sediments.

4. Tectono- Sequences

Four main sequences are identified based on stratigraphic and structural observations together with important unconformities surfaces, seismic expression and onlap /downlap/ truncation relationships. In total seven horizons corresponding to formation tops with relatively known age have been identified and interpreted, including the key ones for petroleum exploration. These horizons are named by age in order to use a uniform nomenclature and avoid formation name constrains.

The events are (**Figure 4.1**):

a)   Paleo- proterozoic (Guyana shield),

b)   Neo- proterozoic (rocks with Greenvillian age),

c)   Lower Paleozoic unconformity (Ordovician?),

d)   Upper Paleozoic unconformity,

e)   Upper Cretaceous,

f)   Oligocene (Top of Carbonera C1),

g)   Miocene (Top of Leon Formation) and;

h)   Pliocene.

Cenozoic and Mesozoic horizons were identified and correlated with available well logs / well tops and check shots; while Paleozoic horizons have been identified and described based on extrapolated information from surroundings areas. The Figure 4.1 shows the seismic expression and the well logs expression of three wells (well No.2, No. and No.) along the study area.

Present-day structure of southern Llanos basin shows a general Paleo- proterozoic basement platform dipping moderately towards the south-east overlaid by a Neo- proterozoic NS trending igneous and metamorphic fold and thrust belt (Figure 4.1). Paleozoic rocks are described in two sequences and its upper boundary is a major unconformity that is relatively easy identified along the study area. Triassic-Jurassic and Lower Cretaceous rocks are absent, while Upper Cretaceous rocks are onlapping at top of the Paleozoic sequence with a pinching-out termination towards the east (Figure 4.1). Cenozoic rocks are clastic sediments filling the second foreland basin stage.

This last sequence has been widely studied in previous works. It contains both the main reservoir rocks and regional seal of the basin. So far, they are identified as three control horizons: top Oligocene representing main reservoir rocks, top Miocene for regional seal and Pliocene for overburden rocks.

Structures in older tectono- sequences, specially the basement highs identified in the seismic and the gravimetric data are going to be described as the Neo-proterozoic /Paleozoic fold and thrust belt. Previous works have named this features in different ways, including: Chafurray high, Melon-El Viento high, Candilejas high and La-Voragine high. These features

Four EW regional transects, are located through the area and show the behavior of the structures along the dip (Figure 3.1). The transects together with structural maps and time thickness maps are used to described the main seismic character, illustrate the evolution, and depict structural features such as Precambrian structural highs and fault families.

4.1 Tectono- Sequence 1: Precambrian basement

The Southern section, Transect A (Figure 4.2) and structural maps at top of Paleo- proterozoic (Figure 4.3A) and Neo- proterozoic (Figure 4.3B) are shown to describe the sequence. In order to support geological ideas and decrease uncertainty in the interpretation, a gravimetrical analysis is also presented.

Rocks from this tectono- sequence are assumed to be the regional basement. Two main sequences are identified, Paleo- proterozoic (sequence 1A) and Neo- proterozoic (sequence 1B). The age and general geological characteristics of these sequences are extrapolated from surrounding areas. Guyana shield outcrops towards the east for the Paleo- proterozoic and towards the southwest in the Putumayo basin and Eastern Cordillera subsurface data for Neo- proterozoic.

Sequence 1A is composed essentially by granitoids rocks (Cordani et al, 2010) while sequence 1B is composed of igneous and low grade metamorphic rocks with sedimentary protolith. New geochemical studies (Ibanez-Mejia, 2011) show that metamorphic rocks sampled from surrounding areas, as Putumayo basin, are related with Greenvillian ages. This fact evidences younger basement forming structural highs towards the south-west and occurrence of Paleo- proterozoic basement towards the east. An important west-dipping fault zone (fault family 2) with a regional detachment at top of the Paleo- proterozoic is dividing both basement terrains. The eastern area is interpreted as a NS trending fold and thrust belt (fault family 2) and the western area as a main depocenter forming ahead the thrust system (Figure 4.2).

4.1.1   Sequence 1A: Paleo- proterozoic

Well Character

No wells have reached Paleo- proterozoic rocks. Lacking of hard data made the top of this sequence an interpretative horizon.

Seismic character

The top is marked by a broad, high amplitude reflection with moderate continuity. In the seismic interpretation Paleo- proterozoic is located below undeformed sediments towards the east. It can be followed because is relatively shallow and the acoustic impedance has high values due to the difference between the crystalline Paleo- proterozoic and the overlaying undeformed sedimentary column. Towards the west, the Paleo- proterozoic occur below igneous metamorphic rocks from the Neo- ptroterozoic. Its top is difficult to define in this area because the seismic is not penetrating deep enough and seismic resolution is poor. (Figure 4.2)

The seismic expression for the basement is poor due to some strong chaotic subhorizontal reflectors that are crossing each other. This feature is interpreted as younger intrusive tabular dikes and sills with different composition than the host rock. Intrusions are an important cause of basement reflections in the continental crust. They are characterized with: high amplitude, short, sharp and simple waveforms. An analog of this seismic character can be seen in the synthetic reflectors model of Proterozoic diabasic intrusions occurred in Buck Mountains, and tested in the sequence known as Bagdad Reflection sequence (BRS), west-central Arizona, USA (Litak and Hauser, 1992).

In the case of Guyana shield, diabase dikes and sills are described in the southeastern of Venezuela (Briceno and Shcubert, 1990) and Western Brazil (Shcneider Santos et al., 2000). These outcropping features support the mafic intrusive character of continental crust reflections in the area of study.

Time structural map

Top of Paleo- proterozoic basement is the deepest surface of the area and has been interpreted as a reflector with positive values of acoustic impedance. The structural map is built in the east part of the area because it is relatively shallow and is overlaid by sedimentary units. The map (Figure 4.3A) shows contours between 1450 and 3524 ms dipping around 5-10⁰ westwards with some subvertical to vertical normal faults (Fault Family 1). A small and elongate depocenter can be

identified in the west part of the area (Figure 4.3A). It is dividing two main highs and may imply a structural feature with EW direction.

