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PALEOCENE-MIDDLE MIOCENE FLEXURAL-MARGIN MIGRATION OF THE NONMARINE LLANOS FORELAND BASIN OF COLOMBIA

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A foreland basin is a dynamic system whose depositional systems migrate in response to changes in tectonic uplift patterns, sedimentary filling processes and isostatic rebound of the lithosphere. The Paleocene-middle Miocene foreland system of the Llanos foothills and Llanos basin of Colombia includes regional unconformities, abrupt changes in lithology/stacking patterns and flooding surfaces bounding reservoir and seal units. Here we integrate a systematic biostratigraphic study, stratal architecture and tectonic subsidence analyses, regional seismic profiles, and provenance data to define the diachronism of such surfaces and to document the direction of migration of foreland depozones.

In a flexurally-deformed basin, sandstone composition, rates of accommodation and sediment supply vary across and along the basin. We show how a coeval depositional profile in the Llanos foothills-Llanos foreland basin consists of litharenites interbedded with mudstones (seal rock, supplied from the orogenic front to the west) that correlate cratonward with organic-rich mudstones and coal (source rock), and to amalgamated fluvial-estuarine quartzarenites (reservoir rock, supplied from the craton to the east) adjacent to a subaerial forebulge (unconformity). This system migrated northward and eastward during the Paleocene, westward during the early-middle Eocene, and eastward during the Oligocene. In the lower-middle Miocene succession of the Llanos basin, identification of flooding events indicates a westward encroaching of a shallow-water lacustrine system that covered an eastward-directed fluvial-deltaic system. A similar process has been documented in other basins in Venezuela and Bolivia, indicating the regional extent of such flooding event may be related to the onset of Andean-scale mountain-building processes.

Keywords: *nonmarine foreland, sequence stratigraphy, Colombia, Andes, tectonics, depositional system, biostratigraphy analysis, subsidence, paleocene, miocene, Mirador formation, Barco formation, Llanos Orientales.*

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Una cuenca de antepaís es un sistema dinámico cuyos sistemas deposicionales migran en respuesta a cambios en los patrones de deformación, relleno de cuenca y rebote isostático de la litosfera. La cuenca de antepaís de los Llanos Orientales de Colombia incluye registro del Paleoceno-Mioceno medio con discordancias regionales, cambios abruptos de patrones de apilamiento/litologías, y superficies de inundación, limitando unidades reservorios y sellos. En este estudio integramos análisis de bioestratigrafía, arquitectura estratigráfica, subsidencia tectónica, perfiles sísmicos regionales y procedencia para definir el diacronismo de dichas superficies y para documentar la dirección de migración de los sistemas deposicionales en una cuenca antepaís.

En una cuenca flexural, la composición de las areniscas, los patrones de acomodación y aporte de sedimentos varían dentro de la cuenca. Este artículo presenta un perfil deposicional entre el Piedemonte hasta la cuenca de los Llanos el cual incluye litoareniscas interestratificadas con lodolitas (roca sello derivada del frente de deformación) que correlacionan hacia el Este con lodolitas carbonosas y carbón (roca fuente). Siguiendo hacia el Este continúan cuarzo areniscas fluvio-estuarino (roca reservorio derivada de áreas cratónicas) adyacentes a la zona de levantamiento flexural, con exposición subaérea (discordancia). Este sistema migró hacia el Norte y Este durante el Paleoceno, hacia el Oeste durante el Eoceno temprano-medio, y hacia el Este durante el Oligoceno. En la sucesión del Mioceno inferior-medio de los Llanos, la identificación de eventos de inundación indica un avance hacia el Oeste de sistemas lacustre someros, cubriendo el sistema fluvio-deltaico que avanzaba hacia el Este desde el Piedemonte. Un proceso similar ha sido documentado en otras cuencas en Venezuela y Bolivia, indicando la extensión regional de este evento de inundación, el cual puede estar relacionado con el inicio del levantamiento de los Andes.

