NON-MARINE, LATE EOCENE-OLIGOCENE SEQUENCE STRATIGRAPHY AND CHANGING FLUVIAL STYLE IN THE NORTHERN LLANOS FORELAND BASIN OF COLOMBIA

A Thesis

Presented to

the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Lucia Torrado

December 2012

NON MARINE, LATE EOCENE-OLIGOCENE SEQUENCE STRATIGRAPHY AND CHANGING FLUVIAL STYLE IN THE NORTHERN LLANOS FORELAND BASIN OF COLOMBIA

Lucia Torrado

APPROVED:

Dr. Janok P. Bhattacharya, Chairman

Dr. Paul Mann

Dr. John Londono

Dr. Mark A. Smith, Dean
College of Natural Science and Mathematics

Dedication

To my parents and my dear grandfather, Eduardo.

ACKNOWLEDGEMENTS

I gratefully thank my supervisors, Dr. Janok Bhattacharya and Dr. Paul Mann from the University of Houston for their guidance, knowledge, and feedback throughout this project. Special thanks to the Caribbean Basins, Hydrocarbon, and Tectonic consortium (CBTH) for providing me a work space and allowing me to be part of such a dynamic group. I would also like to thank my committee member, Dr. John Londono for his constructive ideas.

I would like to express my gratitude to Mr. Jesus Aboud and Petromagdalena for providing me the data for this project. I would also like to thank deeply my dear friend and colleague, Mr. David Izquierdo for his guidance with the Kingdom software, patience, and keen interest in my project.

Special thanks to my supervisors at Shell, Mr. Pablo Buenafama, Mr. Bench Esquito, Dr. Ramon Loosveld, and Mr. Jaap Veldkamp for providing me the opportunity of experiencing a targeted internship and allowing me to show the results of my work. A special acknowledgement goes to Mr. Luis Carlos Carvajal Sr. for his feedback and encouragement during the development of this thesis.

Finally, I would like to thank my parents, Ramon and Lily for all their love and support through my studies; thanks to my little Garu, my new friends from Texas and Colombia for all the good times, and to Luis Carlos, for his unconditional love.

NON MARINE, LATE EOCENE-OLIGOCENE SEQUENCE STRATIGRAPHY AND CHANGING FLUVIAL STYLE IN THE NORTHERN LLANOS FORELAND BASIN OF COLOMBIA

An Abstract of a Thesis

Presented to

the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Lucia Torrado

December 2012

ABSTRACT

The Llanos foreland basin (LFB) of Colombia is the country's most prolific oil producer, with most known oil fields found in anticlines bounded by normal faults. The objective of the study is to assess the reservoir potential of the Late Eocene-Oligocene Carbonera Formation, a 400-1800m-thick reservoir unit of fluvial deposits with many areas of unexplored stratigraphic traps related to unfaulted, sand-filled fluvial channels. We integrated 700 km^2 of 3D seismic data volumes with 9 wells in the eastern Casanare province near the Jordan oil field, and additional 2D lines tied to 32 wells in a 17 168 km^2 area near the Rubiales field. Interpretation of reservoir distribution including a gamma-ray facies analysis of wells were combined with interpretation of multiple 3D attributes including coherence, curvature, and spectral decomposition. Well analysis shows that of the eight members of the Carbonera Formation, two members, C7 and C1, are clean, well-sorted fluvial sandstones with porosities up to 20%. Mineralogy, plant debris, and coals indicate floodplain aggradation in members C8, C6, and C4 with brackish water indicating fluvial connectivity to the Caribbean Sea to the northeast. Correlations between wells and attribute maps show that the Carbonera Formation represents tidally influenced fluvial deposits within straight to meandering channel belts seen as strong, high-amplitude, concave reflections on seismic data. Well logs record two regressive- transgressive cycles with higher preservation of lowstand deposits. On seismic time slices, channel belts exhibit: 1) moderate width to depth (W/D) ratio and high sinuosity for the main drainage; 2) low to moderate width to depth (W/D) ratio and low sinuosity for the tributary channels; 3) a decrease of sand content in the middle

members of the formation; and 4) wider channels with thicker floodplain deposits and localized sandstone bodies in members C5 and C3. Well subsidence curves from this area of the LFB show an increase of total subsidence due to the rapid uplift of the Eastern Cordillera in Oligocene time and eastward widening of the LFB. The clastic source area for the LFB shifted from the Guyana Shield to the east (represented by the members C7 and C5) to a source area produced by the uplift and erosion of the Eastern Cordillera to the west (represented by the members C3 and C1). Flattened time slices show changes in paleoflow directions of rivers from southwest to northeast, controlled by the eastward migration of the flexural high of the LFB in the Late Eocene–Early Oligocene, to a NW to SE direction of flow in the Middle Oligocene that likely corresponds to the development of tributaries feeding a larger axial fluvial system. Increases in short-lived accommodation of the LFB led to large embayments produced by the ingress of brackish waters up the main fluvial system from the Caribbean Sea.

Table of Contents

Figure captions

1. History of this master's project

Following my graduation in 2008 with a B.S. degree in geology from the Universidad Nacional de Colombia in Bogota, I worked for AIP Ltda. and Hocol S.A. for several different exploration projects including offshore areas of Los Cayos basin, and the Pacific forearc basin, along with projects on the Upper Magdalena, and Llanos basins. From this previous work experience, I learned that even in such a prolific hydrocarbon basin like the Llanos basin, there is still much work to be done in the area of finding new stratigraphic traps. After my acceptance on the master's program in geology at the Department of Earth and Atmospheric Sciences at the University of Houston in fall 2011, I arrived with the goal of working on the topic of improving methods for finding stratigraphic traps in Colombian basins.

In the spring of 2011, Dr. Janok Bhattacharya, whose main interests include sequence stratigraphy, fluvial and deltaic systems, agreed to supervise my MS study on this topic provided I could obtain subsurface data.

During the summer of 2011, I went back to Colombia to acquire a 3D seismic and well subsurface data set in the Casanare area of the northeastern Llanos basin. I approached Mr. Jesus Aboud, Mr. David Izquierdo, and Mr. Rafael Lopez from the oil company Petromagdalena whom kindly provided the data I needed, and were very helpful in getting me started on the project.

By the summer of 2011, Dr. Paul Mann and his Caribbean Basins, Tectonics and Hydrocarbons (CBTH) consortium arrived to the University of Houston from the University of Texas at Austin. His interest in Latin-America, specifically Colombia, and his knowledge about regional tectonics and petroleum systems encouraged me to become part of his group, although I was not financially supported as a research assistant of the CBTH project. I was allowed to have access to the CBTH database including papers, reports, thesis, presentations, geologic and paleogeographic maps, as well as being provided with a work space for developing my thesis for the remainder of fall of 2011 to the present time, and the opportunity to travel to the AAPG Convention at Long Beach, California in May of 2012 to present my results at the AAPG student poster session.

In the summer of 2012, I had a 3-month student internship with Shell at the Wood Creek office in west Houston where I worked with their Latin-American onshore group. My main objective was to integrate 2D seismic data, well logs, image logs, and side wall cores to describe the depositional model for each unit of the Carbonera section in the heavy oil area of blocks CPE2, and CPE4 blocks. I worked closely with my supervisor Mr. Pablo Buenafama, my mentor Mr. Jaap Veldkamp, along with Mr. Bench Esquito and Dr. Ramon Loosveld, and geology disciplinary advisors Dr. Brad Prather and Mr. Chris Gonzalves. By the end of the summer, I was allowed by Shell to include the results of my internship in this thesis which helped developing the final results of the thesis. In the thesis, the area Casanare area is called the “western study area” and the Shell heavy oil area is called the “eastern study area”.

2. Introduction

In recent years, a wide variety of geophysical techniques have been developed to image plan views of depositional environment and other geological features extracted from 3D seismic volumes. These methods have developed into a rapidly evolving discipline known as seismic geomorphology that has also become an important oil and gas exploration method (Davies et al., 2007). The generation of time slices and horizon slices from 3D volumes can be studied using different seismic attributes, such as coherence, opacity, curvature, and roughness. These attributes enhance discontinuities within the 3D seismic cube that may then be interpreted as subsurface depositional systems, geomorphologic features, faults and fracture patterns, and ultimately be used to estimate lithologies (Davies et al., 2007). Thus, seismic geomorphology provides interpreters with a tool that allows them to visualize preserved subsurface landscapes and their evolution through time and space.

The use of seismic geomorphology, combined with the development of a depositional model aids the explorationist in the process of reservoir characterization. Part of the success of the oil companies in the study area of the northern Llanos foreland basin (LFB) (Fig. 1) is based on many years of acquired knowledge of the geologic clastic depositional system, and the most common trap type, typically a four-way closure structure associated with a normal fault (Ecopetrol, 1995). Stratigraphic traps are not common in the LFB because few previous 3D seismic stratigraphic studies have been carried out in order to identify paleochannels in the subsurface. The electric and seismic response of these stratigraphic features provides other tools to potentially discriminate between favorable and nonfavorable lithologies for hydrocarbon accumulation as whether fluids are present in the rocks, in order to reduce the drilling risk in less explored areas or in the absence of a sealing fault. Several other reasons that account for well failure may include the absence of structural traps, common pullup structures due to velocity anomalies associated with a “fault’s shadow”, low velocities in certain formations, and long distance migration and biodegradation.

The study area is located at the northern and eastern portion of the foreland Llanos basin, Colombia as shown in Figure 1.

The 1.1-km-thick section in the study area is composed of a succession of siliciclastic sediments deposited throughout the Cenozoic era. During the Campanian, the accretion of the Western Cordillera to northwestern South America resulted in a change of the depositional environment from shallow marine to transitional-fluvial conditions (Cooper et at., 1995) (Fig. 2). These non-marine conditions prevailed until the Oligocene, represented by the Carbonera Formation which is the main reservoir in this area of the basin (Fig. 3).

The subsurface rocks in the study area of the Llanos foreland basin (LFB) were analyzed using 3D seismic data, and closely spaced well data in order to interpret their stratigraphic evolution in time and space based on identification of features such as channel belts, floodplains, interfluves, incised valley fills, as well as their migration patterns, and the tectonic effects on reservoir distribution (Fig. 2). Moreover, the 3D data were used in combination with well data in order to establish criteria for recognizing and predicting sand versus mud-filled channel belts in potentially hydrocarbon-rich fluvial deposits from the Oligocene and ultimately predict reservoir properties in unexplored interwell areas (Escalona and Mann, 2006). By joining these tools with previous geologic models and their correlation to well data, the results will help make drilling paleochannel stratigraphic traps more successful in the northern LFB

3. Regional setting of the Llanos foreland basin

The LFB, covering approximately 194,000 km^2 of northeastern Colombia, is a sub-Andean basin formed during series of Late Cretaceous to recent tectonic events (Moreno et al., 2011; Nie and Horton, 2012; Fig. 2). The LFB is considered one of the most prolific hydrocarbon basins along the eastern flank of the Andes in South America (Barrero et al., 2007). Exploration in the LFB has been mainly focused on structural-type traps consisting of gentle dipping monoclines associated with antithetic faults. There is little published work on stratigraphic traps (Osorio et al., 2008).

The LFB exhibits a typical configuration of foreland basins: an asymmetric sedimentary wedge deposited on top of the gently westward dipping surface of the Guayana shield; clastic sedimentary rocks onlap and eventually pinch-out against the eastern boundary of the LFB (Fig 4). The LFB is deeper along its western, fault-bounded side adjacent to the fold-thrustbelt of the Eastern Cordillera. Towards the south, the LFB

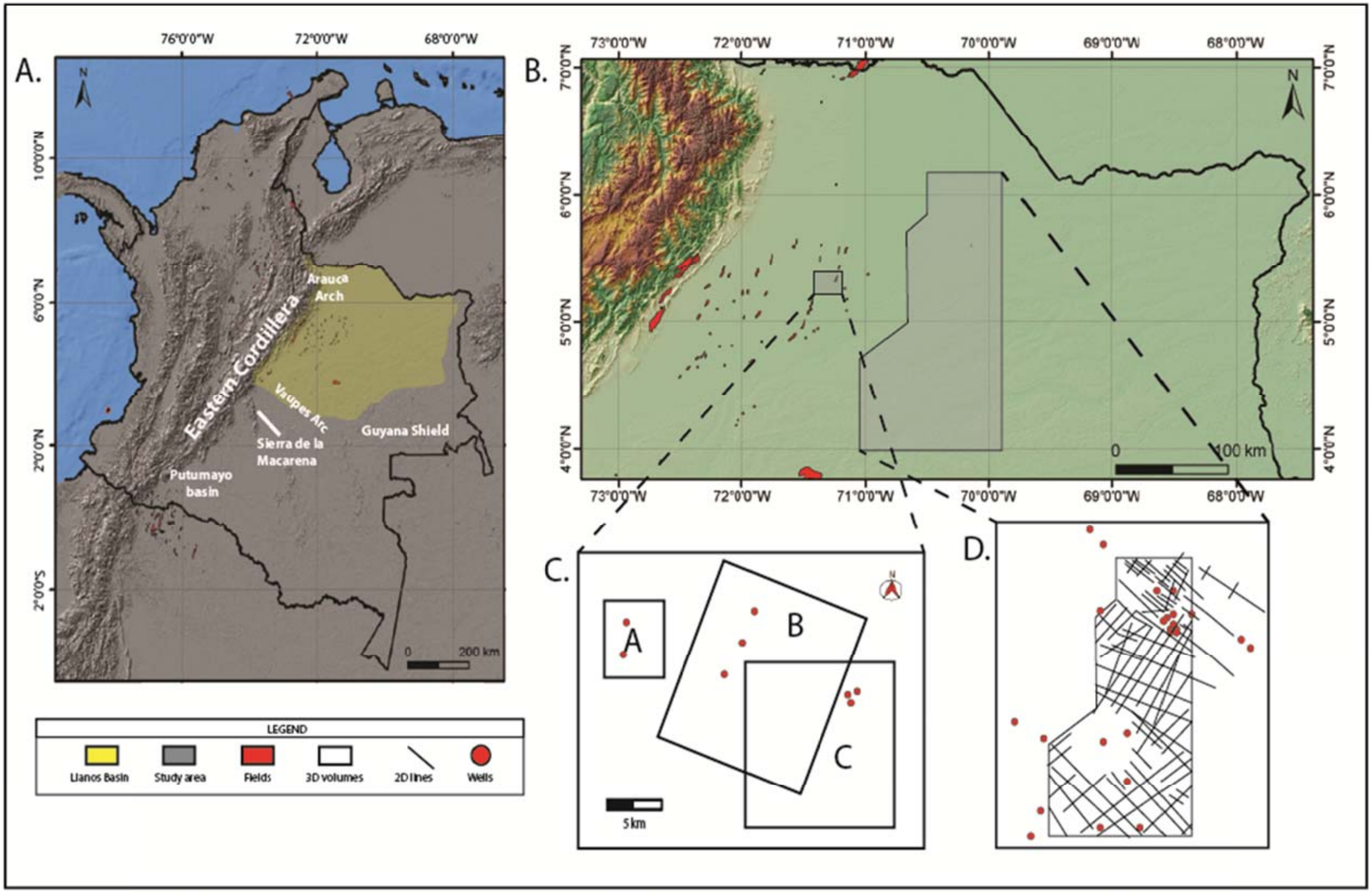


Figure 1. A. Location of northern Llanos foreland basin (LFB, yellow area) in Colombia, northwestern South America. B. Zoom of northern Llanos basin in Casanare province of Colombia and Eastern Llanos. C. Location of 3D seismic volumes A, B, and C of Casanare Province database. D. Location of 2D lines and wells of Eastern Llanos database.

is bounded by two ranges of exposed Precambrian and Cretaceous rocks, the Serrania de la Macarena and the Vaupes arch respectively (Restrepo-Pace and Cediel, 2010). These highs separate the LFB from the Putumayo foreland basin of southern Colombia (Barrero et al., 2007) (Fig. 1A). The Arauca arch, a subtle structural boundary, constitutes the basin's boundary in the north (Fig. 1A).

During the Triassic–Early Cretaceous, rift basins developed as a result of the separation of North and South America as the Caribbean Sea opened (Cooper et. al., 1995). A back-arc megasequence of alluvial, deltaic, and basal transgressive strata with interbedded shales was deposited during Early Cretaceous time. This sequence is represented by three units: the central Gacheta Formation shale enclosed by the sandstones of the Une Formation, deposited during a marine transgression with continuous subsidence, and the shallow marine regressive sandstone of the Guadalupe Formation (Cooper et al., 1995, Figure 2).

By late Cretaceous and early Cenozoic, the basin evolved into a foreland basin adjacent to the topographic load added by the accretion of the Central Cordillera of western Colombia (Moreno et al., 2011; Nie and Horton, 2012; Gomez et al., 2005) (Fig. 2). Accretion of the Western Cordillera during Campanian and Maastrichtian time resulted in a change in the depositional environment of the LFB from shallow marine to transitional-non marine. The Barco Formation and Los Cuervos Formation, consisting of estuarine basal sandstone deposits, are overlain by a shaly sequence deposited during the Paleocene (Cooper et al., 1995).