The deeper area is located to the west, where the Paleo- proterozoic top is interpreted as the regional detachment (Figure 4.2) of the Neo- proterozoic fold and thrust belt. This characteristic can be observed in the southern part of the study area. There is no seismic evidence of the Paleo- proterozoic basement continuity under the Neo- proterozoic fold and thrust belt in the western part (Figuere 4.3A).

4.1.2   Sequence 1B: Neo- proterozoic

Well character

Few wells have reached and sampled metamorphic rocks. Most of them are located in the structural high towards the south.

Original well reports from well-18, well-3 and well-2 (Ecopetrol, internal report) describe basement rocks as phillites, micaceous schists, green schists and quartzites (Figure 4.3) . These rocks have been grouped as the Neo- proterozoic sequence due to their geological affinity. For this unit geochronological analyses in well reports were no available in order to verify its absolute age.

Seismic character

The top is marked as high, positive amplitude, continuous reflector tie to well-2 (Figure 4.1). Seismic character of this unit is poor; however rocks from this sequence generate some coherent internal reflectors. This is due to the mixed metamorphic and igneous character of the Neo-proterozoic rocks. The seismic character of igneous rocks is relatively homogeneous whereas foliation of low- medium grade metamorphism generates relatively continuous reflectors. There is no evidence if undeformed sedimentary rocks from Neo- proterozoic ages has been deposited overlaying the Paleo- proterozoic in the east area interpreted as foreland basin (Figure 4.2).

Time structural map

The Neo- proterozoic map shows contours between 400 and 2000 ms. Shallow contours describe two main structural highs to the south and plunging out toward the north. These anticline structures are located in the hanging- wall of NS trending reverse faults (fault family 2) and are interpreted as part of a fold and thrust belt (Figure 4.3B).

There is not clear seismic evidence if Fault family 2 was active during the Neo- proterozoic but it is evidence of Paleozoic reactivation. Local, relatively small and elongate NW depocenters with Paleozoic onlapping reflectors shows a reverse sense during Lower Paleozoic. This implies a paleogeographic barrier of Neo- proterozoic rocks during this age (Figure 4.3B).

Separation of Fault family 2 is separated into a north and south segment (Figure 4.3B). This may indicate an EW lateral ramp. The south segment is characterized by well developed faults with a significant displacement and the north segment is less deformed and the structure is plunging out (Figure 4.4).

4.2 Tectono- sequence 2: Paleozoic

Transect C in the central part of the area of study (Figure 4.4), a structural map at Upper Paleozoic unconformity (Figure 4.5A), and a thickness map (Figure 4.5B), are shown to describe the main geological characteristics.

The Paleozoic is mainly composed by marine shales and continental/shallow marine sedimentary rocks. It is divided in two sequences, Lower Paleozoic and Upper Paleozoic, based on extrapolated information from surrounding areas (Eastern Cordillera and Amazonas basin). Lower Paleozoic sequence is related with continental and ahallow marine environments, while and Upper Paleozoic sequence related with deep marine environments (Duenas, 2006).

Outcropping rocks of this age in the Eastern cordillera shows metamorphic units (Quetame complex) (Burgl, 1967), while rocks from the Amazonas basin and the Macarena range are described as intercalation of mudstone and sandstones (Araracuara formation /Guejar formation). This sequence overlies the Neo-proterozoic rocks (sequence 1A) with an onlap relationship. It is overlaid unconformable by Upper Paleozoic strata. The top of sequence 2A is represented by an unconformity surface which is difficult to trace and tie across faults, due to compressional deformation pulses that generate several internal unconformities with the similar seismic character.

Upper Paleozoic top reflector is a regional erosive surface. It is known as top Paleozoic unconformity and can be correlated with the reflector known as economic basement from previous works (Figure 4.1 and Figure 4.4).

Importance of this sequence is related with outcropping Upper Paleozoic units of surrounding basins, specifically with Eastern Cordillera and Amazonas basin are described as fine grained sediments with potential as source rock (Farallones group/ Piparial formation)(Herrera and Rodriguez, 1996)

4.2.1 Sequence 2A: Lower Paleozoic

Well character

Even though there is no well-log available for this sequence wells drilled in high structural areas have reported samples and palinological description of Lower Paleozoic. Based on these reports, Lower Paleozoic can be divided in two groups: a) meta- sediments described as micro- micaceous shales and compacted sandstones in wells located towards the west, e.g wells-8 and well-16 (Ecopetrol, Internal report); and b) white sandstones and mudstones with palinological information in wells located to the east, e.g well-14 reported a zone of *Veryhachium trispinosum* (Ecopetrol, Internal report) (Figure 4.5).

Seismic character

The top is marked as a moderate amplitude and continuous reflector. Seismic character is parallel to sub-parallel towards the east while to the west is highly deformed and the seismic character within the sequence is more chaotic. In this area it is difficult to describe a consistent pattern, however the erosive character of the unconformities generates positive reflectors, which are easier to identify and are mainly associated with this sequence.

The transect C (Figure 4.4) shows the Lower Paleozoic sediments mainly located in small and elongated Neo- proterozoic depocenters formed on top of the thrusts (Fault Family 2), which are interpreted as piggy back basins.

Local unconformities and faults are identified within this sequence. Furthermore, steep changes in dip, truncation and termination of reflectors towards the west of the study area have been interpreted as triangular zones. Triangular zones are characterized by two detachment faults from Fault family 2 and a back thrust. This evidences a compression event at some point in the Lower Paleozoic (Figure 4.4).

Towards the south-eastern area s Paleozoic foreland basin is interpreted. The transect A (Figure 4.2) shows the reflectors with sub-parallel and parallel arrangement with approximately 2 ms of thickness suggests that sequence 2A may occur. There is not hard data (well data) that evidences Lower Paleozoic in this area.

4.2.2 Sequence 2B: Upper Paleozoic

Well information

Original well reports do not differentiate Upper Paleozoic sediments but a recent palinological study in Paleozoic marine shale samples of the well SM-4, located towards the south of the study area, presents ages from Late Devonian to Lower Carboniferous (Duenas, 2006), enclosed in this interpretation as Upper Palaeozoic sequence.