Palabras clave: *cuenca de antepaís continental, estratigrafía de secuencias, Colombia, Andes, tectónica, sistemas deposicionales, análisis bioestratigráficos, subsidencia, tectónica, Paleoceno, Mioceno, formación Mirador, formación Barco, Llanos Orientales.*

INTRODUCTION

Sequence stratigraphy models have emphasized in the utility of correlating key stratigraphic surfaces with chronostratigraphic value, such as unconformities and marine flooding surfaces (Galloway, 1989; Van Wagoner, Mitchum, Campion, & Rahmanain, 1990), rather than using lithostratigraphic units. The sequence stratigraphic approach has proved to be very powerful along marine to marginal passive-margin basins for defining reservoir units filling incised valleys and for predicting the position of reservoir units in offshore settings (Vail, Mitchum, & Thompson, 1977; Van Wagoner *et al*., 1990). In tectonically-active continental basins, however, upstream river profiles are more vulnerable to tectonic and climate fluctuations, whereas downstream river profiles are more susceptible to sea-level fluctuations (see review in Holbrook, Scott, & Oboh-Ikuenobe, 2006). This paper concentrates on correlation of the Paleocene-middle Miocene succession that includes two reservoir units in the Llanos foothills, the Barco and Mirador formations. These fluvial units accumulated in upstream settings and at the migrating boundary of the forebulge-foredeep depozones of the Llanos foothills and Llanos foreland basin of Colombia (Bayona *et al*., 2006).

The flexural geometry of a foreland basin, combined with the lateral changes in rates of accommodation space/sediment supply, makes it possible to correlate the unconformity formed by forebulge uplift with areas where the rate of accommodation space/sediment supply is the highest within the foredeep. The merging of different key stratigraphic surfaces and migration of foreland depozones is well documented by empirical data (Gómez, Jordan, Allmendinger, & Cardozo, 2005a), as well as conceptual (DeCelles & Giles, 1996; Currie, 1997) and numerical (Flemings & Jordan, 1990) models.

In one section or well, depositional sequences in a migrating nonmarine foreland system are recognized on the basis of regional unconformities and changes of facies assemblages with distinctive architectural elements (e.g., low-sinuosity versus high-sinuosity fluvial systems; Currie, 1997). When the foredeep depozone migrates cratonward, the rapid increase of rate of accommodation space and decrease of sediment supply produces the vertical juxtaposition of fine-grained on coarse-grained lithologies due to a rise of base-level position. When foredeep migration occurs in the opposite direction, coarse-grained lithologies unconformably overlie the former depositional sequence due to a base-level drop. Those abrupt changes in lithology/stacking patterns can be identified in outcrop (Céspedes & Peña, 1995; Jaramillo, 1999; Gómez *et al*., 2005a, Bayona *et al*., 2006) or wells (Fajardo, Rojas, Cristancho, & Consorcio G&G Going System, 2000). Spatial and temporal variations of rates of accommodation space/sediment supply in the nonmarine Paleogene Magdalena-Llanos foreland basin of Colombia have been associated with migration of a flexural wave (Gómez *et al*., 2005a, Bayona *et al*., 2006).

This paper determines whether those abrupt changes in lithology/stacking patterns (or "base-level turnarounds" in the terminology of Ramon and Cross, 1997) can be used for correlation of reservoir units between the Llanos foothills and Llanos foreland basin. We focus on compositional and stratal architecture of reservoir units, as well as in abrupt changes in lithology/stacking patterns in units overlying reservoir units. The diachronism of such changes is documented by rigorous palynological analysis of fine-grained strata overlying reservoir beds. Provenance is also addressed by comparing units above and below base-level turnarounds because a compositional variation of framework sand grains may indicate whether tectonic uplift had exposed new source areas in the orogen (Rogers, 1994).

Regional setting and study areas

Three major orogenic belts are the result of the complex interaction of the Nazca, Caribbean and South America plates: the Western Cordillera (WC), the Central Cordillera (CC) and the Eastern Cordillera (EC) (Figure 1). The EC is a doubly vergent thrust belt placing Cretaceous and Paleogene rocks over a thick Cenozoic succession in the Magdalena Valley to the west and the Llanos basin to the east. Paleozoic and other basement rocks are exposed at the axial zone of the Eastern Cordillera (Santander and Floresta massifs) and along the southern Llanos foothills segment (Quetame and Garzon massifs). A summary of geological evolution of the Colombian Andes (Western, Central and Eastern Cordilleras) can be found in Cediel, Shaw, and Cáceres (2003).