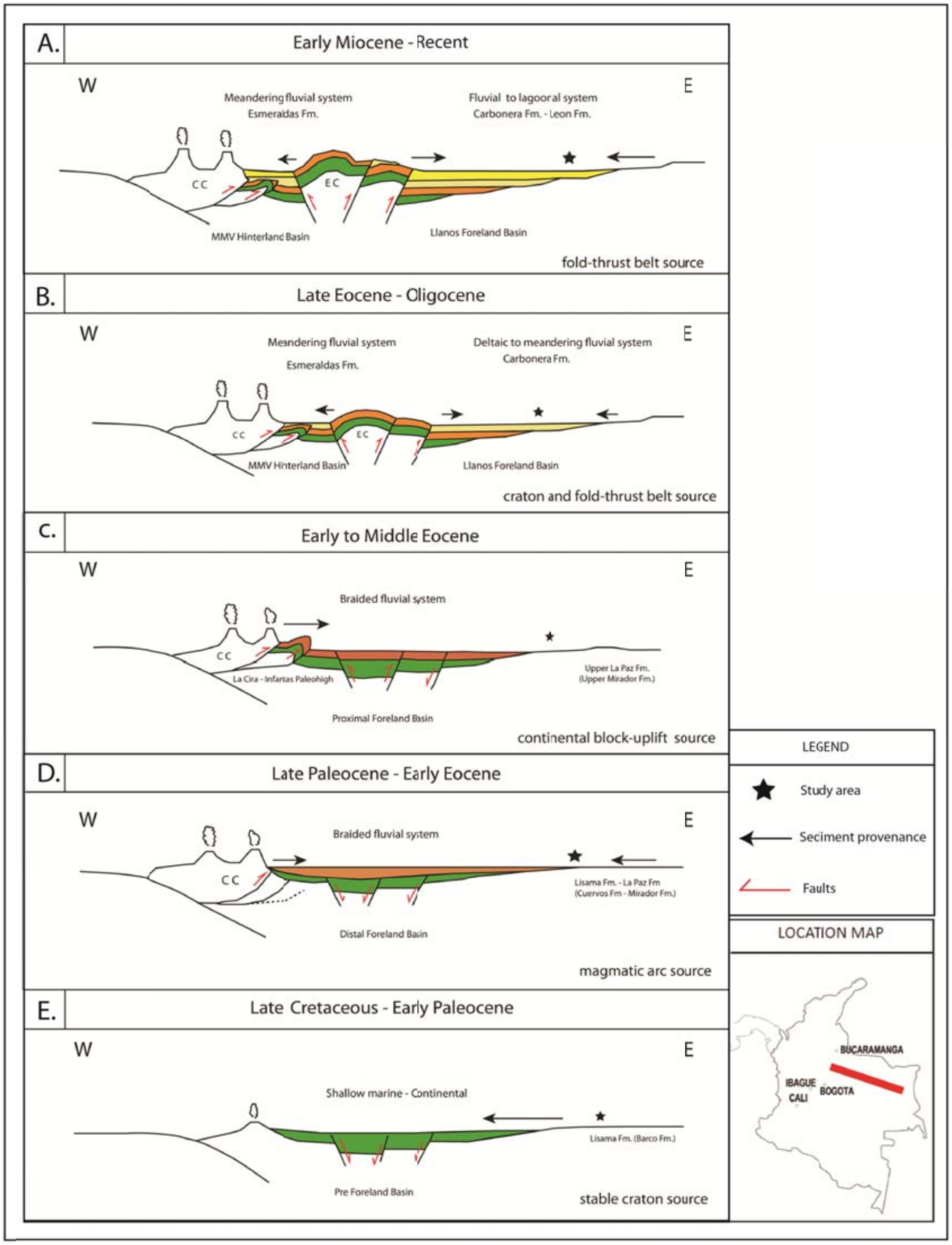


Figure 2. Late Cretaceous to Late Miocene tectono-sedimentary evolution of the Eastern Cordillera, Middle Magdalena basin, and adjacent LFB modified from Moreno et al (2011) and Nie et al (2012). A. Early Miocene-recent: continued uplift of the Eastern Cordillera and subsidence of the adjacent LFB with most clastic source areas located in the fold-thrust belt; B. Late Eocene-Oligocene: initial uplift of the Eastern Cordillera with sources located in both the fold-thrust belt and craton; C. Early-Middle Eocene formation of the LFB prior to the uplift of the Eastern Cordillera; most source areas located within continental rocks to the west; D. Late Paleocene-Early Eocene; most source areas are located in a magmatic arc to the west; E. Late Cretaceous-Early Paleocene; rift basin predating the foreland basin; source areas are mainly from the craton.

The Mirador Formation has been defined as a massive coarse- to medium-grained sandstone, resting unconformably on top of the Paleocene sediments over a wide area of the basin constituting the main reservoir rocks of the Llanos basin (Villegas et al., 1994). Well data indicate that the Barco Formation, Cuervos Formation and the Mirador Formation are missing in the study area as the units eventually pinch-out against the eastern flank of the basin. By middle-late Eocene, braided fluvial systems prevailed in the Llanos basin represented by the Mirador Formation and the La Paz formation in the Middle Magdalena valley (Moreno et al., 2011, Figure 2).

The Oligocene epoch marks a time of major changes in the paleogeography of Colombia (Fig. 3). A large section of the Central Cordillera subsided, especially in the Magdalena Valley, Lower Magdalena Valley, Llanos basin, and Llanos foothills (Villamil, 1999) combined with sedimentary loading of the Eastern Cordillera (Gomez et al., 2005) allowing an increase in accommodation space. This rapid subsidence pulse has been described by Campos (2011) as the “maximum tectonic flexure area” that affected the study area in the Casanare Province of the northern LFB (Fig. 4). Large river systems flowing parallel to the eastern flank of the Eastern Cordillera were developed with an Oligocene paleoflow direction to the northeast (Fig. 3). The clastic sediment supply was mainly from the eastern Guayana Shield with lesser sources from the Eastern Cordillera to the west (Fig. 3). This fluvial system has also been defined as the “Proto-Orinoco

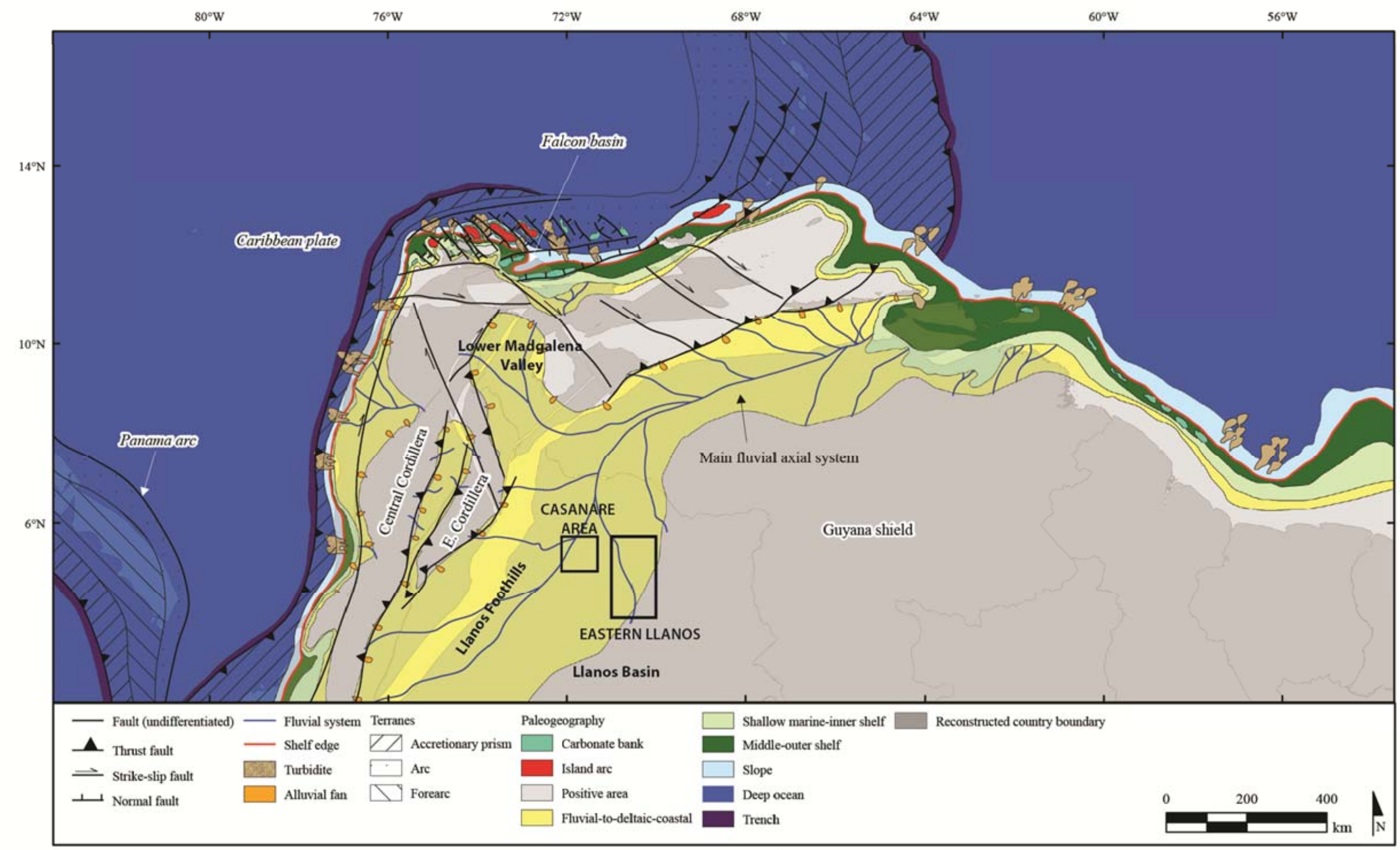


Figure 3. Middle Oligocene (30 Ma) paleogeographic map of northern South America from *CBTH* Atlas (2012) showing location of the study area. During this period the study area and fluvial Carbonera Formation was located in the upper reaches of the proto-Orinoco River which flowed to the northeast and east and emptied into the central Atlantic Ocean.

river system” (Villamil, 1999) even though the modern Orinoco River did not acquire its present course until the Miocene (Pestman et al., 1994). For the purpose of this study, this fluvial system will be referred as the “Main axial fluvial system”.

The Late-Eocene Oligocene Carbonera Formation (Palinologic zones 22 – 25, Muller et al., 1987) is a thick succession of interbedded regressive sandstone members (C1, C3, C5, and C7 members) and transgressive mud members (C2, C4, C6, and C8 members) of coastal plains with clastic sediment coming from the Guyana Shield (Cooper et al., 1995) (Fig. 4B). The Carbonera Formation records an eastward migration of foreland-basin-related subsidence with a thickening, and a gradual increase in sand percentage and amount of continental clastic rocks from east to west (Fig. 4A). Due to its relatively broad distribution across the basin, the Carbonera Member 2 is considered an intraformational regional seal (Ecopetrol, 1995; Cooper et al., 1995). The sandier units, particularly the Carbonera 1 and Carbonera 7 members, are considered the main reservoir in this part of the LFB, whereas the Mirador Formation is considered the main reservoir in parts of the LFB to the southwest (Fig. 4B).

Conformably overlying the Carbonera Formation, the shaly Leon Formation was deposited during the Middle Miocene over a wide area of the Llanos basin under enclosed, quiescent, lagoonal conditions (Bayona et al., 2008) (Fig. 4B). Provenance and drainage areas of the fluvial deposits in the Middle Magdalena basin and Llanos basin became separated during during the Oligocene as a result of the uplift of the Eastern

Cordillera (Fig. 2). After the uplift of the Eastern Cordillera, the Llanos basin became separated completely from the Middle Magdalena Basin, and both basins acquired their present shape and extent (Nie and Horton, 2012, Figure 2). Deposition of a thick fluvial sequence, referred to as the Guayabo Formation took place from the upper Miocene until the Pleistocene (Fig. 4B). These rocks are discordantly overlain by Quaternary alluvial sediments composed of unconsolidated gravels of variable thickness (Cooper et al., 1995).

4. Seismic and well data used in this study

The subsurface data used for this study comprises a total of three, post-stacked migrated 3D seismic surveys and nine wells covering an area of approximately 580 km^2 of the Cubiro block located in the Casanare Province, referred as “Eastern study area” in this thesis (Fig. 1). The three seismic surveys are referred to as “Survey A”, “Survey B”, and “Survey C’ (Fig. 1C). This data was acquired for exploration purposes by company Petromagdalena and provided by fall of 2011.

The average vertical resolution for “Survey A” and “Survey B” is 20 meters; horizontal resolution is 25 meters. The dominant frequency is 35 Hz. In the case of “Survey C” the dominant frequency is 45 Hz with a vertical resolution of 15 meters and a horizontal resolution of 20 meters. The Carbonera Formation ranges between 1.2 s and 1.8 s in the eastern study area with an average seismic velocity of 1,750 m/s calculated from well data.

Additionally, around seventy 2D lines and well data from 32 wells from a 17 168 km^2 area of the eastern blocks CPE (heavy oil exploration blocks) were provided by Shell during a summer internship in 2012, along with some legacy data from ANH. The two study areas are separated by 57 km. Well data included well logs, drilling reports, side wall core descriptions, biostratigraphy and palynology studies, and boreholes images. The data provided by Shell was used with permission in this thesis. The results from the targeted internship in the LFB are shown in this project.

Lastly, access to complimentary data including reports, thesis, presentations, paleogeographic and geologic maps, was obtained through the database of the Caribbean Basins, Tectonics and Hydrocarbons Consortium (CBTH).

5. Methodology

A major advantage of 3D seismic technology is that it allows seismic data to be displayed in horizontal or "map" form. For this study, a series of attributes (coherence, curvature and spectral decomposition) at a sampling interval of 2 milliseconds (ms) were calculated in order to estimate seismic character variations that produce sharp discontinuities, such as faults and/or stratigraphic boundaries like fluvial channel belts (Davies et al., 2007). Moreover, flattened time slices for the three (3) seismic cubes were extracted from the attributes cubes in order to map and observe the seismic geomorphology of these deposits, along with the effects of faults and folds. The horizon interpolation was done at the top of four sandy and potential reservoir members of the Carbonera Formation: Carbonera Member 1, Carbonera Member 3, Carbonera Member 5 and Carbonera Member 7 (Fig. 4B).

Along with the attribute interpretations, seismic and gamma ray facies analysis were conducted to improve the interpretation of depositional facies. The seismic and gamma ray facies analysis is based on recognizing seismic lapout terminations that are confined to a unit with a seismic character different from the adjacent units at a determined seismic sampling rate (Zeng, 2004). The identification of possible major flooding surfaces, sequence boundarie(s), and the extent of marine influence was carried out using seismic geomorphology, well data and previous paleogeographic reconstructions. Slope, channel sinuosity, and width/depth calculations were also done to determine the architecture of fluvial channels.

Finally, in order to understand the effects of tectonics in fluvial migration patterns, subsidence curves were calculated from well data and compared to previously proposed basement flexural models (Gomez et al., 2005; Bayona et al., 2008; Campos, 2011).

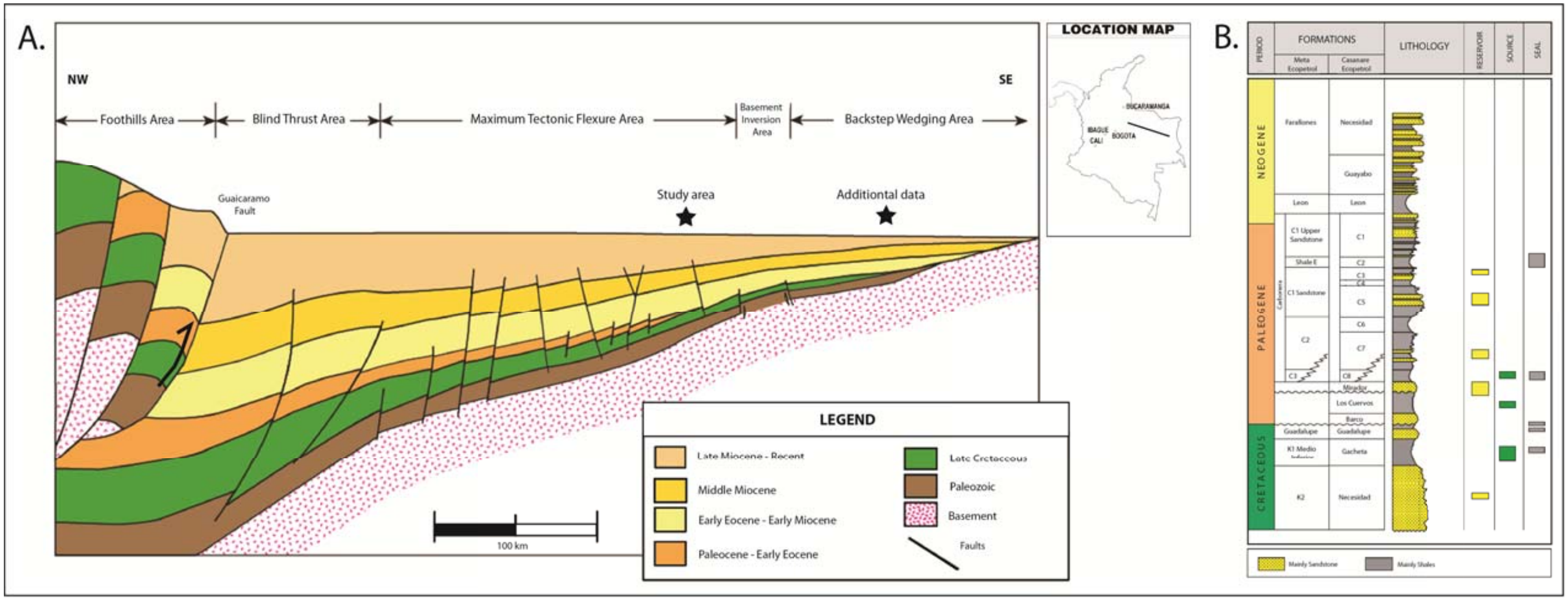


Figure 4. A. Schematic cross section of the LFB modified from Campos (2011) showing tectonic provinces and relative location of 3D seismic study areas (black star to west) and Shell data (black star to east) used for this study and shown in Figure 1B; B. Generalized stratigraphic column of LFB and summary of main elements of its petroleum system (ANH, 2007).

6. Seismic interpretation of the study area

Seismic horizon interpretation was conducted for each of the 3D volumes in the study area based on seismic-to-well ties (Fig. 1B). The horizons interpreted correspond to the top of the four sandy members of the Carbonera Formation and are shown on Figure 5. All of the inlines and crosslines of the volumes were interpreted in order to extract horizon-flattened time slices for further geomorphological interpretation that is discussed in section 8 of this thesis. In the case of the eastern study area shown on Figure 1B, the seismic interpretation and well top picking were provided by Shell and used with permission in this thesis.

An interpreted seismic section crossing all three seismic cubes over a distance of 20 km in the western study area shows slight westward sediment thickening characteristic of a LFB (Fig. 5). High-angle, normal faults penetrate to basement, cut across the whole sedimentary succession, and form broad monoclinal and anticlinal structures that are potential structural traps in the area. On Figure 5B, fluvial channels were highlighted of the Carbonera Formation in yellow.

Paleozoic rocks, commonly referred in articles on the LFB as “economic basement”, is seen as a strong, irregular reflection at the base of the Tertiary - Cretaceous sedimentary sequence. Overlying Cretaceous sedimentary rocks are mostly seen as homogeneous reflections throughout the western study area.