Seismic character

Upper Paleozoic sequence is characterized by homogeneous, horizontal to sub-horizontal seismic character just below a strong positive reflector related with the Upper Paleozoic unconformity. It consists of few reflectors within the piggy back basin and a relative thicker sequence (200 ms) in the southern part (Figure 4.5A).

Structural time map

Upper Paleozoic sedimentation still occurs in piggy back basins. The sequence is characterized by a small shaly sequence (from 50 to 200 ms) composed by few continuous and horizontal reflectors which is related with low grade of deformation and a stable tectonic period.

These basins are small and shallow in the south. The structural high is well developed. They are deeper and bigger towards the northern plunge of the structural high. The onlapping relationship and the disposition of the sediments suggest an uplifted area in the south during the time of its deposition.

Main Paleozoic features are shown in the structural map at top of Upper Paleozoic unconformity (Figure 4.5A), which represents a hiatus of 200 Ma depending on the position within the basin, either Cretaceous or Cenozoic sequence. The main fault families involved are: a) NNE-SSW trending normal faults of low displacement (Fault family 3), b) regional reverse faults (Fault family 2) and c) Reverse northeast oriented faults (Fault family 4).

<u>Thickness time map</u>

Thickness in the piggy back basins is between 600- 1200ms, depocenters in the north are bigger and thicker in the north (Figure 4.4 and Figure 4.5). Paleozoic sequence is considerable thin in areas next to the hanging wall of NS faults, it comprises around 50ms maybe as a result of large erosion represented by the Upper Paleozoic unconformity (Figure 4.4 and Figure 4.5A).

Evidence of the magnitude of the erosion is identified in the eastern area where the thick Paleozoic sequence seems to be complete. Occurrence of both Lower and Upper Paleozoic sequence are expected in the undeformed and apparently conformable reflectors. (Figure 4.5B)

4.3 Tectono- sequence 3: Cretaceous

The Cretaceous is generally divided in two sequences: Lower and Upper Cretaceous. Lower Cretaceous rocks are not found in the area of study, they are deposited further west. Thus, this tectono- sequence is composed by Upper Cretaceous- Paleocene transgressive and continental sandstones; which overlays unconformable above Paleozoic sediments and its upper limit is an erosive surface. At this point, Upper Cretaceous- Paleocene is in contact with rocks from Cenozoic tectono-sequence.

The absence Lower Cretaceous sequence is known as the regional source rock with the eastern cordillera as the main kitchen and the hydrocarbon migrates laterally, more than 200 km towards the east during Cenozoic times (Moretti and Mora, 2010).

Upper Cretaceous rocks are the oldest known reservoir rocks, fields towards the west produce from this interval (Figure 4.1). The geometrical arrangement of sequence is asymmetric. Top Cretaceous is marked as an unconformity; which is onlapping towards the Neo-proterozoic fold and thrust belt. It has wedge shape, thinning towards the east and a thicker sequence towards the west. The pinching out is interpreted as the forebulge of the first stage foreland basin (Figure 4.6).

Transect B in the central part of the area of study (Figure 4.6), a structural well correlation (Figure 4.7), a structural map at top of Cretaceous (Figure 4.8A) and a thickness map (Figure 4.8B) are shown to describe the main geological characteristics.

4.3.1 Sequence 3A: Upper Cretaceous-Paleocene

<u>Well log character</u>
Wells in the northern area have reported Upper Cretaceous and Oligocene sandstones. Based on a structural well correlation (Figure 4.7) in the northern part the well log character will be described.

Cretaceous is located between 3000 and 9000 *ft.* In well- 8 Cretaceous exhibits low gamma ray and high resistivity with blocky pattern related with massive sandstones (Figure 4.7). The Cretaceous ends with a rise in relative sea level which capped the sandstone with finer sediments. Major Cretaceous stratigraphic features cannot be followed along the well section, the sediments are wedging out at some point between well-8 and well-3 (Figure 4.7). The Well cross section

observations also provides evidence that the Neo- proterozoic fold and thrust belt is uplifted during the Cretaceous.

Oligocene has a coarsening upwards behaviour. From depths where the gamma ray log has relatively high values. Four flooding surfaces can be identified in depths where gamma-log has relatively high values. The stratigraphic cycles are smaller but complete towards the east. The maximum flooding surface and sequence boundary can be followed along the area until well-4. This is evidence of migration of the forebulge in the first stage of foreland basin development towards the east.

Seismic character

Upper Cretaceous unconformity has been interpreted as moderate high amplitude (positive peak reflection) onlapping towards the Neo- proterozoic sequence (Figure 4.6). It is associated with the increase in velocity between the Cenozoic basal shales and Cretaceous sandstones. The seismic character is mainly horizontal to sub-horizontal but erosional truncations are occasionally found in the upper boundary.

Structural time map

The structural map at top of Cretaceous (Figure 4.8A) is restricted to the western portion of the study area. It shows how the Cretaceous thins eastwards and forms an eastward-stepping strata package onlapping a regional Upper Paleozoic unconformity. This pinching-out towards the south is clearly showing that for this age the fold and thrust belt was uplifted and.

Fault family 3, which are related with Paleozoic flexural extension has been inverted for this time. This situation reflects the effect of a compressional event probably related with the uplift of the Central Cordillera. Fault family 2 and Fault family 4 are affecting this sequence due to reactivation during Cenozoic events (Figure 4.8A).

Thickness time map

Thickness map for Cretaceous sequence (including Mirador and Barco formations) suggests the occurrence of a Paleohigh in which the sequence is pinching out. The interval is generally thin (50 ms) in the area. Main depocenters during the Cretaceous are located towards the west near the Eastern Cordillera (Figure 4.8B).

4.4 Tectono- sequence 4: Cenozoic

The Cenozoic rocks were deposited during a foreland basin setting (Figure 2.6B) and is considered as the basin infilling process. It is divided in two sequences: from Oligocene to Miocene (sequence 4A) with prevailing shoreline conditions; and Pliocene (sequence 4B) continental sediments overlying unconformably.