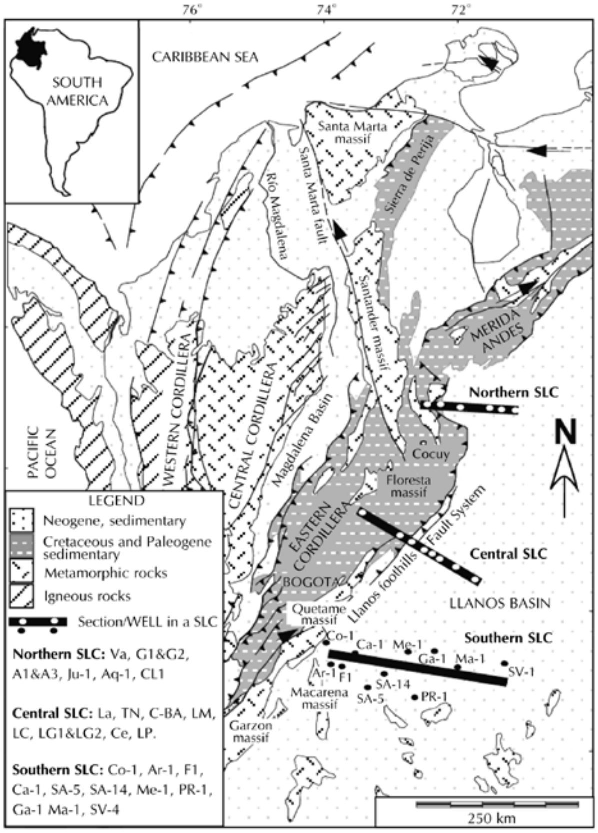

Figure 1. Regional setting of the Eastern Cordillera and Llanos basin, and location of Stratigraphic Lines of Correlation (SLC). Sections/wells are listed from west to east for each SLC. For simplicity, sections and wells were projected to each SLC to construct the stratigraphic correlations shown in Figures 2 to 4. Geographic coordinates of sections and wells are given in Table 1

Several stages of deformation within the EC have been recognized, including deformation in the latest Cretaceous (Branquet, Laumonier, Cheilletz, & Giuliani, 1999; Bayona *et al*., 2006), early Paleogene (Sarmiento-Rojas, 2001; Restrepo-Pace, Colmenares, Higuera, & Mayorga, 2004) and Oligocene (Toro, Roure, Bordas-Le Flonch, Le Cornec-Lance, & Sassi, 2004; Gómez *et al*., 2005a). Previous studies of the Cenozoic evolution of the EC have agreed that: (1) uplift of the CC predated that of the EC (Cooper *et al*., 1995; Gómez *et al*., 2005a), (2) the EC represents the inversion of Mesozoic graben-bounding faults (see a review and details in Mora *et al*., 2006), and (3) the major pulse of rock and surface uplift of the EC occurred in the Late Miocene-Pliocene (Cooper e*t al*., 1995; Toro *et al*., 2004; Gómez *et al*., 2005a).

The Paleocene-Miocene succession in the Llanos foothills and Llanos basin record the filling of a complex nonmarine foreland system that developed since latest Maastrichtian time (Sarmiento-Rojas, 2001; Bayona *et al*., 2006; Cortés *et al*., 2006). The depositional environment changed from dominantly marine during the latest Cretaceous to marginal and continental during the Paleocene. The primary mechanisms driving this shift is the increasing rate of sediment supply associated with exhumation and denudation of the Central Cordillera, according to Gómez *et al*. (2005a). Uplifts or bypassing areas disrupted the Paleocene foreland configuration along the axial zone and eastern borders of the basin (Fabre, 1981, 1987; Sarmiento-Rojas, 2001; Bayona, Cortés, Jaramillo and Llinás, 2003; Restrepo-Pace *et al*., 2004, Cortes, 2004; Bayona *et al*., 2006). Uplifts along the western margin of the basin in Early Eocene time are recorded by an angular unconformity underlying Eocene strata in the Magdalena Valley. For the Late Eocene-Oligocene, Toro *et al*. (2004), Gómez *et al*. (2005a) and Bayona *et al*. (2006) used the evidence of growth-strata patterns, flexural subsidence and thermochronology to document the presence of a western (Magdalena Valley) and an eastern (axial EC-Llanos) depocenters filled with continental and marginal synorogenic strata. There is no record of Miocene strata in the axial zone or on the flanks of the EC, but continental synorogenic deposition continued both in the Llanos (Leon Formation) and Magdalena basins.