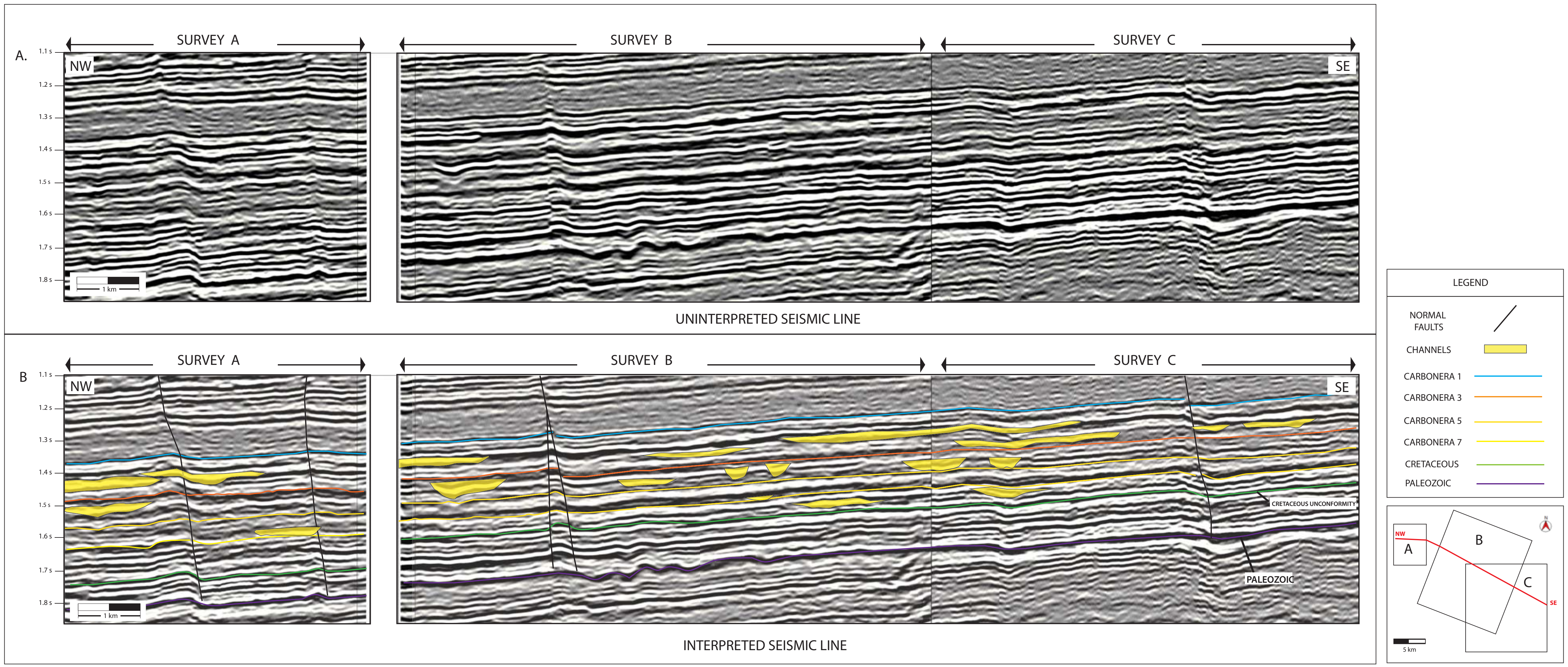


Figure 5. A. Uninterpreted seismic section through 3D seismic survey boxes A, B and C in Casanare Province (location map given as insert map).
B. Interpreted seismic section with fluvial channels of Carbonera Formation highlighted in yellow.

A regional unconformity formed between Cretaceous and Late Eocene strata is seen as a strong reflection with top-lap terminations against the top of the Guadalupe Formation (green horizon shown on Figure 5B).

The seismic character within the Carbonera Formation includes reflection terminations, variations in continuity and shape, changes in seismic reflectivity, changes in amplitude anomalies, and low-dipping reflections with locally-onlapping truncations are related to intraformational and lithologic heterogeneity. Channel belts within this unit are easily seen in seismic section and are highlighted in yellow (Fig. 5B).

The overlying Leon Formation, a wide spread regional seal of Middle Miocene age, is characterized by continuous, wavy reflections with little thickness variations throughout the basin.

6.1 Seismic facies analysis

Seismic facies analysis is a useful tool used for interpretation of the distribution of depositional environments in space and time and overall basin evolution (Mitchum et al., 1977 *in* Yu, 2006). Based on the seismic wave character, amplitude, reflectivity and reflection terminations, nine different seismic facies association were identified within the study area: five characteristic of the Casanare Province and four for the Eastern Llanos area (Figure 6). The interpretation of each seismic facies was supported by well data.

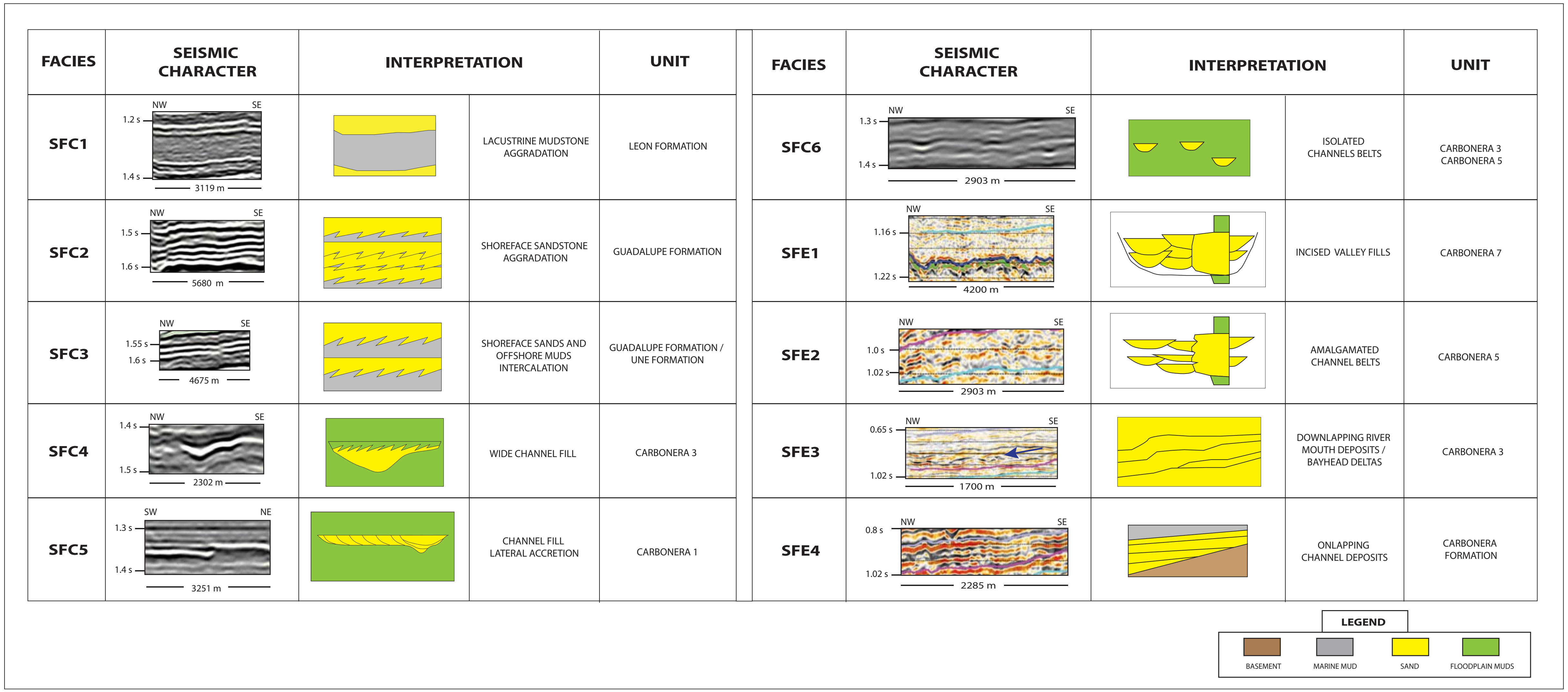


Figure 6. Illustrations of representative seismic facies of 3D and seismic facies abbreviations for data interpreted from seismic survey boxes A, B, and C at Casanare Province and Eastern Llanos database. See text for discussion.

Seismic Facies Casanare 1 (SFC1): Low-amplitude, laterally semi-continuous, low reflectivity, locally wavy; facies corresponds to lacustrine facies from the overlying Leon Formation of Middle Miocene age (Fig. 6).

Seismic Facies Casanare 2 (SFC2): High to moderate amplitude, moderate reflectivity, plane parallel, laterally continuous reflections; well data shows this unit is quartz-rich, fine - to medium-grained, subrounded sandstone with glauconite inclusions. This facies is interpreted as shoreface sandstone of the underlying Guadalupe Formation of Late Cretaceous age (Fig. 6).

Seismic Facies Casanare 3 (SFC3): High to low amplitude, high to moderate reflectivity, parallel to wavy, laterally discontinuous reflection: well data shows quartz-rich, very fine – to medium-grained sandstone, carbonaceous, with pyrite and glauconite inclusions. This facies is interpreted as mudstone-sandstone inter gcalations in a transitional-shoreface environment corresponding to the Late Cretaceous units (Une Formation, Gacheta Formation and Guadalupe Formation).

Seismic Facies Casanare 4 (SFC4): Concave, v-shaped, strong, high-amplitude and high reflectivity reflections with erosional truncation at the base; facies corresponds to incised fluvial channels. The depth of the channel fill varies from 35 to 40 m (Fig. 6).

Seismic Facies Casanare 5 (SFC5): Straight, high-amplitude, moderate-reflectivity, laterally-confined reflections; facies corresponds to isolated channel belts within Carbonera Member 3. Around the channels, moderate to low amplitude, wavy, low reflectivity is interpreted as floodplain muds within Carbonera Members 5 and 3 (Fig. 6).

Seismic Facies Eastern Llanos (SFE1): Low-amplitude, low-reflectivity, chaotic reflections; facies corresponds to sand-rich, incised valley deposits within Carbonera Member 7 (also referred as “Basal Sands” by Ecopetrol (1995) (Fig. 6). This seismic facies correlates to GRF1.

Seismic Facies Eastern Llanos (SFE2): Low-amplitude, moderate to low reflectivity, wavy to chaotic reflections; facies corresponds to sand-rich, amalgamated channel belts within Carbonera Member 5 and near the base of Carbonera Member 3 (Fig. 6).

Seismic Facies Eastern Llanos 3 (SFE3): Prograding, downlapping reflections and clinoforms; facies corresponds to bayhead deltas (river mouth deposits) within Carbonera Member 5 (Fig. 6).

Seismic Facies Eastern Llanos 4 (SFE4): Continuous to semi-continuous, onlapping reflections; facies corresponds to the unit’s pinchout against underlying Cretaceous deposits in the Casanare study area and Paleozoic rocks of the Eastern Llanos basin (Fig. 6).

6.2 Gamma-ray facies analysis of well logs

Based on gamma-ray log values, log shape tied to well cuttings, ten gamma-ray facies associations were identified for both study areas (Fig. 7) and the depositional environments associated with these facies.

Gamma-ray Facies 1 (GRF1): Blocky patterns with sharp base; facies corresponds to thick sand bodies interpreted as aggraded, amalgamated fluvial channels and incised valley fills. (Fig. 7).

Gamma-ray Facies 2 (GRF2): Finning-upwards trend with sharp bottom with an overall "bell shape"; facies corresponds to point bar deposits identified within Carbonera members 7 and 1 in the western study area and within Carbonera members 3 and 5 in the eastern study area (Fig. 7).

Gamma-ray Facies 3 (GRF3): Funnel-shape pattern with coarsening upwards at the bottom and high and sharp gamma ray peak at the top; facies corresponds to crevasse splay deposits (Fig. 7). Lack of foraminifera in well cuttings indicates continental provenance.

Gamma-ray Facies 4 (GRF4): Single gamma-ray peak; facies corresponds to poorly preserved floodplain deposits characteristic of Carbonera Member 7 in the western study area and Carbonera Members 7 and 5 in the eastern study area with both deposits interpreted as the result of lower accommodation (Fig. 7).

Gamma-ray Facies 5 (GRF5): Serrated/ sawtooth patterns with an irregular gamma-ray trend with a lack of character; facies corresponds to mudstone and very fine-grained sandstone interpreted as aggrading floodplain deposits within the Carbonera Member 6 up to the Carbonera Member 3 in the western area and Carbonera Member 3 in the eastern area (Fig. 7).

Gamma-ray Facies 6 (GRF6): Serrated regular patterns with higher gamma-ray values than GRF6; facies corresponds to prodelta mud aggradation due to marine transgressions during the deposition of Carbonera Members 8 and 2 in the western area. This facies is only present in Carbonera Member 2 in the eastern area (Fig. 7).

Gamma-ray Facies 7 (GRF7): Sharp, inverted bow trend pattern; facies corresponds to mud plugs within the Carbonera 3 in the eastern study area (Fig. 7).

Gamma-ray Facies 8 (GRF8): Succession of thickening, coarsening-upwards gamma-ray trends; facies corresponds to sand progradation on a delta plain (Fig. 7).

Gamma-ray Facies 9 (GRF9): Mixed blocky and coarsening-upwards successions in a sand-rich interval; facies corresponds to distributary channels and proximal channel-mouth bar facies, particularly in the eastern study area (Fig. 7).

Gamma-ray Facies 10 (GRF10): Multiple, thin, erratically coarsening-upwards sand units in a sand-rich interval; facies interpreted as channel mouth bars/ strand-plain facies within Carbonera Members 5 in the western study area and Carbonera Member 3 at both western and eastern study areas (Fig. 7).

Gamma-ray Facies 11 (GRF11): Thick, blocky, single sand unit with no floodplain preservation; facies corresponds to incised valley fills. Thickness of this facies is greater than GRF1 (Fig. 7).

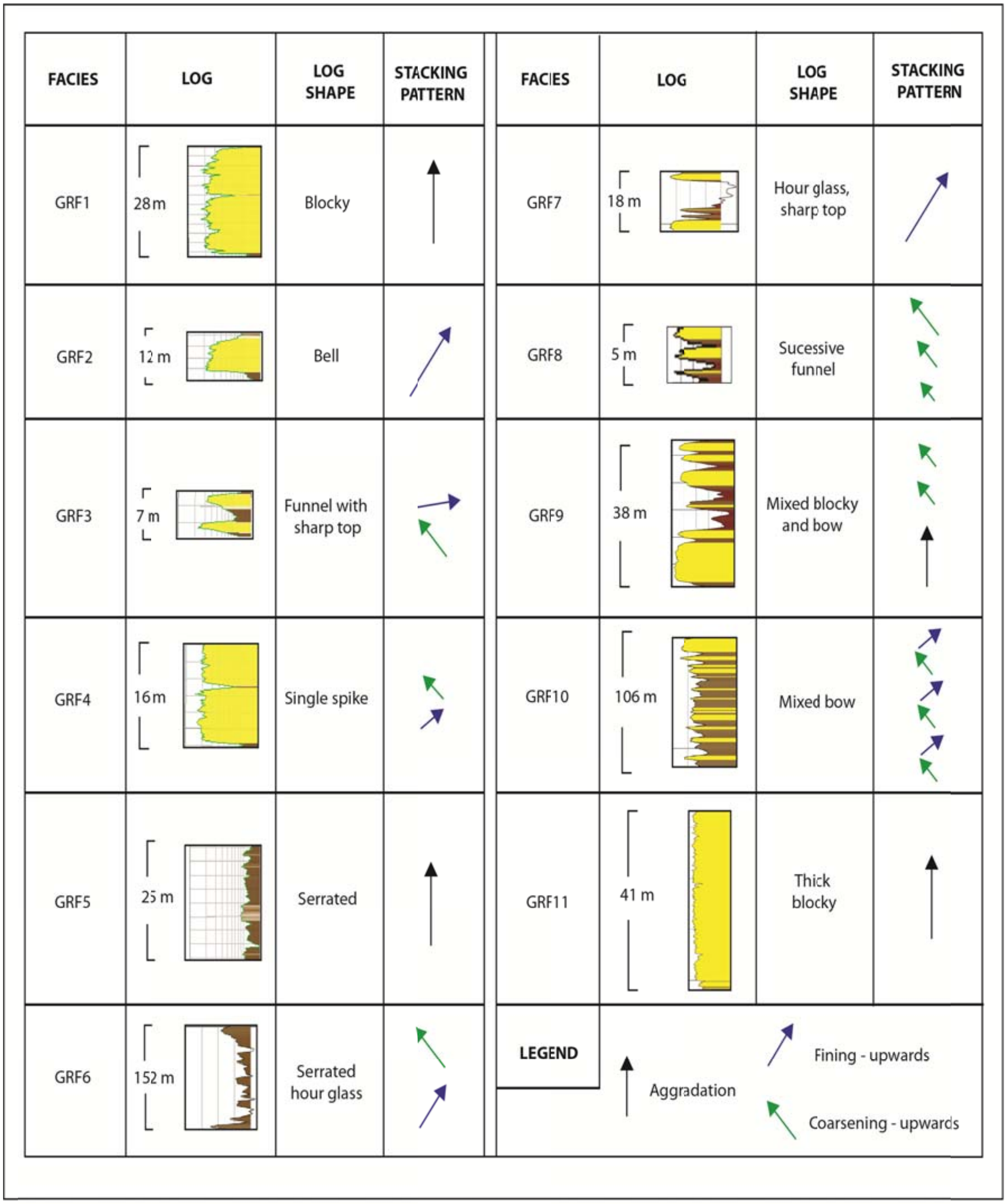


Figure 7. Gamma-ray facies analysis from logs from the study area with gamma ray facies abbreviations for data interpreted from seismic survey boxes A, B, and C. See text for discussion.

7. Sequence stratigraphy

Based on the interpretation of major flooding surfaces, sequence boundarie(s), and extent of marine influence on well logs (Figs. 8, 9) and seismic data (Fig. 10), combined with terminations in seismic sections, it was determined that the Carbonera Formation recorded two transgressive-regressive cycles. The conventional marine sequence stratigraphy model (Posamentier and Vail, 1998) was applied to this largely enclosed-sea, continental setting, where the sequences were influences by short-lived eustatic marine transgressions (Haq, 1987), tectonics and subsidence, as well as sediment discharge from source areas to the west and east of the basin (Blum and Tornqvist, 2000) (Fig. 3).

Four distinctive stratigraphic key surfaces were identified: the Sequence Boundary (SB), the Transgressive Surface (TS), and the Transgressive Surface of Erosion (TSE) locally in the eastern study area and the Maximum Flooding Surface (MFS) (Figs. 8, 9).

The definition of the datum based on the identification of a Maximum Flooding Surface (MFS) at base of the Leon Formation which can be seismically seen as a thin, strong, continuous reflection throughout the study area enclosed within low amplitude seismic characters, typical of this tabular, mud-rich regional sealing unit.