Given the petroleum exploration, important horizons at top of Oligocene, top Miocene and Pliocene were identified. Rocks from Oligocene are characterized by intercalation of continuous sand bodies and shales. These ones are the main reservoir for fields located in the eastern part while Miocene is identified as the regional seal of the area (Figure 4.1).

Sequence 4A shows the beginning of the most important tectonic pulse in which occur the uplift of the Eastern Cordillera. Even though, geochronological analysis conducted in the basin have established an average of 36 Ma, the uplift commenced earlier in the south with around 42 Ma in average (Mora et al., 2010). This situation demonstrates that the uplift is diachronous and has to be analysed independently for each area.

The continuous uplift of the Eastern Cordillera since Early Miocene causes significant subsidence and creates accommodation space, parallel to Fault family 4 in the western portion of the study area. Continental sedimentation of large volumes of conglomeratic and coarse sediments in a short time interval was crucial in the burial of source rocks (Figure 4.9)

Principles of sequence stratigraphy and stacking patterns can be applied to describe geological characteristics and main tectonic episodes for sequence 4A. During these episodes the space generated was filled by sediments displaying aggradational patterns mainly deposited in shoreline conditions.

Transect D in the northern part of the area of study (Figure 4.9), a stratigraphic well correlation (Figure 4.10), a structural map at top of Oligocene (Figure 4.11A) and Miocene (Figure 4.11B), and a thickness map of Pliocene sequence (Figure 4.12) are shown to describe the main geological characteristics.

4.4.1 Sequence 4B: Oligocene- Miocene

Well-Log character

Stratigraphic well correlation, in the south (Figure 4.10), shows a thick sequence comprised of regressive sand packages and trangressive shale layers. In general, muddy facies are characterized by high gamma-ray values and are mainly serrated type indicating low energy environment, while sandy facies exhibits high gamma ray values in a serrated arrangement interpreted as fluvial channels and flood plain deposits.

This sequence finishes with a maximum flooding surface related with top Miocene. It has high gamma-ray values with a typical serrated pattern. Mudstones were deposited in low energy environments and it becomes sandy towards the east. Interbedded sands with low gamma-ray values are relatively easy to identify and can be interpreted as fluvial channels. The well cross section is flattened to this surface.

Cenozoic sedimentological register encompassed six cycles separated by flooding surfaces. These cycles are thicker towards the west and thinner and incomplete towards the east. FS1 and FS2 are pinching-out at some point between well 2 and well 7, which correlates with the location of the Neo- proterozoic fold and thrust belt. FS3, FS4 and FS5 are identified along the well section, with a small thickness but complete cycle towards the east. There is a depocenter change between the parasequences FS1-FS2 and the FS2- FS3. In the oldest one the thickest parasequence is next to the east however in the parasequence FS2-FS3 the depocenter switch towards the west. That implies a paleogeographic change in the area and it is related the time when Neo- proterozoic fold and thrust belt is no longer a paleo- geographic barrier. Based on the well correlation this time is FS3 which is Upper Oligocene (Top of Carbonera).

Seismic character

Top Oligocene is marked by the first high positive amplitude reflector from a set of parallel and sub-parallel strong peaks and troughs associated with the increase in velocity between the sandy and shaly intervals developed as a response to periods of transgression and regression. Some channel shapes with internal high amplitude, interpreted as channel sand-fill of incised valleys, can be distinguished within the Oligocene.

The sequence overlies Paleozoic or Cretaceous depending on the location in the area. Top Miocene is unconformable overlain by Pliocene sequence and its unconformity marks the top of this sequence. Top of Miocene is marked at the first continuous low amplitude reflector of a homogeneous seismic character (similar acoustic impedance between layers) interval of around 200 ms thick (Figure 4.9).

<u>Structural time map</u>

Structural map from top Oligocene (Figure 4.11A) and Top Miocene (Figure 4.11B), which correspond to the youngest regional seal exhibits the same general configuration and major features. These maps shows: NE-SW oriented faults (Fault family 4), which are parallel to the present- strike of the Eastern Cordillera. A reactivated NS reverse faults (Fault family 2), inverted fault family 3 and flexural normal fault (Fault family 5) as response of the uplift of the Eastern Cordillera.

4.4.2 Sequence 4C: Pliocene

Well log character

This sequence consists of a thick sequence characterized by a high variability of Gamma ray values. The well correlation (Figure 4.10) shows a monotonous aggradational stacking pattern through the sequence. Low values of gamma- ray are more evident in the western part of the area. This pattern is typical for continental sediments with large magnitude of accommodation space.

Seismic character

The Top of Pliocene is marked in the first legible reflector of the seismic data and top Miocene as its base. The thick sequence (500-1000 ms) consists in high amplitude reflections with poor lateral continuity due to the continental character of the rocks. The transect D (Figure 4.9) shows a slight onlapping of the unit towards the east showing the foreland arrangement of the basin.

Thickness map and observations

The thickness map shows asymmetrical wedge geometry characteristic foreland basins, where its maximum thickness (~1800 ms) is located in the western part of the study area and the thin part (~200 ms) is located to the south part. This area is identified as the present foredeep along the Eastern Cordillera (Figure 4.12).

4.4.1 Gravimetric Profile

Gravimetric information is useful to define the geometry, limits and depths of crystalline and metamorphic rocks. This method is used in order to decrease uncertainty with complementary information in areas where the seismic resolution is not good enough to trace a confident horizon.

The Figure 4.12 is a bouguer anomaly gravimetric profile at the same location than transect A (Figure 4.12D). It was built base on the ANH, (2009) grid and the seismic interpretation in order to have an approximation of the basement depths. The seismic interpretation has identified two different basement provinces: Neo- proterozoic and Paleo- proterozoic (Figure 4.12A). This arrengment produces a gravimetric anomaly that can be identified in the bouguer anomaly map. The anomaly in this profile has values between 0 and 30 mGal and is located towards the west (Figure 4.12B).