Stratigraphic correlation of the paleocene-middle miocene succession

The Paleocene - middle Miocene foreland succession of the Llanos foothills and Llanos basin includes, in stratigraphic order, the Barco, Cuervos, Mirador, Carbonera and Leon formation. At least eight flooding and unconformities surfaces (Cooper *et al*., 1995) or 12 base-level turnarounds (Reyes *et al*., 1991; Fajardo *et al*., 2000) have been identified in the eastward-thinning clastic wedge of the Llanos basin (Cooper *et al*., 1995). These studies proposed that the Paleocene Barco Formation and the Eocene Mirador Formation, the reservoir units in the Llanos foothills, are bounded at the base by an unconformity (or an abrupt decrease of accommodation space/sediment supply rates) and at the top by a flooding surface (or an abrupt increase of accommodation space/sediment supply rates). In the Llanos basin, sandstones of

Table 1. Palynological analysis carried out at different sections/wells in each stratigraphic line of correlation (SLC). Only palynological samples with more of 50 grain counts were used to calculate the percentage of marine influence (sum of dinoflagellate, foram linings and marine acritarcha over the total number of palynomorphs)

Section (*)/ Well	Geographic coordinates North (°)	Geographic coordinates West (°)	Total of samples analyzed rock sample	Total of samples analyzed ditch cutting	Samples with >50 points rock sample	Samples with >50 points ditch cutting	Interval sampled
Northern SLC							
Va*	7,16	72,45	81		31		Maastrichtian-Eocene
G1	7,04	72,17		125		84	Eocene-Oligocene
G2	7,04	72,17		132		103	Oligocene-Miocene
A1	6,95	71,85		16		17	Campanian-Oligocene
A3	6,98	71,82	1	3	30	31	Turonian-Miocene
CL1	6,94	71,13		4		4	Campanian-Oligocene
Central SLC							
La (Paz de Rio)*	6,02	72,74	27		18		Middle Eocene - mid-Oligocene
La (Cosgua)*	5,93	72,78	24		18		Paleocene-Middle Eocene / Pardo (2004)
TN (Q. San Antonio)*	4,84	73,21	15		15		Maastrichtian-Paleocene / Guerrero and Sarmiento (1996)
TN (Q. Piñalerita)*	4,96	73,04	69		39		Paleocene-Eocene / Jaramillo (1999); Jaramillo and Dilcher (2001); Jaramillo (2002)
TN (Q. Guadualera)*	4,8	73,19	55		44		Late Eocene - mid-Oligocene
C	5,11	72,66	111		55		Turonian-Eocene
BA	4,98	72,74		76		75	Oligocene-Miocene
BA	4,98	72,74	144		124		Turonian-Eocene
LM	5,07	72,51		14		2	Campanian-Oligocene
LC	5,05	72,45		11		6	Campanian-Oligocene
LG	5,03	72,35		22		15	Campanian-Oligocene
LG	5,03	72,35	2		2		Oligocene
Ce	4,9	72,25		13		3	Campanian-Oligocene
LP	4,81	72,08		22		12	Campanian-Oligocene
Southern SLC							
Co-1	3,77	73,73		100		62	Turonian-Miocene
Ar-1	3,52	73,69		65		30	Turonian-Miocene
Cu-1 (near Ga-1)	3,79	72,04		34		4	Paleozoic; Oligocene-Miocene
SA-5	3,25	73,23		47			Eocene-Miocene
Ca-1	3,64	73,4		13			Paleozoic; Oligocene
SV-4	3,53	71,64		11			Paleozoic; Oligocene-Miocene
SA-10	3,06	72,83		27			Paleozoic; Oligocene-Miocene
SA-14	3,4	73,05		56		43	Oligocene-Miocene
PR-1	3,12	72,7		32		20	Miocene