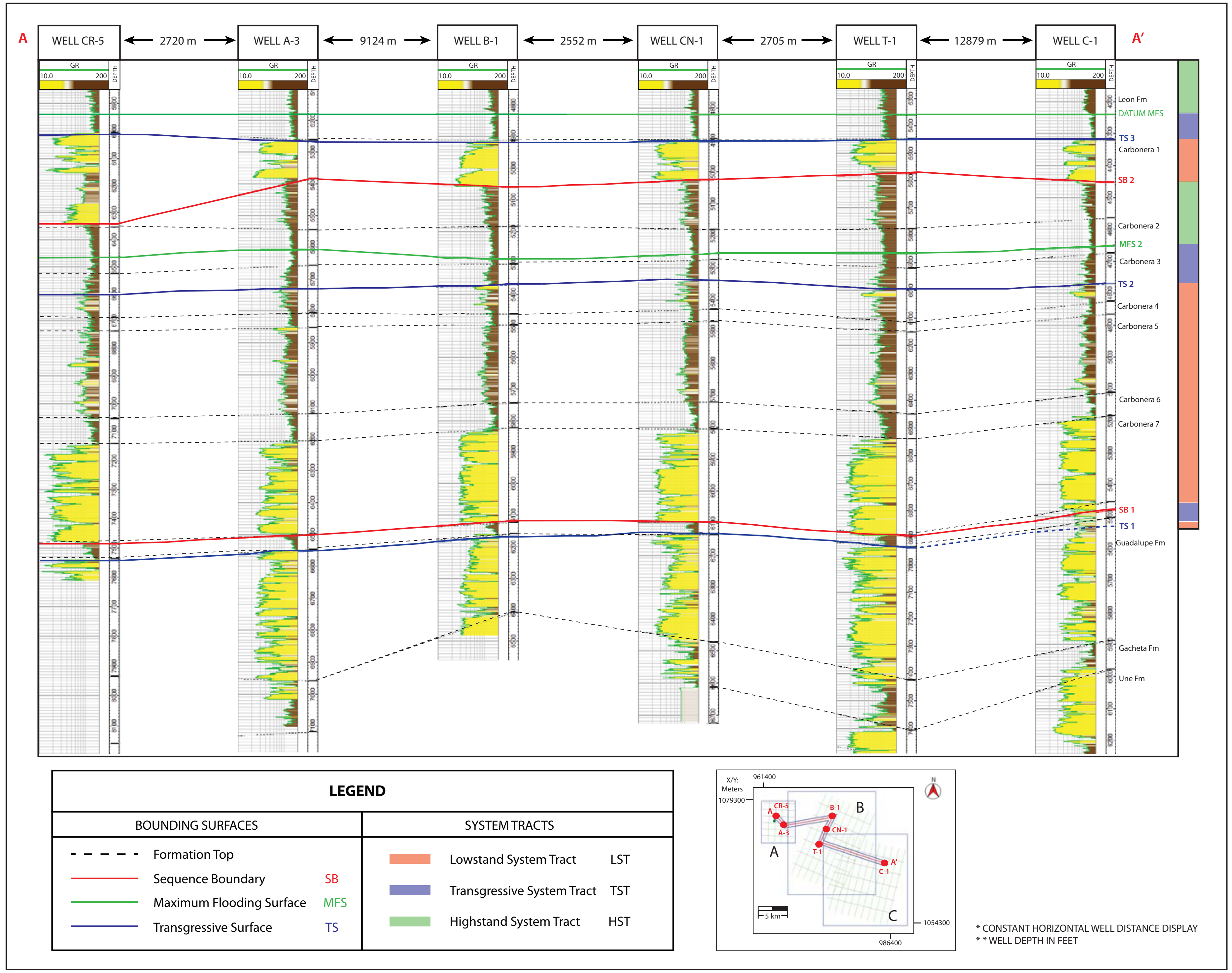


Figure 8. Well log correlation and sequence stratigraphy of the Carbonera Formation in the study area (location of wells shown on inset map). Formation tops and major bounding surfaces are shown as dotted lines; sequence boundaries are shown as red lines; transgressive surfaces are shown as blue lines; maximum flooding surfaces are shown as green lines. Lowstand system tract is in red, transgressive system tract is in blue, and highstand system tract is in green.

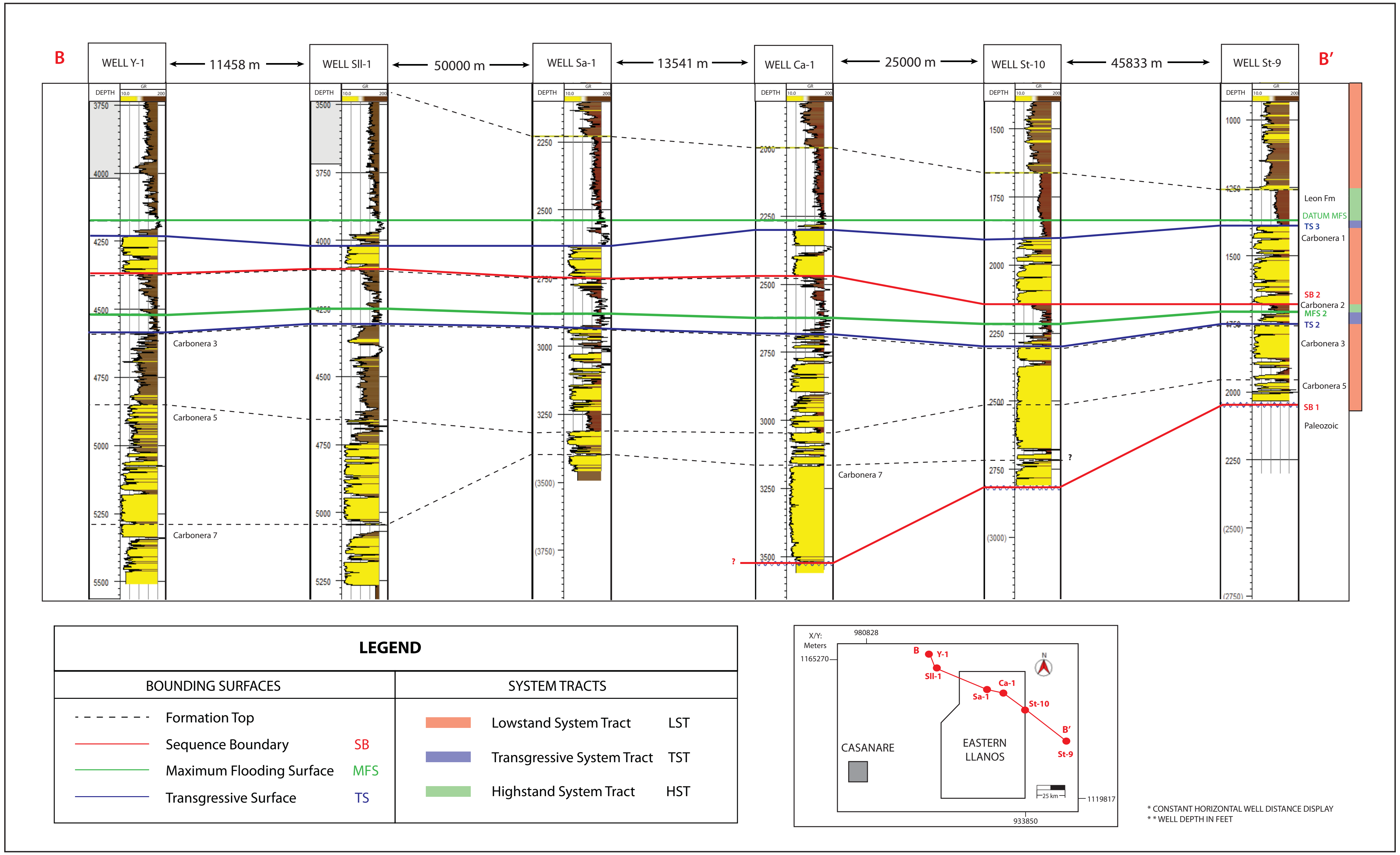


Figure 9. Well log correlation and sequence stratigraphy of the Carbonera Formation in the study area (location of wells shown on inset map). Formation tops are shown as dotted lines; sequence boundaries are shown as red lines; transgressive surfaces are shown as blue lines; maximum flooding surfaces are shown as green lines. Lowstand system tract is in red, transgressive system tract is in blue, and highstand system tract is in green. Carbonera members 4, 6 and 7 where not preserved in this area.

This surface represents the maximum flooding during the transgression of the “Leon lake” in the Early Miocene (Bayona et al., 2008) and is clearly recognizable in well logs with the highest gamma ray value close to the base of the Leon Formation marked by coal, siderite and dolomite-rich layers (Bayona et al., 2008). Major components of the seismic stratigraphy of the study area are described below:

a. In the western study area, a thin amount of the **Transgressive Carbonera Member 8** was preserved (Fig. 9). The base of this unit is a Transgressive Surface separating Cretaceous and Tertiary deposits. This unconformity surface, TS1, overlies Late Eocene sedimentary rocks of the Mirador Formation ~ 20 km to the west.

b. **Sequence Boundary 1 (SB1)** is defined within Member C7 as the first sharp, low gamma-ray peak that marks an overall progradation sequence. Carbonera Member 8 may be occasionally eroded by the Carbonera Member 7, therefore the SB1 also coincides with a lacuna between the Carbonera Formation and underlying Tertiary deposits further west (Bayona et al., 2008). Overall, the Carbonera Formation uncomformably overlies Paleocene and Late Cretaceous beds in the central Llanos area, and Late Cretaceous and Paleozoic beds in the eastern and southern Llanos basin. Deposition of the Carbonera Formation was younger northward and eastward, thus the SB represents a diachronous surface separating non-conformable successions of marine transgression (Carbonera Member 8), marine regressions further east (Guadalupe Formation) and fluvial progradation (Carbonera Member 7) of different channel belts. This unconformity is recognizable in seismic sections as thick, high amplitude strong reflection (see SFC2 Fig. 6) with toplap truncated reflections of the underlying Guadalupe Formation and may also comprise the TS1 (Fig. 10).

c. **Transgressive Surfaces (TS)** records a regional transgression with a sharp high gamma-ray peak where marine-influenced muds overlie fluvial and/or coastal plain deposits overlying Cretaceous Guadalupe Formation, and Carbonera Members 3 and 1 (Fig. 8, Fig. 9). Mud deposits of Carbonera Members 4 and 6 exhibits fining to coarsening-upward patterns indicating floodplain progradation and aggradation with some possible tidal fluctuations, but show no evidence for major marine transgressions. The fine-grained strata corresponding to the Carbonera member 6 only shows evidence of eastward migration of coastal-plain environments (Bayona et al., 2007). Thus, the contact between the Carbonera member 7 and member 6 would not mark a transgressive surface.

d. **Member 2 of the Carbonera Formation** is widely distributed across the LFB and its wide extent may be attributed to an early Miocene eustatic sea level rise at approximately 25 Ma (Haq, 1987). This surface is characterized by a distinct basinward migration of facies and a gamma ray bow trend that separates pro-delta marine muds from fluvial plain deposits. Towards the east, this surface is represented by a clear lithologic change at the top of the Carbonera Member 2 Member, where a diachronous ravinement surface (TSE) has been preserved in the eastern study area (TS2 in Fig. 9), whereas in the western area the event occurs within Carbonera Member 3 (TS2 in Fig. 8). Therefore, the TS2 at the western study area is slightly younger that in the eastern study area. In seismic sections, Carbonera Member 2 is observed as a low-amplitude, muddy marine facies (TS2 in Fig. 10) that also suggests that this unit records a Highstand System Tract (HST).

e. **Sequence Boundary 2 (SB2)** is manifested by a sharp, low-gamma-ray peak correlating with sand-rich, fluvial erosive deposits at the base of Carbonera Member 1 and unconformably overlying marine muds of Carbonera Member 2. Unlike Sequence Boundary 1 (SB1), this boundary reflects a major change in the sequence architecture, i.e. the initiation of the LST. Maximum Flooding surfaces (MFS1 & MFS2) are defined within Carbonera Member 2 and Carbonera Member 8 as maximum gamma ray high peaks that separate retrogradation and progradation successions and mark the maximum transgression of the shoreline. The MFS1 may not be completely preserved or may be below well resolution of the seismic data (Fig. 10).

In summary, the Carbonera Formation is represented by two regressive- transgressive system tract cycles, starting from the base with deposition of Carbonera member 8 within a Transgressive System Tract (TST). The onset of Lowstand System Tract (LST) is marked by progradation of fluvial sediments of the Carbonera Member 7 with conditions of relative lowstand sea level due to high sediment supply; development of estuarine valley fills (Malagon, 1997) and incised valley fills (Rubiales field, Ecopetrol, 1995) along the southwest and southeastern margins of the LFB. Lowstand conditions prevailed during deposition of Carbonera Member 6 to Carbonera Member 3 (Torres et al., 2001) as accommodation increased, aggradation increased, as a eustatic drop of sea level defined by Haq (1987) took place. The muddier Carbonera Member 6 and Carbonera Member 4 are interpreted as floodplain aggradation related to small, tectonically-triggered transgressions produced by accommodation and lowering of the slope of the LFB that allowed partial flooding of the basin even though global sea level was relatively low.

By Late Oligocene, continued increase in accommodation and low relief of the LFB, combined with a short-lived global sea-level rise defined by Hag (1987) at ~25 Ma marked the initiation of the Transgressive System Tract (TST) within the Carbonera Member 3 in the study area and at the base of the Carbonera Member 2 in the eastern study area. These events were followed by a less preserved Highstand System Tract (HST) at the top of the Carbonera Member 2. The progradation of the Carbonera Member 1 fluvial sandstones marks the end of these two cycles related to the LST.

Systems tracts, particularly the HST, may be absent or poorly represented in the unit in a fluvial-dominated setting. The TST is represented in a small part of the unit and is barely distinguishable in seismic sections, whereas the LST contains the thick and easily recognizable deposits.

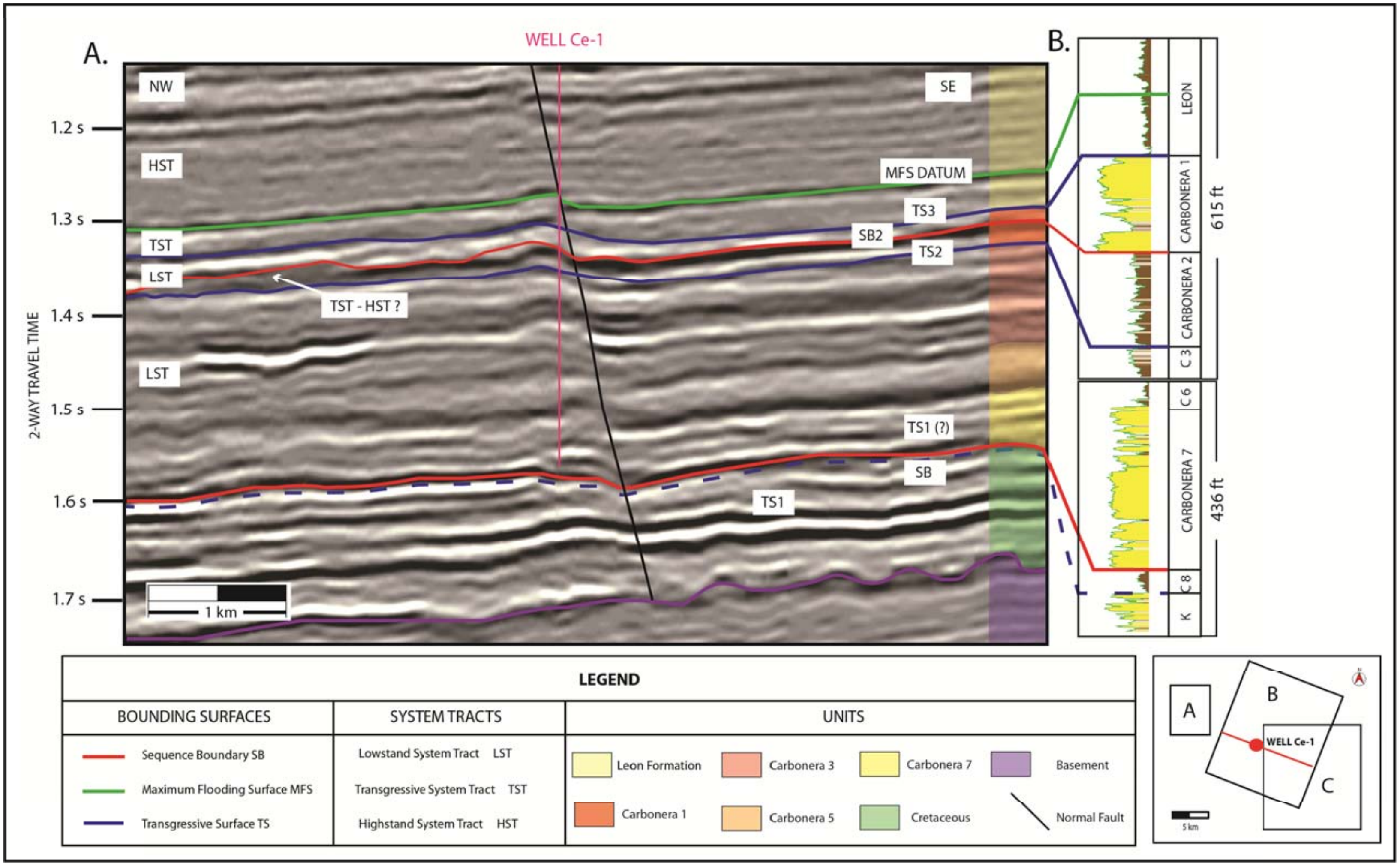


Figure 10. Seismic sequence stratigraphy of the Carbonera Formation in the study area. A. Inline across 3D seismic survey box B showing main bounding surfaces, system tracts, members of the Carbonera Formations and location of well control. Inset box shows line location. B. Correlation from seismic section in A to lithologic units in well Ce-1 in depth.

8. Multi-attribute analysis to characterize fluvial deposits

8.1 Application of coherence attribute

Coherence, also known as similarity, is a post-stack seismic attribute that measures the continuity between seismic traces in a specified window along a picked horizon (Bahoric, 1995). An estimate of 3D seismic coherence is done by calculating localized waveform similarities in the inline and crossline directions. The lateral seismic character variations may result in a sharp discontinuity with low coherence along faults and/or stratigraphic boundaries. For this study, a coherence cube was generated for every 3D seismic survey shown in Figure 1 and flattened time slices along the Carbonera Member 7, 5, 3 and 1 were extracted in order to map variations in channel belts morphology in two-way travel time (see Figure 11). Faults are distinguishable from sedimentary features by their linearity and crosscutting effects.