The depth profile model (Figure 4.12C) consists in a main depocenter towards the east represented in the gravimetric data by low values. It is related with the basin that is formed adjacent to the Neo- proterozoic fold and thrust belt. Values for Neo-proterozoic rocks t are high (around 20 mGal) implying an igneous and metamorphic characteristic. The strong break on the profile agrees with the deformation front interpreted in the seismic and can be identified as the boundary between Neo- proterozoic rocks related with Greenvillian ages and Paleo- proterozoic rocks related with Guyana shield. The positive slope of the anomaly towards the east can be interpreted as the wedge geometry of a foreland basin.

5. Discussion

5.1 Proposed basin evolution

An alternative basin evolution is presented based on 2D seismic and well-log observations for the south Llanos basin. It involves identification of compressive reactivated pre- Cenozoic features, which implies a control of early structural features in subsequent stages of deformation.

Several stages of deformation have been identified in the southern Llanos basin since the Lower Paleozoic until Cenozoic. The proposed evolution compromises several sequences grouped in three main stages: Paleozoic and Upper Cretaceous- Cenozoic. Its boundary is the Upper Paleozoic unconformity and comprises more than 200 Ma. Although Mesozoic stages are not present in the area they are also described based on information from surrounding areas as the Eastern Cordillera.

Figure 5.1 and 5.2 synthesizes events and structural features for both periods. Each one shows a northeast- southwest schematic cross-section showing the principal events and a map view of the structural features distribution.

5.1.1 Precambrian: Paleo- proterozoic and Neo- proterozoic basements

There are two different Precambric basements beneath the southern Llanos basin: a) Paleo- proterozoic basement related with Guyana shield and b) Neo- proterozoic orogenic belt. Most of the previous works in the area shows the Paleo- proterozoic as a stable craton as the main basement of the area (Gonzalez, 2011).

The main difference between both interpretations is the assumption of Greenvillian-age underlying the sedimentary record instead of the typical basement correlation with Guyana shield rocks. This is supported by new geochemical data (Ibanez-Mejia, 2010), seismic interpretation and a simple gravimetric model, where the positive anomalies in the bouguer gravimetric map and no- sedimentary well samples at some locations have been explained by the occurrence of this igneous-metamorphic belt (Figure 4.12 and Figure 5.1) buried under the Llanos foreland basin.

The Paleo- proterozoic chaotic seismic character is explained due to the occurrence of mafic dikes (Figure 4.2). This is one of the key features to identify it in the eastern part of the area beneath the sedimentary record, however in the western part the seismic quality is poor and it is difficult to interpret. The occurrence of the oldest basement beneath the Neo- proterozoic in the

west is supported by Fault family 2 interpretation in the southern area, which has a detachment on the Paleo- proterozoic top (Figure 4.2) and a simple gravimetric model in the southern that agree with the gravimetric anomalies (Figure 4.12).

The Precambric scenario is still controversial. Based on the seismic interpretation, it is an active Neo- proterozoic fold and thrust belt (Fault family 2); where, normal faults affecting the Paleopropterozoic (Fault family 1 at Figure 4.2) are interpreted as flexural- induced faults. They are considered as the extensional response of the allocthonous? Neo-proterozoic block above the flexed lithosphere. Furthermore, the unexpected thick column of sediments in the eastern part (Figure 4.2) can be explained with a foreland basin filled with Neo- proterozoic sedimentary rocks, which means an active Fault family 2 for this period (Figure 5.2A).

The Figure 5.2B shows the areal extension of Neo- proterozoic structural high and how they are controlled by NS reverse faults (Fault family 2). This structural style can be follow to the south and they may explain structures orientation and exposure of Neo- proterozoic rocks at the Macarena range and the upper limit of the Garzon complex (Eastern Cordillera).

5.1.2 Paleozoic

Paleozoic is divided in two stages: Lower Paleozoic fold and thrust belt and Upper Paleozoic transgression. The Figure 5.2 summarizes key events and features as: triangular zones and the piggy back basins and the Upper Paleozoic unconformity.

This interpretation differs from the classic extensional setting (Ceron, 1998) for the Paleozoic, in which the high structural basement in the southern Llanos basin is identified as the shoulder of a Lower Paleozoic graben which has been preserved through time (Figure 1.4B). Recent interpretations are also pointing- out the role of pre-foreland structures in the southern part of Llanos basin. Gonzalez (2011) identified Paleozoic reverse faulting with detachment in crystalline basement, which are correlated with the Fault family 2 in this interpretation (Figure 1.4C).

<u>Lower Paleozoic fold and thrust belt</u>
Previous (Neo- proterozoic?) structures have been reactivated in the lower Paleozoic. Evidences of an active Fault family 2 can be identified in the seismic. This family has a reverse sense during Lower Paleozoic, onlapping and truncated reflections (Figure 4.2) are evidences of a Paleozoic fold and thrust belt.

The Paleozoic fold and thrust belt creates Lower Paleozoic piggy back basins. These small and elongated basins are located ahead the thrust (Fault family 2), where their onlapping sediments are syn- tectonic (Figure 4.4). The continued compression from the east results in shortening and triangular deformation zones within the piggy back basins. This explains the strong deformation, changes in dip and truncation of reflectors in basins toward the east and little or no deformation towards the east (Figure 4.4).

A foreland basin develops adjacent to the Paleozoic fold and thrust belt (Figure 5.1A). This is interpreted base on the parallel and subhorizontal seismic character in the eastern area (Figure 4.2) and to the Paleozoic well samples. Some wells show the sedimentary character of the Paleozoic rocks in this area (Figure 5.2B), which can be correlated as an extension of the Cambrian basin proposed by Feo- Codecido et al., (1984) in Venezuela (Figure.2.4B).

Other geological features identified in previous works can be also correlated in the area. The metamorphic complex of low-grade metamorphic rocks (Quetame complex) in the Eastern cordillera (Burgl, 1967 and Ordonez-Carmona, et al., 2006) can be primary correlated with some metamorphic samples from wells located in the eastern part of the study area (Figure 5.1). However, more studies are necessary to confirm if there are affected by the same metamorphic event.