The image quality of the coherence attribute depends of the signal-to-noise ratio and errors in static corrections, velocity analysis and time-based migration (Chopra, 2007). For example, the acquisition and processing parameters used for Block A were superior to parameters used for Blocks B and C. Carbonera Member 7 lacks major channel systems in comparison to Carbonera Member 3, even though in well section (Figs. 8, 9) Carbonera Member 7 is composed mainly of channel base deposits. This means that the coherence for the data frequency windows (~8– 80 Hz) is not effective for

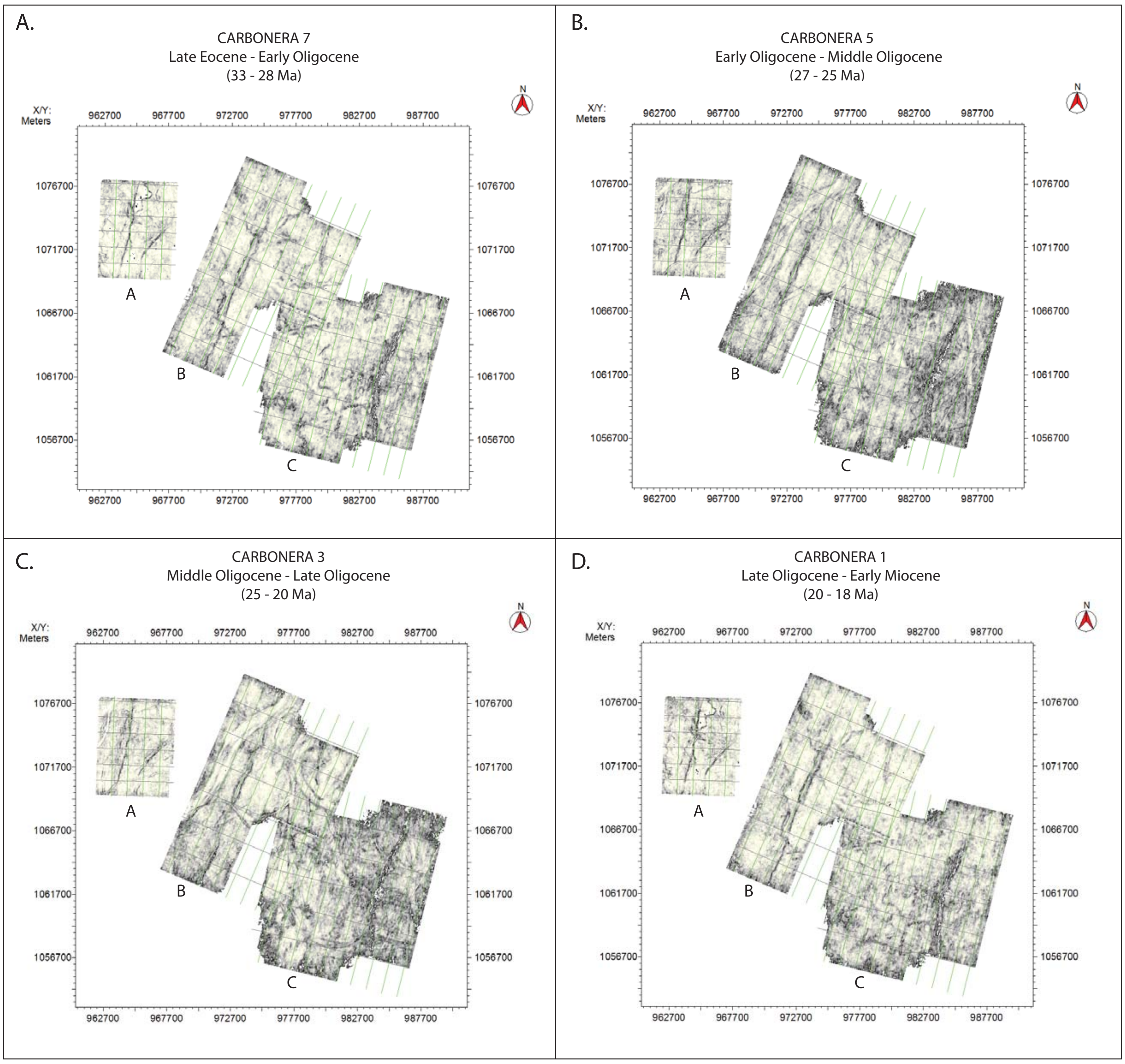


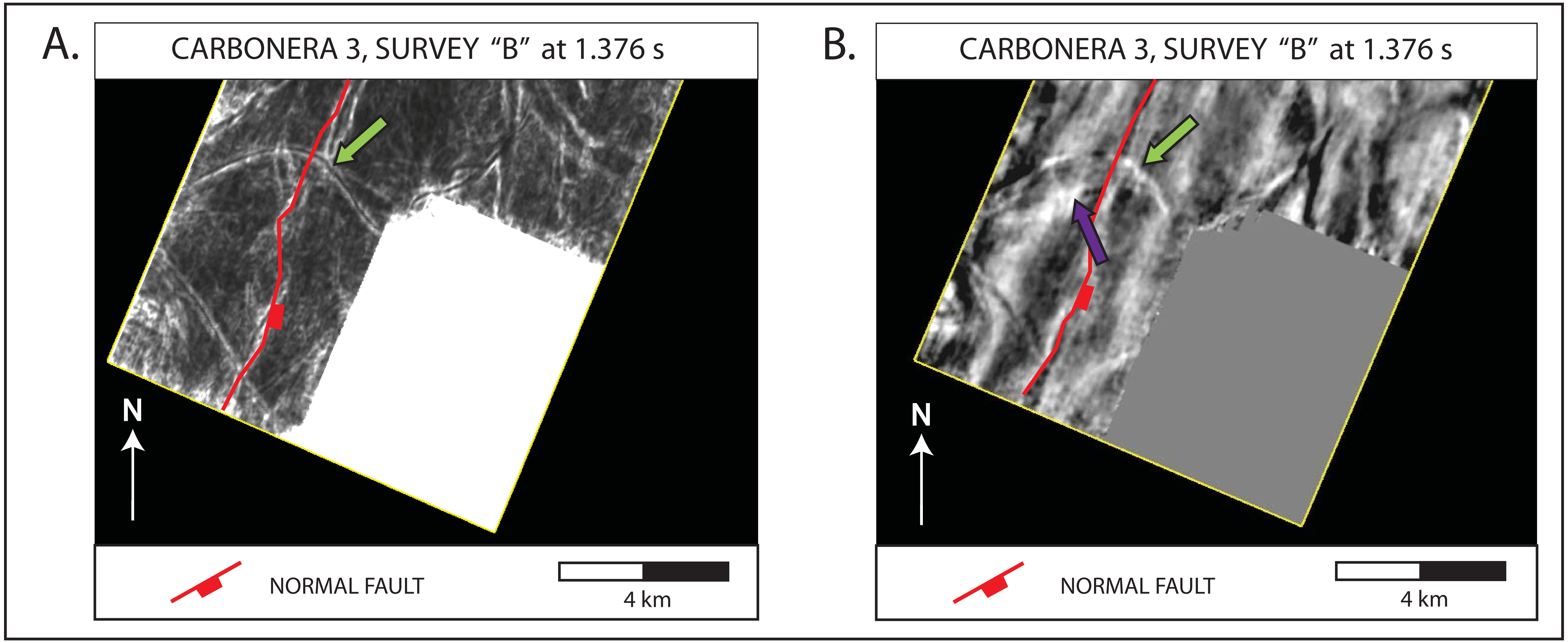
Figure 11. Uninterpreted flattened time slices through similarity cubes of Survey A, B and C of the study area. Flattened time slices extracted from: A. Carbonera Member 7; B. Carbonera Member 5; C. Carbonera Member 3; and D. Carbonera Member 1

identifying stratigraphic features identification below ~1.7 seconds two-way time. Therefore, the amount of channels highlighted in the surveys depends strongly on the interval of the extracted time slice and seismic resolution and reprocessing inherent to the 3D seismic cube used.

8.2 Application of spectral decomposition

Spectral decomposition is a common geophysical method for imaging and mapping bed thickness and geological discontinuities in 3D seismic volumes (Partyka et al., 1999). This attribute is based on conversion of seismic data to frequency domain within different bands in order to delineate variability in bed thickness and to identify stratigraphic features such as channels and structurally faulted complex areas. For each of the 3D volumes used in this study, ten different bands were calculated (banding based on an octave scale) in a frequency window of ~8 -85 Hz. The objective of conducting spectral decomposition was to highlight stratigraphic features that coherence could not resolve and to test that idea that detailed reservoir characterization could benefit from using different attributes.

In Figure 12A, the channel indicated by the green arrow and delineated by the coherence attribute is interpreted as a single, narrow, highly entrenched, mud-filled channel. However, compared to the time slice through the frequency cube (Fig. 12B), the thinner scrolls (indicated by the purple arrows) are now prominent and can be re-interpreted as a wider channel belt with point bar deposits. Using spectral decomposition,



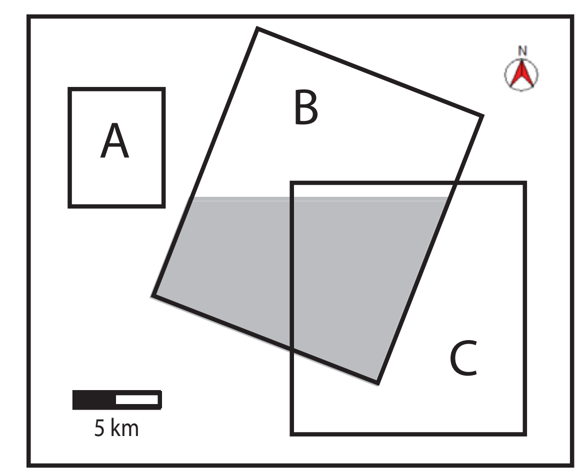


Figure 12. Time slices extracted at 1.376 seconds TWT within Carbonera member 3 in 3D seismic survey box B using: A. Coherence attribute cube; green arrow points at an apparent single channel; and B. Spectral decomposition cube at sub-band of 46.3 – 55.9 Hz; purple arrow indicates scrolls deposited in a meandering channel belt. C. Location map of 3D seismic boxes and area shown in Figures A and B.

It was concluded that most of the channel belts of the Carbonera Formation, particularly Carbonera Member 3, show evidence of lateral accretion of point bars.

8.3 Application of curvature attributes

The curvature attribute is a measurement of the bending of seismic reflections and is independent of the frequency at which the seismic volume was acquired (Marfurt and Chopra, 2012). Most positive curvature attributes emphasize the greatest positive values and will show "positive" features such as mounds, fold and flexures, (Marfurt and Chopra, 2012). Negative values of this attribute emphasize bowl-shaped features like synclines.

Features that have undergone differential compaction can also be enhanced by curvature measurements. The lateral changes accompanying the loss of rock volume as it lithifies depends on the type of lithology and the overlying deformation. In general, shales compact easier and reduce pore space faster than sand, so channels that are filled with sand cutting through a shale matrix may resemble "structural" highs, i.e. seen as ridges in the curvature cube (Chopra et al., 2007). Channels that are filled with shale and separated by sandier interfluves will appear as structural lows, whereas incised valley fills eroding previously compacted rocks, would appear as low, regardless of their type of fill.

As seen in Figure 13, the curvature attributes for 3D survey A highlights a channel at the top of the Carbonera Member 3. The most-positive curvature defines the

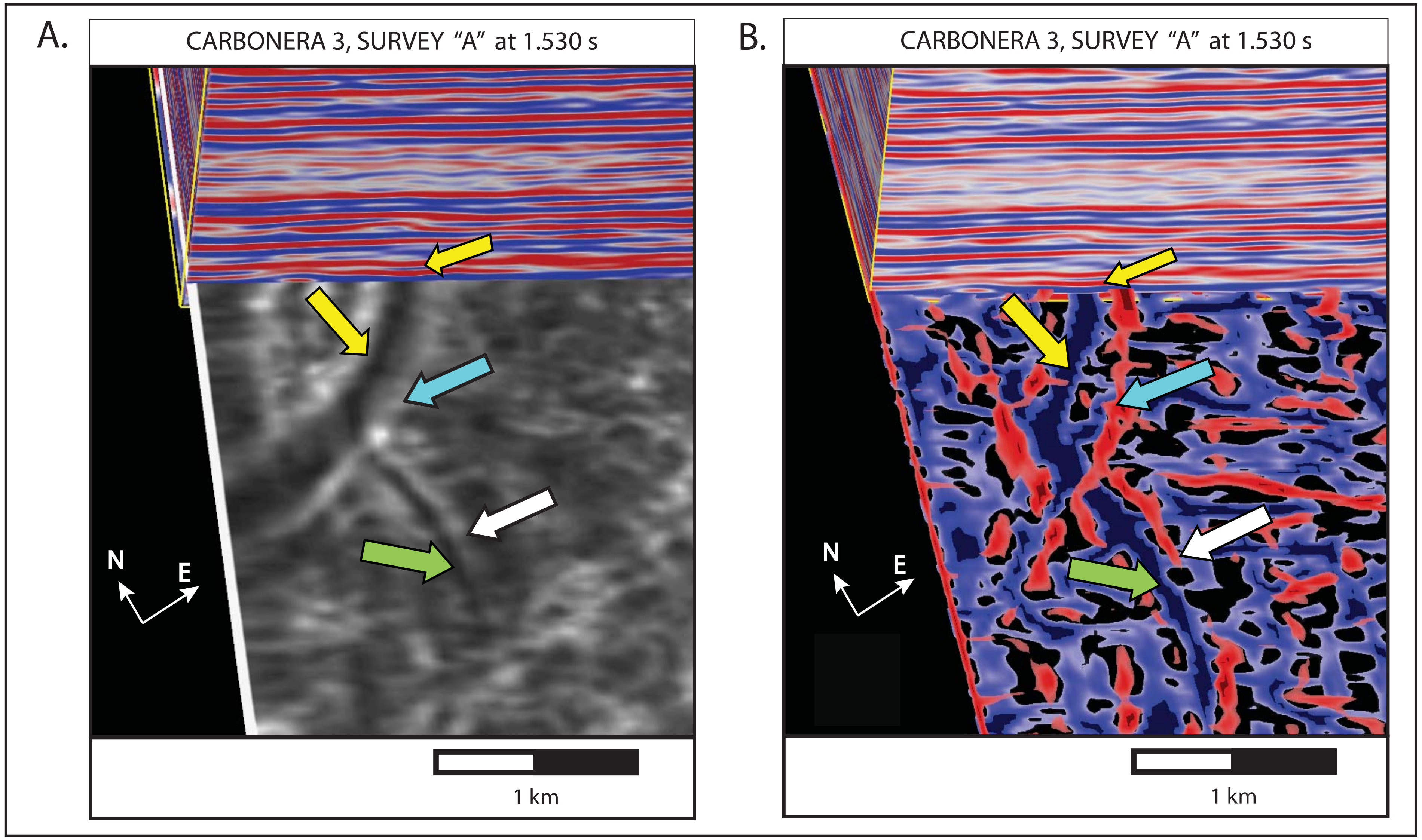
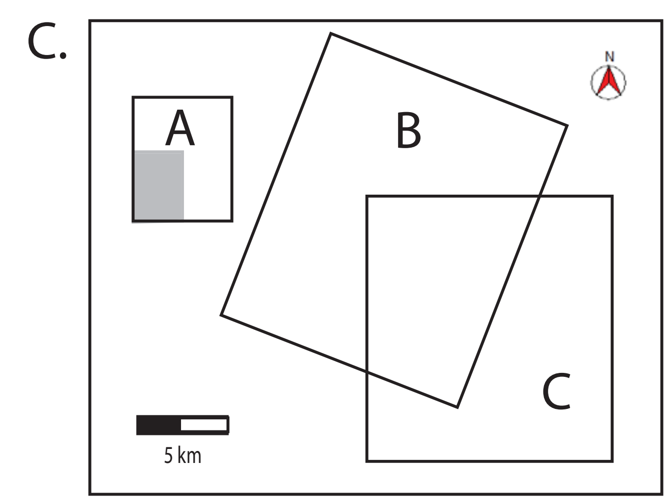


Figure 13. Chair display of survey A at 1.530 seconds TWT through Carbonera member 3 showing a vertical slice through seismic amplitude and: A. Coherence attribute cube; and B. most negative curvature attribute (blue) co-rendered with most positive curvature attribute (red) where moderate curvatures are rendered transparent. Blue and yellow arrows indicate edges and axis of the shallower channel respectively. White and green arrows indicate edges and axis of the deeper channel respectively. C. Location map of 3D seismic boxes and area shown in Figures A and B.



flanks of the channels as potential levees and over-bank deposits, while the most-negative curvature defines the channel axis filled with a finer lithology.

In the case of the shallow valley overlying Carbonera Member 3 in Survey B (Fig. 14), the combination of curvature attributes with coherence allowed the definition of the internal architecture of the valley. While coherence only shows a single channel with apparent constant width, the curvature image reveals several channel belts of variable width within a shallow valley (Fig. 14C); point bar deposits are highlighted by the most negative curvature attribute (Figure 14A); and where more positive curvature is delineated along the valley's edges (Figure 14B). Differential compaction is also seen in the seismic amplitude section at the top of the shallow valley re-inforcing the idea of a mud-dominated valley (Reijenstein et al., 2008) capped with marine mudstones. Intermediate values within this valley colored as light blue; white and light red colors may be the results of the effectiveness of the curvature attributes in the cube and not necessarily indicate a homogeneous lithologic compaction. On the other hand, coherence is not sensitive to structural deformation of the surface; rather it defines areas of the channel flank based on lateral change in the waveform (Chopra and Marfurt, 2007).