The proposed tectonic setting for Lower Paleozoic (Figure 5.1) can be a result of the subduction event described in the regional reconstruction for northern south-America (Williams, 1995) (Figure 2.5A). Where, the metamorphic complex and a Paleozoic fold and thrust belt in the west and a foreland basin toward the east are an evidence of a Lower Paleozoic orogonesis in the southern Llanos basin (Figure 5.1B).

Upper- Paleozoic transgression

A general north plunging-out of the Paleozoic fold and thrust belt can be followed in the seismic (Figure 4.5) and in the bouguer anomaly map (Figure 1.3). These features can be explained by the transgression from the north during the Upper Devonian (Duenas, 2006). Marine rocks, mainly black shales indicate a transgression in the area during this period (Duenas, 2006). This lithological characteristic and its subhoriozontal seismic character (Figure 4.4) shows a relatively calm period, when the piggy back basins and the foreland basin were filled- up. This generates late relaxation structures as normal faults from family 3 (Figure 5.1b).

Previous works, suggested reactivation of fault family 2 (Gonzalez, 2011) based on the Upper Carboniferous unconformity described by Duenas, (2006). Despite this, both interpretations agree that the Upper Paleozoic sedimentation is located in the piggy back basins.

During the Permian the sediments have been eroded across the area, therefore there is no record of sediments of this age in the basin (Gonzalez, 2011). This period is identified in the seismic as the Upper Paleozoic unconformity and may imply reactivation of pre-existing structures (Figure 4.4). All these geological features in the southern Llanos basin agree with regional reconstructions for Upper Paleozoic with the assembly of Pangaea (Figure 2.5B), where the northern south-America is showed as a positive relief area which correlates with the interpretation

5.1.3 Mesozoic

Mesozoic is divided in two stages: a Jura-Triassic continental rifting and a Lower Cretaceous post-rift.

Jura- Triassic continental rifting

The southern Llanos basin was the uplifted shoulder of a Jura- Triassic continental rifting. There is no evidence of Jura- Triassic sediments in the area, wells reported Paleozoic rocks beneath Upper Cretaceous/ Cenozoic sequence (Figure 4.1).This period is considered as a main erosive period because the area was a positive high relief. However, surroundings areas as the Eastern Cordillera was affected by continental rifting (Cediel, 1968) withJurassic red beds displaying as a pronounced wedge in the Eastern Cordillera. They represent syn-rift sequence (Kammer and Sanchez, 2006). This event is consequence of the drifting apart between North and South America during the Caribbean opening (235-130 Ma).

Lower Cretaceous Post-rift

Lower Cretaceous sediments from an epi- continental sea with high sea levels (Guerrero, 2002) were filling up the accommodation space created by the rifting stage. Areas in the eastern Cordillera had a regional subsidence and a back-arc setting (235-130 Ma) (Cooper et al, 1995). The southern Llanos basin has no evidence of Lower Cretaceous rocks, well reports have not identified rocks form this period, so for this period southern Llanos basin is still identified in the seismic as the Upper Paleozoic unconformity and it is interpreted as a positive relief area.

5.1.4   Upper-Cretaceous- Cenozoic

Upper Cretaceous- Cenozoic is characterized as a foreland basin setting. It is divided in two sequences: Cretaceous- Lower Oligocene foreland basin and Upper Oligocene- Recent foreland basin. The Figure 5.2 summarizes key events and features for this period.

Most previous papers are focused on these later sequences. It is widely accepted that the Llanos basin is a multi-stage foreland basin and is related with a Late Cretaceous- Cenozoic system. The first stage is the result of Central Cordillera uplift and the basin covers the Upper Magdalena basin and the Llanos basin, while the second is the result of the Eastern Cordillera uplift and basin is restricted to the Llanos basin (Cooper et al., 1995 and Gomez et al., 2005).

Upper Cretaceous- Lower Oligocene: First stage of foreland basin

In the southern Llanos basin, a pinching out from Upper Cretaceous and Lower Oligocene can be identified in the seismic due to the onlapping reflectors in the central area towards the Upper Paleozoic unconformity (Figure 4.7) and the low values of the time thickness map (Figure 4.8 B) in the east. It can also be identified in the well correlation. The 2D stacking pattern (Figure 4.6) shows the complete and uniform cycles Upper Cretaceous and Lower Cenozoic pinching-out towards the east.

These pinching-out are the most important feature of the southern Llanos for this period. it is It is interpreted as the forebuldge of the first stage of foreland basin in the area, with the main depocenter parallel to the Central Cordillera towards the east (Figure 4.8A). This observation has also been detail described and demonstrated by previous works (Gomez et al., 2005) (Figure 2.6A).

Through time the forebulge of the basin has migrated to the east. Figure 4.6 shows how the younger parasequences are pinching-out further east than the Cretaceous. This observation agrees with observation in previous works for flexural modelling (Campos, 2011). The Figure 5.2A shows the termination from the younger sequence located to the east than the Upper Cretaceous pinching-out in a foreland tectonic setting.

In addition, Upper-Cretaceous and Lower Cenozoic sequences are onlapping towards the Paleozoic sequences (Figure 4.6 and 4.8B). This means, that the Paleozoic fold and thrust belt was reactivated and should be considered as a paleo- geographic barrier from Upper Cretaceous. Figure 5.2B shows the east boundary (forebuldge) of the Upper Cretaceous foreland basin.

<u>Upper Oligocene-Recent Second stage of foreland basin</u>

The tectonic setting for this period is interpreted as a foreland basin. The undeformed sequence with parallel and subhorizontal seismic character (Figure 4.10) and the slightly wedge arrangement of the Cenozoic rocks (Figure 4.11) confirms the proposed second stage of foreland basin (Gomez et al., 2005).

Pre-existing structures and Cenozoic structures are related with two different pulses. Fault family 2 reactivation and Fault family 3 positive inversion are related with Miocene pulse while Fault Family 4 and Fault Family 5 are related with the last period of deformation (Figure 5.2A). This agrees with previous works that define the deformation and the uplift of the Eastern Cordillera as diachronous with at least two phases of deformation: Miocene and intense Pliocene-Pleistocene phase (Mora et al., 2010).

The 2D stacking pattern in the well correlation (Figure 4.9) shows evidences major changes in the basin configuration. Oligocene parasequences (FS1 and FS2) are truncated towards the Paleozoic fold and thrust belt. This means that the feature was still a positive relief for this period and a source of sediments due to the occurrence of a depocenter next to it (Figure 4.9). However, for Miocene parasequence (between FS2 and FS3) it can be identified a switch of depocenters towards the west, related with the first pulse described by Mora et al., (2010). Only until Pliocene-Pleistocene this feature was buried by Cenozoic continental conglomerates and the Cenozoic foreland basin has the present day configuration (Figure 5.2B)

5.2 Mechanism controlling Paleozoic fold and thrust (Fault family 2) belt front

The Paleozoic fold and thrust belt is described as a series of NS trending reverse faults in an area of structural disruption. This EW feature is interpreted as a right-lateral ramp.

A Lateral ramp develops by a volumetric constriction in the direction of the tectonic transport, in which the thrust faults are transferring the displacement to some cross strike fault (Pohn, 2001). Evidences for this feature in the area of study are: a) the abrupt termination of fault along the strike, b) Major morphologic changes c) long, straight EW striking river and c) seismic character.

There is an abrupt termination of the NS thrust in the central part and persists towards the west in the northern area. The displacement of the lateral ramp is estimated based upon the frontal thrust offset between section A and section B. The maximum thrust displacement is 15km (Figure 3A).

Morphologic changes can be observed toward the east, in the Eastern cordillera. Figure 5.3A is showing a DEM of the area, where the high attitude of the Eastern Cordillera can be differentiate from the foreland Llanos plain area. However, towards the east of the study area a small salient in the morphology can be identified.

This change is also identified in the geological map of the area (Gomez et al., 2009). The salient is E-W faulted contact between a Cambrian metamorphic unit and a Cretaceous unit. It can be related with a lateral ramp instead of the almost 80 degrees bending of the thrust fault proposed by the map (Figure 5.3B)

This feature is also controlling fluvial drainage; an abrupt change in the orientation of drainage into relative straight E-W section is showing that the lateral ramp is a relatively young feature or at least reactivated during the Pliocene-Pleistocene phase, that encompassed the last tectonic pulse.

Evidences in the seismic can be seen in a SN transect (Figure 4.3C). The seismic evidence of the lateral ramp consists in the transition area between a low deformated area in the south and a high deformed area in the north. The low deformation area corresponds to the foreland basin interpreted after the deformation front. While the high deformated is related with fold and thrust belt, where the deformation front can still identified. The lateral ramp has a steep angle and is classified as thick skin structure.

Lateral ramps are identified as a consequence of fold and thrust belt tectonics and are relatively common elements in mountain ranges (Pohn, 2001). In the Eastern Cordillera dextral-strike faults system (Algeciras fault system) has been interpreted based on Landsat TM images (Velandia, et al., 2002). Furthermore, small scale interpretation of right-lateral displacement has been identified in Cano Limon field; which is located, north of the basin (McCollough, 1990).

Regional interpretation in the north also supports the idea of a dextral movement during the Cenozoic. In general, dextral movement is related with the Oblique Caribbean-South America convergence, where a clear fault family can be identified in the margin (Escalona and Mann, 2006 and 2011).

5.3 Mechanisms for Paleozoic thrust and fold belt uplift and paleogeography

One of the main issues that represent the Upper Paleozoic unconformity time gap (~200 Ma) in the sedimentological record is define the quantity of erosion and its paleogeographic implications. The amount of erosion based on the seismic observations, was estimated from a detail of Transect A (Figure 4.2), where the uplift and the erosion rates where more significant. The transects towards the north have less amount of erosion due to the plunging out of the Paleozoic fold and thrust belt and is assume that the foreland basin area has insignificant or no erosion.

The Figure 5.4 shows a detail of the seismic flattening at the Upper Paleozoic unconformity horizon. The erosion modelling is based on the Paleozoic well-top reached in the well-11 at 847m that correspond to 823 ms in the Transect A (Figure 4.2). The Paleozoic shows at least 650 ms of eroded sediments at top of the thrust, which means at least 1600 m of sediments eroded during this period from the analyzed piggy back basin . The difference between the calculate erosion and the total thickness in the foreland basin area could be explained by the accommodation space available. The accommodation space in the piggy back basin was less than the one available in the foreland basin. This implies that originally the thickness for both areas differ and has to be analyzed independently.

The mechanism of erosion are the reactivation of the fault family 2 during the Upper Palaeozoic and the shoulder uplift role of the area in the continental rifting during the Jura- Triassic (figure 5.2). Based on the seismic observation in the study area, there is no evidence of the direction of the reworked sediments or which are the main depocenters. Previous works assume that the main depocenter for the Jura- Triassic is the Eastern Cordillera (Cediel, 1968), however maybe the reworked sediments are also filling the foreland basin to the east.

The positive relieve character of the Paleozoic fold and thrust belt was maintained until the Late Cenozoic. This paleogeographic implication can be seen in the Figure 5.3 where the Cenozoic reflectors are onlapping the Upper Paleozoic unconformity until the Pliocene sequence. The well correlation also support this observation (Figure 4.9). FS3 (which corresponds with Carbonera C4) is the first para- sequence to occur along the structural high.

5.4 Petroleum significance

The Llanos Basin possesses an active petroleum system as demonstrated by the amount of oil discovered to date, particularly in its western region. Discoveries are related to Upper Cretaceous and Lower Cenozoic sandstones reservoir and main oil families are restricted to Cretaceous hydrocarbon generation facies: marine carbonatic for Aptian (Fomeque formation), marine siliciclastic for Cenomanian (Chipaque formation), and marine deltaic for Conician- Turonian (Gacheta formation) (Moretti and Mora, 2009)

However, the oil exploration in the southern area has been unsuccessful, probably because of the vague idea on the role of Pre-Foreland structures. Most of the dry wells in the southern Llanos, are drilled in the NS trend. The reactivation of Fault family 2 during the Lower Paleozoic, Cretaceous, Miocene and Pliocene-Pleistocene has an implication in terms of preservation of traps and biodegradation of oil (Figure 5.5).