8.4 Application of acoustic impedance crossplot

Another useful method for lithologic discrimination to assist in sedimentary interpretations is the calculation of acoustic impedance from well data. Acoustic

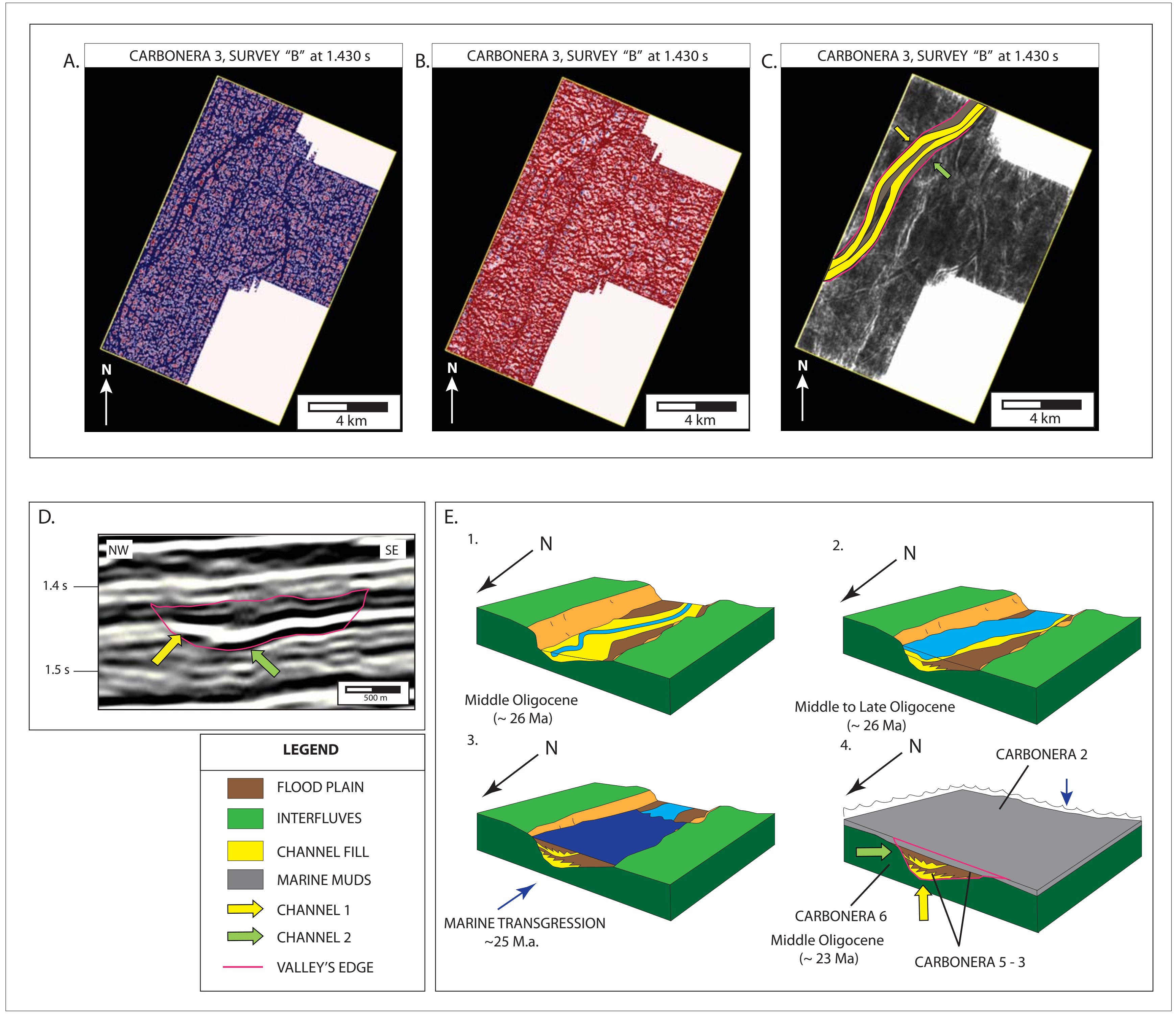


Figure 14. Time slice extracted at 1.430 seconds TWT within Carbonera Member 3 in 3D seismic survey box B through, A. most negative curvature attribute cube, B. most positive curvature attribute, c) re-interpreted valley morphology on coherence cube, D. seismic display of shallow valley, and E. schematic reconstruction of shallow valley formation (Modified from Posamentier in Reijenstein et al., 2008).

impedance varies with rock properties including lithology, porosity, formation fluid, fluid pressure and compaction (Escalona, 2003). Impedance curves calculated for the Carbonera Formation from four different wells show similar trends to the general curve shown in Figure 15B.

In general, clean sandstones were visually differentiated from shale deposits by acoustic impedance highlighted in the colored polygons on Figure 15A. Overall, the lowest values of acoustic impedance and higher density values are associated with shale-prone lithologies. Intermediate with high density and resistivity values correspond to sandstones with hydrocarbons.

9. Discussion

The migration of the foreland axis of the LFB and basinal flexure related to regional shortening had a significant control on the flow direction and alignment of fluvial channel belts in a SW-NW trend by Late Eocene – Middle Oligocene time as recorded in the directions of paleochannels from Carbonera Member 7 to the Carbonera Member 3 (Fig. 3). The orientation of these channel belts is the same as the numerous, flexure-related normal faults trending parallel to the ENE axis of the LFB but not in an EW direction as has been described in the literature (Osorio et al., 2008). The normal faults exhibit an en echelon pattern in map view with elongated and sinuous fault systems that lack an oblique-slip component (Corredor, 2012).

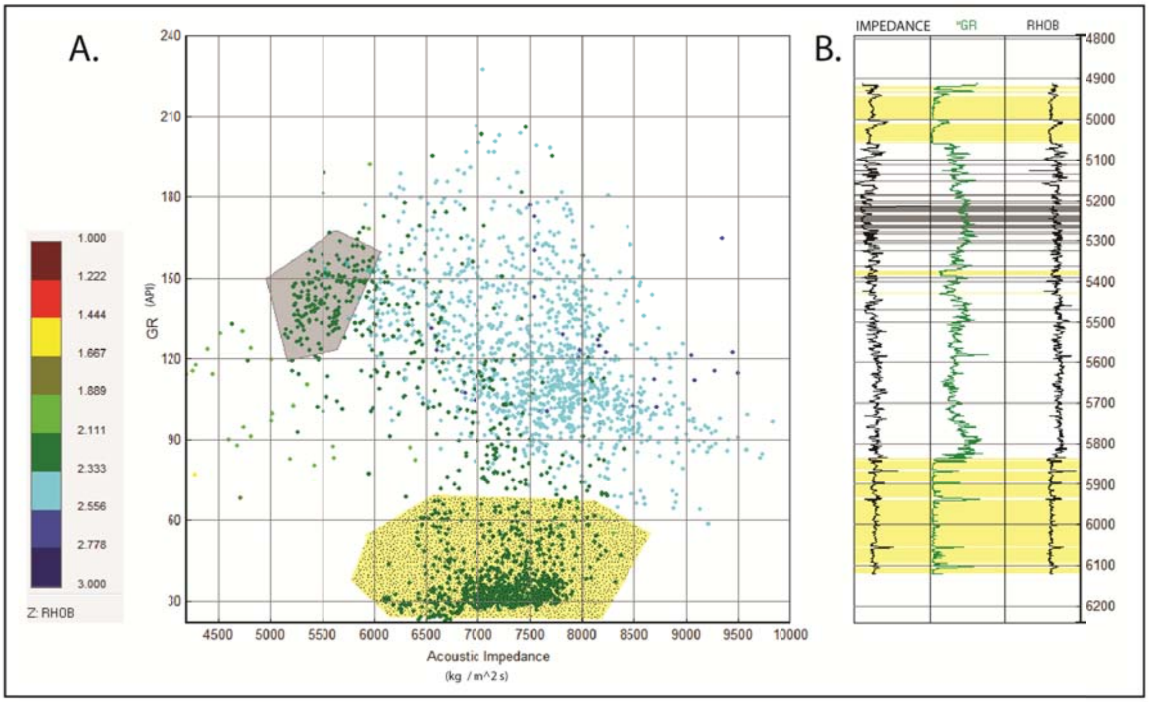


Figure 15. A. Gamma ray log values compared to calculated acoustic impedance values for Well B-1 in the study area (see Figure 8 for location); B. Impedance, gamma ray and density curves for Well B-1.

The change in fluvial dynamics and paleoflow directions during the Late Eocene–Oligocene epoch (Fig. 3) corresponds to a prolonged pulse of increased flexural subsidence from the Late Eocene (34 Ma) to Early Miocene (23 Ma) of the LFB during the uplift of the Eastern Cordillera uplift (Campos, 2011, Fig. 16C, D).

As shown in Figure 16A and B the increase on subsidence during the Oligocene affected the entire LFB at slightly different rates. Deposition started later during the Middle Oligocene in Eastern Llanos as the edge of the basin reached further into the Guyana Shield, whereas the units to the west are slightly older and record longer lived subsidence. This variation in basin floor subsidence across the LFB also may explain the

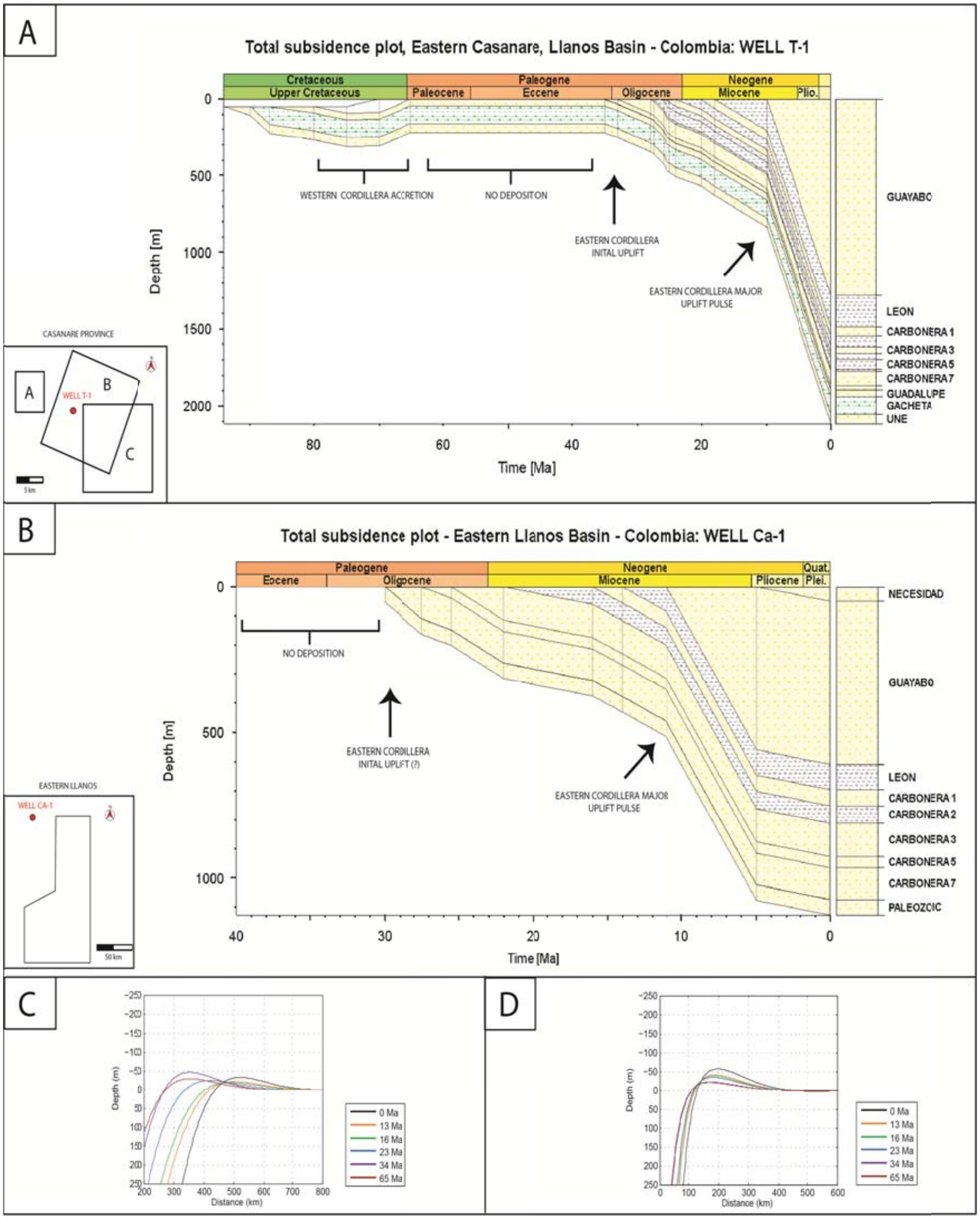


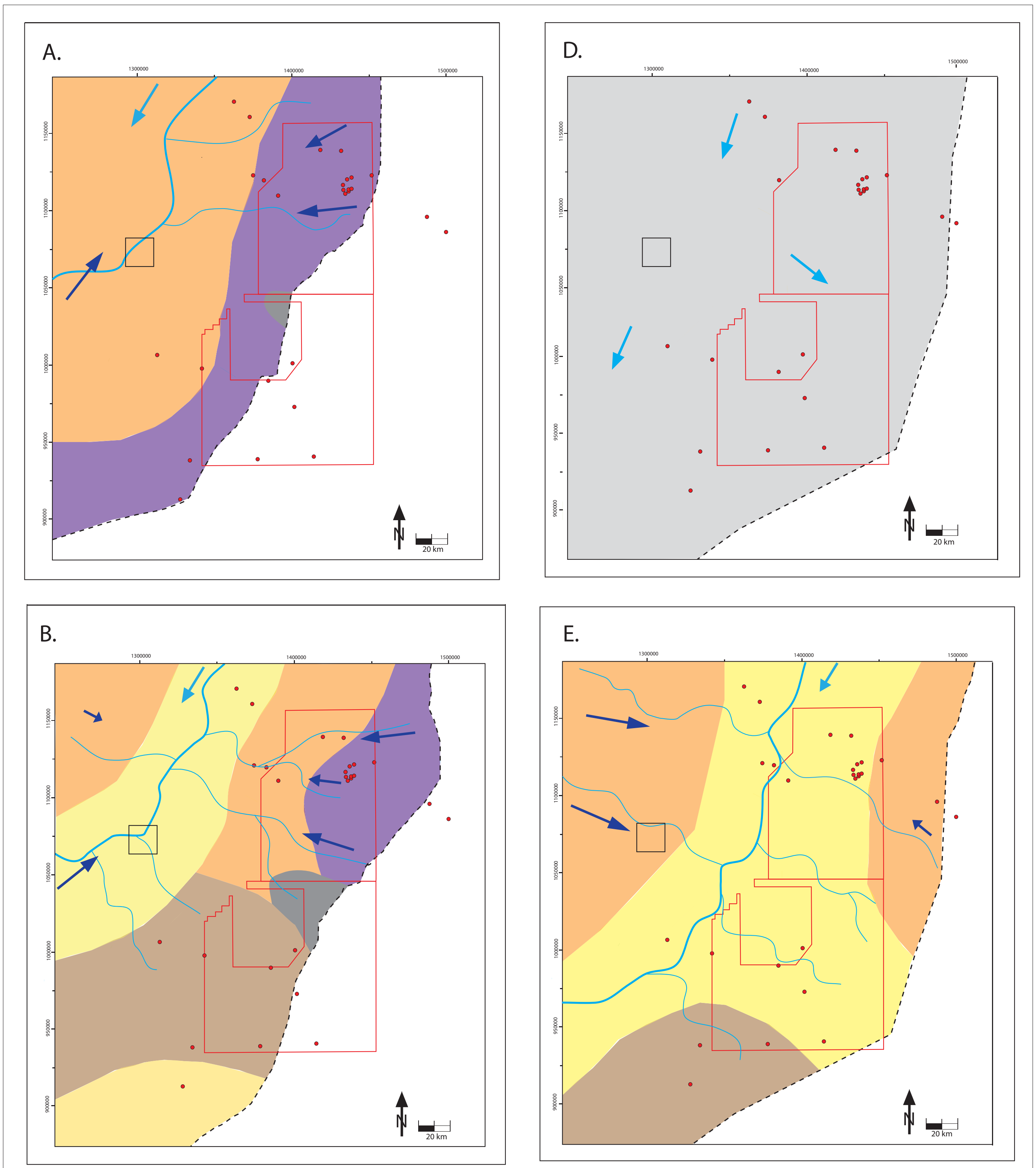
Figure 16. Total subsidence plot calculated and basement flexure curves from the central LFB modified from Campos (2011): A. Total subsidence plot calculated from well T-1 at Casanare Province; B. Total subsidence plot calculated from Well Ca-1 at Eastern Llanos; C. Sedimentary load deflection from Campos (2011) in Oligocene time (purple line); and D) Tectonic load deflection in Oligocene time (purple line) from Campos (2011). Total Organic Carbon (TOC) and Hydrogen Index (HI) values taken from Organic Geochemistry Atlas of Colombia, ANH (2010). Geothermal gradient values taken from Bachu et al., (1995).

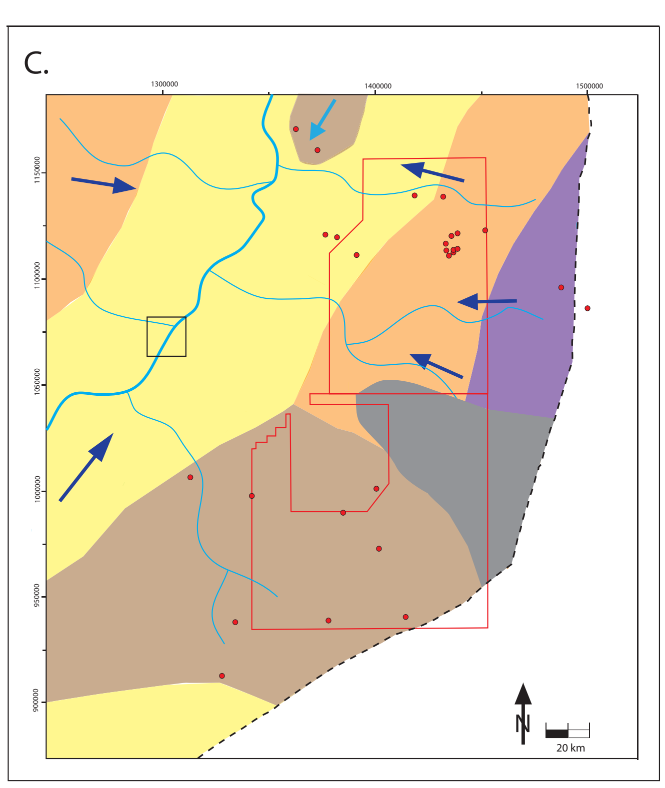
diachronity of the major bounding surfaces, i.e. the trangressive surface and sequence boundary.