Furthermore, the positive relief of the Paleozoic fold and thrust belt until Late Oligocene generates a paleogeographic barrier for hydrocarbon migration before this period, which limited the amount of oil that can migrate from the Eastern Cordillera to the southern part (Figure 5.4). To increase the prospectivity of the area the thick Paleozoic sequence has to be taken into account.

5.4.1   Source rocks

The main source rocks are Cretaceous and Cenozoic. Cretaceous source rocks (Fomeque, Gacheta and Chipaque formations) are the most important and detail studied in the Eastern Cordillera (Moretti and Mora, 2009). They are related with intervals at Lower Aptian- Albian, Turonian and Cenomanian. However there is no evidence of occurrence of these rocks in the study area. On the other hand, Cenozoic source rocks related with Lower Paleogene interval (Cuervos formation) are considerate inmature.

The conventional petroleum system model is that the hydrocarborns found in the Llanos basin are migrated from the Eastern Cordillera to the foreland basin. Rodriguez (2006). The main issue for the southern Llanos basin is that the Paleozoic thrust and fold belt was uplift until Late Miocene (Figure 5.4). This limited the quantity of migrated oil and is a risk for oil exploration.

An alternative source rock can be proposed for Paleozoic interval. It is represented by Guejar formation at the Macarena range (Trumpy,1943) or Negritos formation (Ulloa and Perez,1982). However, there is not any geochemical analysis available to confirm the Paleozoic as a source rock.

5.4.1 Reservoir

The most important reservoir in the area is the Oligocene (Sequence 4A). However, thickness and lateral continuity of the reservoir is regular (Figure 4.10) and can be significant to increase the risk. Other reservoir intervals are restricted to the western part of the area as the Upper Cretaceous-Lower Oligocene sequence, which is picnching out towards the Paleozoic fold and thrust belt.

5.4.2 Traps

Based on the present interpretation, there are 4 main zones with different structural styles and trapping mechanisms. Location and Boundaries of these areas could help to better refine future exploration activity in the area (Figure 5.5)

Area I: Paleozoic Piggy-Back basins

The Paleozoic has a significant potential due to the relative thick sedimentary column. It has potential as a source rock, due to some marine shales observable in the seismic and in some well description (Duenas, 2006). Also lower intervals have potential such as reservoir rocks (Castro, 2004). Risk is always present due to the enormous uncertainty and lack of well information. The principal risk is due to preservation of structures and high grade of diagenesis as result of tectonic reactivation.

Area II: Cretaceous Pinching out

This central area consists of a thin zone of Cretaceous sedimentary onlap into the Paleozoic fold and thrust belt. This change in lateral facies between the sedimentary rocks and the impermeable Neoproterozoic rocks can create stratigraphic traps.Quality of the reservoirs may improve towards the east. Cretaceous units have more percentage of sand because is closer to the sediment source area of the area, the Guyana shield.

Area III: Normal Cenozoic faults

This area encloses Fault family 5. They are normal faults related to the second stage of foreland basin. They are the result of lithosphere bending due to tectonic loading. Most of the oil wells in the foreland area are related with this trap (example, Valdivia field figure 1.2). The main reservoir are continental sands from Oligocene sequence (Carbonera formation). Previous reports show that the source rock is buried beneath the Eastern Cordillera or in the foredeep of Llanos basin. Most representative example is the transect D (Figure 4.9)

<u>Area IV: Reverse faults of the uplift of the Cordillera</u>

As a result of the uplift of the Eastern Cordillera, the area adjacent to the foothill contains buried folds and thrusts (Fault family 4). This area is the most successful for hydrocarbon exploration until now and it contains oil fields with significant reserves as Castilla and Apiay fields (Figure1.2).

6. Conclusions

Seismic interpretation of southern Llanos basin reveals that the present-day foreland configuration is the result of different deformation stages. The proposed evolution exposed four main phases: Lower Paleozoic fold and thrust belt, Upper Paleozoic transgression, Upper Cretaceous-Oligocene foreland basin and Upper Oligocene- Present day foreland basin. It also compromises two different Precambric basements: Paleo- proterozoic rocks related with Guyana shield and Neo-proterozoic igneous and metamorphic orogenic belt.

The Neo- proterozoic fold and thrust belt detachment is at top of the Paleo- proterozoic with a NS orientation (Fault family 2). This correlates with the positive anomalies in the bouguer anomaly map and the present-day Macarena range arrangement. Fault reactivation of this structure has identified in three stages: Lower Paleozoic, Upper Cretaceous and Miocene and is considered as a risk for preservation of potential traps.

The Neo- proterozoic thrust is controlled by an EW –striking right lateral ramp which is a transition area between two thrust segments. It also explains the change in the drainage pattern and an abrupt geographic termination in the Eastern Cordillera.

The Lower Paleozoic rocks occur in small and elongated Piggy back basins ahead the reactivated Neo- proterozoic fold and thrust belt. Within these basins structures as triangular zones are prospective areas for hydrocarbon exploration. Low grade metamorphism towards the west can be a risk for reservoir potential.

The Upper Paleozoic is considerate a calm period where a main transgression from the north occur. This event explains the plunging-out of the fold and thrust belt. Upper Paleozoic rocks are considered as a potential source rock due to the occurrence of black shales, however this petroleum system has not been proved.

The Cretaceous forebuldge is the eastern limit of a large foreland basin, located towards the west of the southern Llanos basin. This feature shows that the Neoproterozoic fold and fault belt was a positive relief during the Cretaceous and only until Miocene the structure was buried beneath a continental unit. This limit the hydrocarbon migration because the fold and thrust belt behaves as a paleogeographic barrier.

7. Recommendations

– Check the structural model and the proposed evolution a balanced cross section is recommended to be done. For this will be necessary: vitrinite information to identify the burial history and geochronological information to identify precise timing.

– Build a basin modeling in order to test the petroleum system under this structural model. For this geochemical data from well samples, outcrops and oilseeps are needed.

– Seismic and wells with deeper target are suggested to be done in order to decrease the uncertainty in the older sequences.

8. References

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