Widening of the LFB allowed the Carbonera Formation to expand towards the eastern flank of the basin, whereas earlier Eocene deposits (Mirador, Los Cuervos, and Barco formations) are not present in the eastern area. A shift of the main paleoflow direction of rivers started in the Early Oligocene during deposition of the upper part of Carbonera Member 3. This shift included an eastward migration of the fluvial axial system (Fig. 3), as transverse tributaries from the western flank of the basin developed and lengthened, as well as pronounced thickening towards the western flank from source by the uplifting Eastern Cordillera (Fig. 2). Deposits from Carbonera Member 3 and Carbonera Member 1 recorded the shiftsin paleochannel directions to the NW-SE.

9.1 Tectonic effects on changing fluvial style of the Carbonera Formation

For years, in the eastern study area, the Guyana Shield has been defined as the main provenance area for Oligocene fluvial sediments, where channels had an E-W paleoflow direction (Ecopetrol, 1995, Osorio et al., 2008). However, new orientations observed with seismic attributes and variations of the Carbonera Formation channel's paleoflow direction at central- eastern LFB (Fig. 17), and locally at western study area (Fig. 18) has been observed in each of the Carbonera Members. Farther northwest, towards the foothills area, there is fewer occurrences of these channels (Carvajal, 2007).





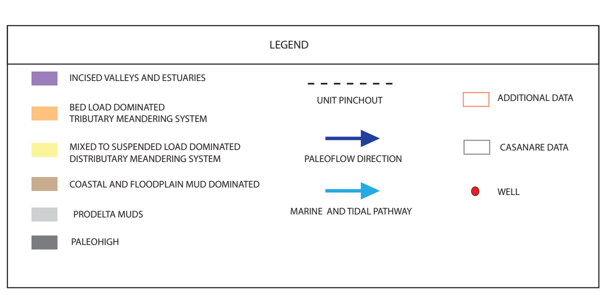


Figure 17. Paleoflow direction and changing fluvial style of reservoir members of the Carbonera Formation in the study area: A. Carbonera 7; B. Carbonera 5; C. Carbonera 3; D. Carbonera 2; and E. Carbonera 1 at study area (black square) and additional study area from Shell in the eastern Llanos basin (red rectangles).

This interpretation has important implications in key concept as to a better understanding of the basin, its geometry, sediment provenance and interpreted depositional environments (Osorio et al., 2008).

Carbonera 8: This unit was deposited during a marine transgression due to global sea level rise around 35 Ma following deposition of Eocene sediments. The thickness of the unit expands westward: in the study area only a few meters of the unit is preserved, whereas in the eastern study area this unit was not deposited or has been eroded. The unit also shows major thickening in the Medina and Cuisiana areas (northwestern LFB close to Llanos foothills) that could be related to crustal flexure (Casero et al., 1997). Pre – Oligocene faulting and deformation in the northern Eastern Cordillera has also been described by Corredor (2012).

Carbonera 7: Fluvial paleoflow direction from east to west was part of a greater fluvial system that started to develop during the Late Eocene as the initial uplift of the Eastern Cordillera added a tectonic load and flexure of the lithosphere allowed eastward widening of the LFB. Early workers (Van der Hammen, 1961; Dengo and Covey, 1993; Cooper et al., 1995, Jimenez and Van der Hammen, 2007) linked the appearance of Late Miocene to Pliocene fluvial facies in LFB to the onset of uplift in the Eastern Cordillera. However, more recent provenance studies (Gomez et al., 2005, Moreno et al, 2010, Nie and Horton, 2012) provide evidence for an earlier Eastern Cordillera uplift in Paleogene time (Fig. 2). By Late Eocene time, the Llanos basin was connected to the Maracaibo basin

(Ayala et al., 2012) and may have served as a marine pathway to the Caribbean Sea but this passage had closed by Oligocene time (Gomez et al., 2005; Hoorn et al., 1995). The main source area for Member 7 is the Guayana Shield. Lithic-rich sandstones are common in the eastern study area and clean sands are characteristic in the western study area.

Carbonera 5: The Eastern Cordillera was not fully uplifted at this time (Fig. 3) but localized uplifts provided areas of positive relief and new source areas for the LFB. Part of the Santander Massif and Los Cobardes Anticline (Moreno et al., 2011) already formed a positive source area by Early Oligocene time. The predominance of floodplain deposits in the eastern study area indicates that accommodation was higher than sediment supply. The Guayana Shield remains the main source area with some slight influence from the uplifting Eastern Cordillera.

Carbonera members 4 and 6: These members were deposited under conditions of increased accommodation in a low relief plain. This setting combined relative sea level rise with floodplain and lagoonal facies aggradation. Moderate sediment supply did not exceed the effects of accommodation.

Carbonera 3: In the Middle Oligocene, small tributaries developed and merged into a main fluvial axial system (Fig. 3). By this time, mountain building in the Eastern Cordillera not only generated a major tectonic load with renewed accommodation, but also increased rainfall along its eastern flank (Mora et al., 2010), resulting in erosion and increase in sediment supply. This pronounced increase in sediment accumulation rate (ca. 600m/my) has been documented by Parra et al., (2010).

These factors produced an increase in channel belts at the top of Carbonera Member 3 as observed in the seismic data (Fig. 18). By this time, the Magdalena Basin to the west started developing as a hinterland basin (Saylor et al., 2012) and the fluvial system that prevailed during the Paleocene and Eocene - represented by Cuervo, Barcos and Mirador Formations - started to flow independently from the newly developed fluvial system of the LFB (Nie and Horton, 2012). As a result, the connection between the Magdalena and Llanos basins was closed. Both the Guyana Shield and the Eastern Cordillera remained source areas for this member.

Carbonera 2: A marine transgression coincided with a global sea-level rise and a low relief was recorded by transgressive deposits with occurrences of fish scales, shark teeth, and microfossils of marine affinity (Bayona et al., 2008) (Figure 17E).

Carbonera 1: By Late Oligocene, the fluvial morphology of the Carbonera Member 1 recorded the maximum, eastward migration of the main axial fluvial system as a result of the initiation of the most important uplift phase of the Eastern Cordillera (Figs. 17, 18D).

In the proximal Llanos basin detrital geochronology also documents the appearance of clasts and zircons coming from sources in the Eastern Cordillera since the Latest

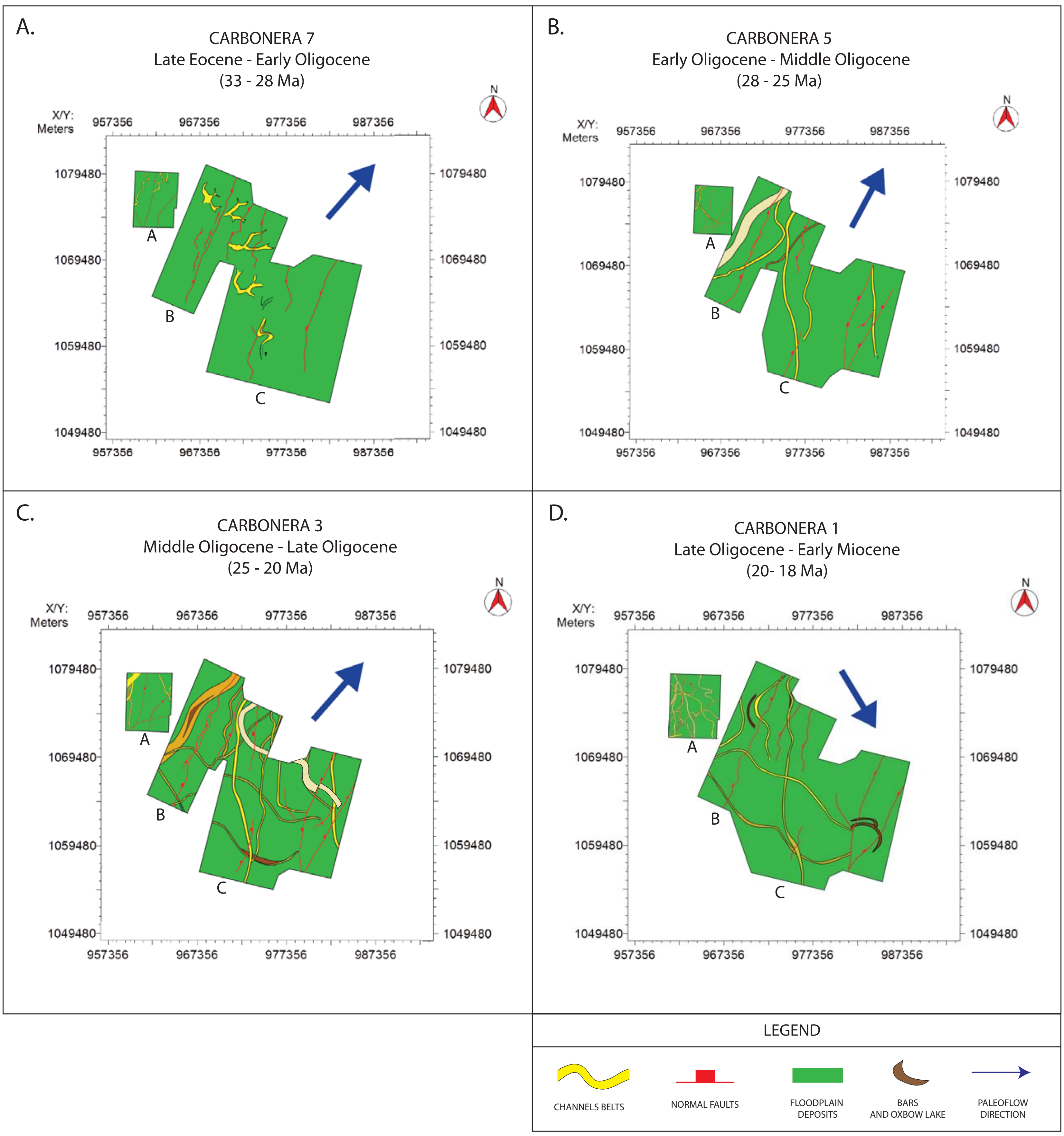


Figure 18. Interpreted flattened time slices through similarity cubes of 3D seismic survey boxes A, B and C in the study area showing paleoflow direction (arrows) for: A. Carbonera Member 7; B. Carbonera Member 5; C. Carbonera Member 3; and D. Carbonera Member 1.

Oligocene (Horton et al., 2010). This confirms that active deformation and advance of the Eastern Cordillera started by the Latest Oligocene (Mora et al., 2010), and the rotation of the fluvial system in a clockwise migration direction (Gamero, 1995).

The combination of temporary inundations of a ramp-type and low-lying fluvial plain with widespread flooding accompanying flexural-related subsidence allowed a tabular lithology to spread over a wide area and produce a "layer cake" stratigraphy in the Carbonera Formation that is evident in seismic sections. River channels reworking sediments of the fluvial plains also contributed to the widespread aerial distribution of the sandier members.

9.2 Paleogeography of LFB during the period of Late Eocene to Late Oligocene

An open question is whether the shalier members of the Carbonera Formation are purely the result of a marine transgression or were formed by floodplain aggradation (Fig.3). If in fact these are marine transgressions, there is still a debate about the location sea pathway and the discharge area of the sediments (Bayona et al., 2008, Villamil, 1999).

Santos et al., (2008) conducted a study of salinity conditions for the Late Eocene units of the LFB including the Mirador Formation and the base of the Carbonera Formation in the eastern study area where higher salinity values indicated marine incursions into the area. Furthermore, the presence of glauconite in the well cuttings, a mineral diagnostic of shallow marine settings, indicates marine influence in the muddier members as well as in floodplain deposits from the sandier members.

As previously discussed, this event may have been a small marine incursion produced by a combination of tidal influence and a steady increase of accommodation space in the LFB. The concept of tidal influence was introduced by Hoorn et al. (1995). Plant debris found in the Carbonera Formation has been interpreted as vegetated tidal flat and low diversity assemblages of *Skolithos* ichnofacies described by Malagon (1997) have been associated to tidal environments. The presence of glauconite, a mineral restricted to shallow marine settings, in Carbonera Members 8, 6, 4 and 2, along with a *Skolithos* ichnofacies assemblage, supports the hypothesis of tidal influence in the study area during this time. Additionally, in the eastern study area, cross bedding directions observed in borehole images for the shaly Carbonera members showed opposite flow directions cross bedding from the sandy members and support the tidal hypothesis further in the eastern area.

A recent palynological study by Ochoa et al., (2012) observed that the similarity in floras of the Late Eocene Usme and Concentracion Formations (Carbonera Formation in LFB) in the Central Llanos Foothills and Llanos Basin, respectively, indicated that these depositional systems were still connected by Late Eocene – Early Oligocene time. As suggested by Gomez et al., (2005), Saylor et al., (2012) and Hoorn et al., (2010) the connection between the large depositional systems of the LFB and Eastern Cordillera probably started to break during the Early to Middle Oligocene, i.e. around the deposition of Carbonera 5 in the eastern study area, and not during the Early Miocene as proposed by Cooper et al (1995). Westward increase in thickness of the LFB records the onset of the major pulse of uplift for the Cordillera Oriental. Moreover, the similarity between depositional environments of the Magdalena Valley basins, Eastern Cordillera and LFB remained strong until Late Eocene – Early Oligocene (Parra et al., 2009). This supports the idea of a fragmentation of a single foreland basin (Hoorn et al., 2010, Ochoa et al., 2012) with onset of exhumation pulses by Early Oligocene (Delgado et al. 2012) , which isolated the LFB from the Magdalena Basin around Middle to Late Oligocene (Gomez, 2005; Saylor et al., 2012; Nie and Horton, 2012).

In addition, a major pulse of uplift of the Eastern Cordillera at Early to Middle Miocene increased Oligocene accommodation and deposited the Leon formation which has been described as an enclosed lake or lacustrine environment, hence the wide distribution of this unit, its homogeneous seismic character, and its relatively small thickness variations. The Merida Andes (Mann and Escalona, 2006) uplifted as well, closing the connection to open sea in northern Venezuela by the Middle Miocene.

Another possible connection between the LFB and the paleo-Amazonas River in Oligocene time has been proposed by Hoorn et al., (1995), where the paleo-Amazonas River was marked by fluvio-lacustrine and estuarine systems that where still partially connected to the main fluvial system observed in the study area (Hoorn et al., 2010).

The paleo-Amazonas was dominated by palm and tropical low-land vegetation with presence of marine palynomorphs (dinoflagellates and foraminifera) indicating

episodic marine incursions. Moreover, Hoorn et al. (2010) proposed the existence of a Sub-Andean river system connected to the Atlantic Ocean by a series of coastal seas in the Oligocene that connected the Llanos basin with the current drainage area of the Orinoco River and not through the current location of the Maracaibo basin as suggested earlier by Hoorn et al. (1995), Gomez et al., (2005), and Villamil (1999). However, this southern Llanos seaway crossing the Andes to the Pacific Ocean has not been widely explored yet, so the question remains whether this was also a source for marine fossils with shallow marine affinity (Bayona et. al, 2008). There was also no apparent connection between the Llanos and Putumayo foreland basin by Oligocene time, due to the presence of pre-existing Paleozoic highs that acted as sediment barriers, e.g. Melon basement high at the southern Llanos Basin.

10. Fluvial architecture of the Carbonera Formation

The Carbonera Formation shows a predominance of meandering channel belts deposits with variable sinuosity, and depth (D) and width (W) ratio, within an average slope of ~0.02 degrees (Table 1) calculated from flattened slice from the biggest channel at top of Carbonera Member 3. Width measurements were also made from flattened time slices from coherence curves, so the width/depth ratio would be higher. The parameters for defining the sediment type are based on Miall (2006) and Rosgen (1994)(Fig. 19).

UNIT	WIDTH (m)	AVERAGE DEPTH (m)	W/D Ratio	AVERAGE SINUOSITY
CARBONERA7	200-350	25	16	1.16
CARBONERA 5	200-500	25	20	1.2
CARBONERA 3	400-1100	36	14	1.04
CARBONERA 1	200-850	30	12	1.43

Table 1. Width (m), depth (m) and sinuosity values for the channel belts of Carbonera Member 7, 5, 3 and 1.

Carbonera 7: This member exhibits channels that are narrow, deep, low sinuosity, and sand to mixed load dominated with meandering channels and lateral pointbar accretion. In the eastern study area, this unit is dominated by coarse - to- medium-grained sandstones within incised valley fills with no preservation of the underlying Carbonera Member 8. Primary porosity reduction takes place as a result of precipitation of diagenetic cement from lithic leaching due to the proximity of the source area (i.e. the Guyana Shield).

Carbonera 5: This member exhibits isolated channel belts dominated by floodplain and interfluve aggradation, combined with lagoon deposits and rapid sedimentation rate due to lowering of the slope of the LFB. The slight increase of sinuosity also marks a higher avulsion frequency with more probabilities for preservation of shale-prone channel abandonment facies (Slingerland and Smith, 2004; Lynds and Hajek, 2006). In the eastern area, this member exhibits a series of medium grained, amalgamated fluvial sandstones.

Carbonera 3: The presence of wider, slightly more sinuous channels in this member was observed at the base of this member, whereas narrower, low sinuosity channels occur higher in the member. The widest and deepest small-scale valley fill seen at top of Carbonera Member 3 is eroding into Carbonera Member 5 and showed an absence of tributary channels within the valley system, which indicates that the shelf has not been fully exposed in order to create and migrate a knickpoint (Posamentier and Allen, 1999). This feature may not result in sand-rich channel deposits, but rather a mud-dominated channel due to the effect of sea level rise. i.e. deposition of Carbonera Member 2 during a time of high sediment supply. Therefore, coarse-grained, sand-rich, bed load sediment is expected mainly at the base of these wide channels. In the eastern study area, delta mouth sand bar deposits were identified at the top of this member, might also account for development of relatively good quality and continuous reservoir sand.

Carbonera 1: Wide, slightly sinuous meandering channels with abandoned loops form oxbow lakes at the top of this unit. These smaller features may be filled by silts and clay during the Early Miocene major transgression (Leon Formation) and form effective barriers to lateral hydrocarbon flow.

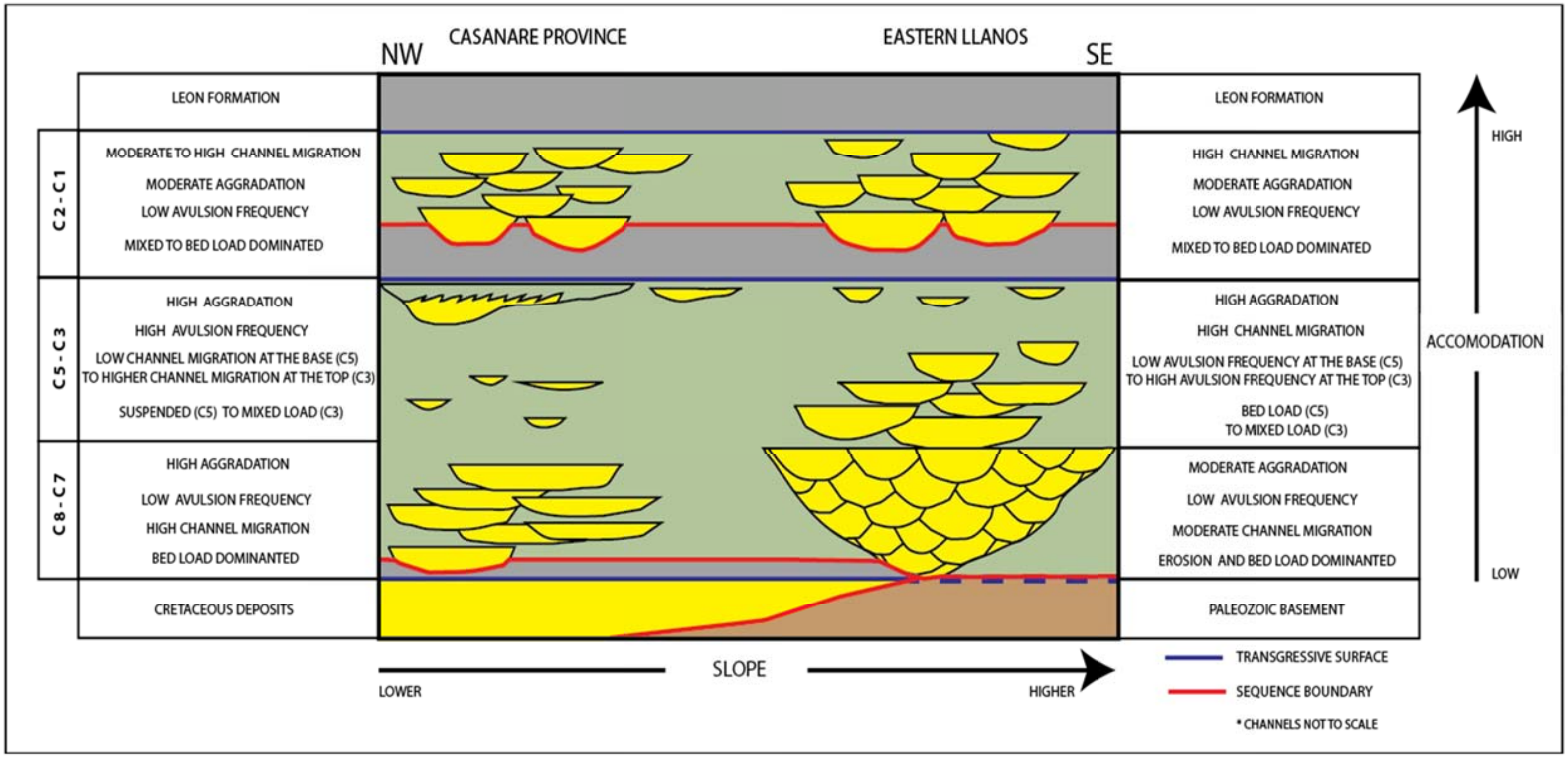


Figure 19. Channel morphology evolution in time and space, sequence boundaries (red line), and transgressive surfaces (blue lines) in the west and eastern study areas of the LFB. See text for description.

11. Conclusions

1) The Carbonera Formation shows a predominance of meandering channel belts deposits with low sinuosity and variable W/D ratio morphologically controlled by the combination of tectonic effects related to the longterm Cenozoic uplift of the Eastern Cordillera and short-lived transgressions due to eustatic sea level rises at a low-lying alluvial plain (slope of ~0.02 degrees) during the Late Eocene- Oligocene in a ramp-type shelf setting.

2) Migration of the foreland axis of the LFB controlled the flow direction of the fluvial channel belts along a SW-NW trend as recorded in Carbonera Members 7 to 3. Changes in the paleoflow direction are interpreted as eastward migration of the forebulge flexure; transverse tributaries of the main axial system are recorded in Carbonera Member 1.

3) The broad extension of the Carbonera Member 2 recorded a short-lived eustatic sea level rise at ~25 Ma defined by Haq (1987). The presence of glauconite, a mineral restricted to shallow marine settings, in Carbonera Members 8, 6, 4, and 2, along with a *Skolithos* ichnofacies assemblage, supports the hypothesis of tidal influence in the study area during this time. Overall, the unit records two regressive-transgressive cycles with higher preservation of lowstand deposits.

4) The presence of pyrite, siderite, and iron minerals in well cuttings, particularly in floodplain deposits, indicate swampy, brackish conditions. Plants debris suggests

vegetated tidal flats. The setting included a reducing minerals depositional environment with restricted water circulation to an open sea.

5) Shallow valley fill observed in time slice at the top of te Carbonera Member 3 showed an absence of tributary channels indicative of an unincised valley rather than incised valley; the unincised valley may indicate a short-lived sea-level fall where the shelf was not exposed (Posamentier et al., 1999).

6) Carbonera Members 7 and 1 have better reservoir quality in the eastern study are than localized sand bodies within Carbonera Member 3. In the eastern study area, coarse- to medium-grained sandstone deposits with good quality reservoir occurred at Carbonera Members 7, 5, and 3, but exhibit poor intraformational seal preservation.

7) Recommendations include coring, biostratigraphy, and palynology studies for the western area of study, and well coring and 3D seismic acquisition for the eastern area of study.

12. References

Ambrose, W.A., Hentz, T.F., Bonnaffe, F., Loucks, R.G., Brown, Jr. L.F., Wang, F.P., Potter, E.C, 2009, Sequence-stratigraphic controls on complex reservoir architecture of highstand fluvial-dominated deltaic and lowstand valley-fill deposits in the Upper Cretaceous (Cenomanian) Woodbine Group, East Texas field: Regional and local perspectives. AAPG Bulletin, v. 93, no.2, p. 231-269.

Ayala, R.C., Bayona, G., Cardona, A., Ojeda, C., Montenegro, O.C., Montes, C., Valencia, V., Jaramillo, C., 2012, The Paleogene synorogenic succession in the northwestern Maracaibo block: Tracking intraplate uplifts and changes in sediment delivery systems. Journal of South American Earth Sciences, v. 39, p. 93-111.

Bachu, S., Ramon, J.C., Villegas, M.E., Underschultz, J.R., 1995, Geothermal regime and thermal history of the Llanos basin, Colombia. AAPG Bulletin, v. 79, no.1, p. 116–129.

Bahorich, M., 1995, 3-D seismic discontinuity for faults and stratigraphic features: The coherence cube. The Leading Edge, v. 14, p. 1053-1058.

Barrero, D., Pardo, A., Vargas, C.A., Martinez, J.F., 2007, Colombian Sedimentary Basins: Nomenclature, Boundaries and Petroleum Geology, a New Proposal. Special Publication, Agencia Nacional de Hidrocarburos, Colombia, p. 40-72.

Bayona, G., Jaramillo, C., Rueda, M., Reyes-Harker, A., Torres, V, 2007, Paleocene-middle Miocene flexural-margin migration of the nonmarine Llanos foreland basin of Colombia. Ciencia, Tecnologia y Futuro, v.3, p. 51-70.

Bayona, G., Reyes-Harker, A., Jaramillo, C., Rueda, M., Aristizabal, J., Cortes, M., Gamba, N., 2008, Distinguishing tectonic versus eustatic flooding surfaces in the Llanos basin of Colombia, and implications for stratigraphic correlations. Special Publication, Ecopetrol S.A. p. 1-13.

Bayona, G., Valencia, A., Mora, A., Rueda, M., Ortiz, J., Montenegro, O., 2008, Stratigraphy and provenance of Miocene rocks in the distal Llanos foreland basin of Colombia. Geología Colombiana, v.33, p. 23-46.

Blum, M. D., and T. E. Törnqvist, 2000, Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology, v. 47, p. 2-48.

Campos, H., 2011, Tectonostratigraphic and subsidence history of the northern Llanos foreland basin of Colombia, 2011. M.S. Thesis. The University of Texas at Austin, p. 78-93.

Carvajal, L.C., 2007, Caracterización facial, eléctrica y sísmica de la Formación Carbonera en la cuenca de Los Llanos Orientales. B.S. Thesis. Universidad Nacional de Colombia, p. 1-26.

Caribbean Basins, Tectonics and Hydrocarbons (CBTH) Results from Phases I and II (2005-11): Atlas Volume 2011. Section 6.

Casero, P., Salel, J.F., and Rossato, A.,1997, Multidisciplinary correlative evidence for polyphase geological evolution of the foot-hills of the Cordillera Oriental (Colombia). IV Simposio Bolivariano “Exploaración Petrolera en la Cuencas Subandinas”, v. 1, p. 119-128.

Chopra, S., Marfurt, K., 2007, Seismic curvature attributes for mapping faults/fractures, and other stratigraphic features. CSEG RECORDER, November issue, p. 38-41.

Cooper, M.A., Addison, F.T., Alvarez, R., Coral, M., Graham, R.H., Hayward, A.B., Howe, S., Martinez, J.,Naar J., R. Peñas, R., Pulham, A.J., and A. Taborda, A., 1995, Basin development and tectonic history of the Llanos basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia. AAPG Bulletin, v. 79, no. 10, p. 1421–1443.

Corredor, F., 2012, Integration of 3D seismic and advanced structural modeling in the interpretation of segmented extensional fault systems in the Llanos basin, Colombia. Special Publication, ACGGP, p. 1-6.

Davies, R.J., Posamentier, H.W., Wood, L.J., Cartwright, J.A., 2007, Seismic geomorphology: Applications to Hydrocarbon Exploration and Production. Geological Society Special Publication, no. 277.

Delgado, A., Mora, A., Reyes-Harker, A., 2012, Deformation partitioning in the Llanos foreland basin during the Cenozoic and its correlation with mountain building in the hinterland. Journal of South American Earth Sciences v. 39, p. 228-244.

Dengo, C. A., Covey, M. C., 1993, Structure of the Eastern Cordillera of Colombia: Implications for trap styles and regional tectonics. AAPG Bulletin v. 77, no.8, p. 1315-1337.

Ecopetrol S.A., 1995, Cuenca de los Llanos Orientales, estudio geologico regional, Special Publication for Ecopetrol by Beicip Franlab, v. 1, p. 1-160.

Escalona, A., 2003, Regional tectonics, sequence stratigraphy and reservoir properties of Eocene clastic sedimentation, Maracaibo Basin, Venezuela. Ph.D Dissertation. The University of Texas at Austin. p. 185-194.

Gamero, M., 1995, The changing course of the Orinoco River during the Neogene: a review. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 123, p. 385-402.

Gómez, E., Jordan, T., Allmendinger, R.W., Cardozo, N., 2005, Development of the Colombian foreland-basin system as a consequence of diachronous exhumation of the northern Andes. Geological Society of America Bulletin, v. 117, no. 9-10; p.1272-1292.

Haq, B.U., Hardenbol, J., Vail, P.R., 1987, Chronology of Fluctuating Sea Levels since the Triassic. Science, v. 235, no. 4793, p. 1156-1167.

Hoorn, C., Guerrero, J., Sarmiento, G., Lorente, M. A., 1995, Andean tectonics as a cause for changing drainage patterns in Miocene northern South America. Geology v. 23, p. 237-240.

Hoorn et al., 2010, Amazonia through time: Andean uplift, climate change, landscape evolution, and biodiversity. Science, v. 330, 927.

Jiménez, H.D., Van der Hammen, T., 2007, Significado geológico y asociaciones palinológicas de las Formaciones Diablo Inferior (Mioceno Tardío) y San Fernando Superior (Mioceno Medio), Piedemonte Cuenca de los Llanos Orientales, Colombia. Ciencias de la tierra, v. 31, no. 121, p. 482-492.

Lynds, R, Hajek, E., 2006, Conceptual model for predicting mudstone dimensions in sandy braided-river reservoirs, AAPG Bulletin, v. 90, no. 8, p. 1273-1288.

Mann, P., Escalona, A., 2006, Sequence-stratigraphic analysis of Eocene clastic foreland basin deposits in central Lake Maracaibo using high-resolution well correlation and 3-D seismic data. AAPG Bulletin, v. 90, no. 4, p. 581-623.

Marfurt, K., Chopra, S., 2012, Curvature attribute applications to 3D surface seismic data. The Leading Edge, July issue, p. 39.

Miall, A.D., 2006, The geology of fluvial deposits- sedimetary facies, basin analysis, and petroleum geology. Springer, New York, p.50-5, 196-229.

Mora, A., Horton, B.K., Mesa, A., Rubiano, J., Ketcham, R.A., Parra, M., Blanco, V., Garcia, D., Stockli, D.F., 2010, Migration of Cenozoic deformation in the Eastern Cordillera of Colombia interpreted from fission track results and structural relationships: implications for petroleum systems. AAPG Bulletin v. 94, p. 1543-1580.

Moreno, C.J., Horton, B.K., Caballero, V., Mora, A., Parra, M., Sierra, J., 2011, Depositional and provenance record of the Paleogene transition from foreland to hinterland basin evolution during Andean orogenesis, northern Middle Magdalena Valley basin, Colombia. Journal of South American Earth Sciences, v.32, p. 246-263.

Muller, J., Di Giacomo, E., Van Erve, A. 1987, A palynologic zonation for the Cretaceous, Tertiary and Quaternary of Northern South America. American Association of Stratigraphic Palynologists Contribution Series, v19, p. 7–76.

Nie, J., Horton, B.K., 2012, Integrated provenance analysis of a convergent retroarc foreland system: U–Pb ages, heavy minerals, Nd isotopes, and sandstone compositions of the Middle Magdalena Valley basin, northern Andes, Colombia. Earth-Science Reviews, v. 110, p.111–126.

Ochoa, D., Hoorn, C., Jaramillo C., Parra, M., De la Parra, F., 2012, The final phase of tropical lowland conditions in the axial zone of the Eastern Cordillera of Colombia: Evidence from three palynological records. Journal of South American Earth Sciences, v.39, p. 157-169.

Organic Geochemistry Atlas of Colombia, 2010, Special Edition, Agencia Nacional de Hidrocarburos (ANH) and Universidad Nacional de Colombia, v. 13.

Osorio, C.A., Guerrero, J.G., Cardona, P.A., 2008, Rompiendo Paradigmas mediante el Uso de la Sísmica 3D, un caso en el Sector del Casanare, Cuenca de los Llanos Orientales, Colombia. Special Publication ACGGP, p. 1-8.

Parra, M., Mora, A., Jaramillo, C., Strecker, M., Veloza, G., 2005, New stratigraphic data on the initiation of mountain building at the Eastern front of the Colombian Eastern Cordillera. 6th International Symposium on Andean Geodynamics (Barcelona), Extended Abstracts, p.567-571.

Parra, M., Mora, A., Jaramillo, C., Strecker, M.R., Sobel, E.R., Quiroz, L., Rueda, M., Torres, V., 2009, Orogenic wedge advance in the northern Andes: evidence from the Oligocene-Miocene sedimentary record of the Medina Basin, Eastern Cordillera, Colombia. Geological Society of America Bulletin, v. 121, p780-800.

Parra, M., Mora, A., Jaramillo, C., Torres, V., Zeilinger, G., Strecker, M.R., 2010, Tectonic controls on Cenozoic foreland basin development in the north-eastern Andes, Colombia. Basin Research, v. 22, p.874-903.

Partyka, G., Gridley, J., Lopez, J., 1999, Interpretational applications of spectral decomposition in reservoir characterization. The Leading Edge, p. 353-360.

Pestman, P., Santosh, G., Melendez, L., Lorente, M.A., 1998, Marco tectonoestratigrafico y paleogeografico de la Cuenca de Marcaibo y areas vecinas durante el Paleogeno. Sociedad Venezolana de Geologia, v. 23, no. 1, p. 28-45.

Posamentier, H. W., Allen, G. P. 1999, Siliciclastic sequence stratigraphy: concepts and applications: SEPM Concepts in Sedimentology and Paleontology, v. 9, 210 p.

Reijenstein, H. M., 2008, Seismic Geomorphology and High-Resolution Seismic Stratigraphy of Inner Shelf Fluvial, Deltaic, and Marine Sequences, Gulf of Thailand. M.S. Thesis. University of Houston.

Restrepo-Pace, P.A., F. Cediel, 2010, Northern South America basement tectonics and implications for paleocontinental reconstructions of the Americas: Journal of South American Earth Sciences, v. 29, p. 764-771.

Rosgen D., 1994, A classification of natural rivers. Catena, v.22, p. 169-199.

Santos, C., Jaramillo C., Bayona G., Rueda M., Torres V., 2008, Late Eocene marine incursion in north-western South America. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 264, p. 140–146.

Saylor, J.E., Stockli, D.F., Horton, B.K., Nie, J., Mora, A., 2012, Discriminating rapid exhumation from syndepositional volcanism using detrital zircon double dating: Implications for the tectonic history of the Eastern Cordillera, Colombia. Geological Society of America Bulletin, v. 39, p. 202-215.

Sepm Strata, Gamma ray facies, <http://test.seedtechnologies.com/sepmstrata/ page.aspx?pageid=168> Accessed December 3, 2012.

Slingerland, R., Smith, N., 2004, River avulsions and their deposits. Annual Revision Earth Planetary Science, v. 32, p. 257–285.

Torres, M.A, Porta, R., Brisson, I., 2001, Applications and developments of sequence stratigraphy in Latin America: synthesis of exploration and development experiences in the Sub-Andean Basins. Conference Paper, Society of Petroleum Engineers, no. 69446, p. 1-8.

Van der Hammen, T., 1961, Late Cretaceous and Tertiary stratigraphy and tectogenesis of the Colombian Andes. Geologie en Mijnbouw, v.40, p.181-188.

Villamil, T., 1999, Campanian–Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 153 pp. 239–275.

Villegas, M. E., Bachu, S., Ramon, J.C., Underschultz, J.R., 1994, Flow formation waters in the Cretaceous-Miocene succession of the Llanos Basin, Colombia: AAPG Bulletin, v. 78, p. 1843-1862.

Yu, H., Huang, Z.Y., 2006, Intraslope basin, seismis facies and sedimentary processes in the Kaoping Slope, Offshore Southwestern Taiwan. Terrestrial Atmospheric and Oceanic Sciences Publication, v. 17, no. 4, p. 659-677.

Zeng, H, 2004, Seismic geomorphology-based facies classification. The Leading Edge, v. 23, no. 7, p. 644-646.