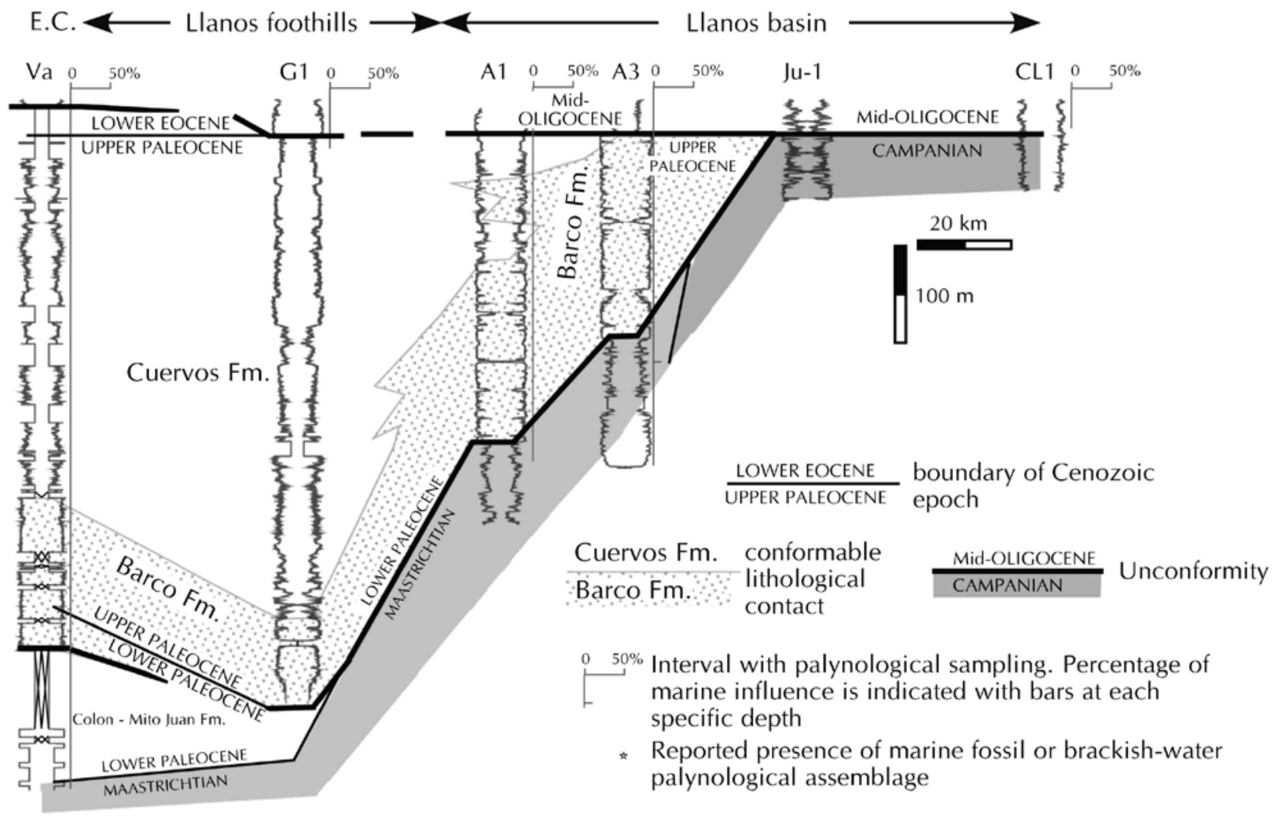

Figure 2. Correlation of Paleocene strata along the northern SLC. See Figure 1 for sections locations and codes. Datum is at the uppermost record of Paleocene strata. Gamma-ray profiles or grain-size trends are duplicated for each section/well. Sandstone beds of the Barco Formation correlate westward with fine-grained strata of the Cuervos Formation. In an eastward (basinward) direction, younger strata onlap older strata as predicted by the migration of depozones in a foreland basin

the lowermost Carbonera Formation overlie Paleocene strata or the basal Cenozoic unconformity in distal settings (Jaramillo *et al*., 2007).

We studied the Paleocene-middle Miocene succession along three Stratigraphic Lines of Correlation (SLC), named the northern, central and southern SLC (Figure 1), in order to characterize the regional extent and stratigraphic significance of those base-level turnarounds in the Llanos foothills and Llanos basin. Key sedimentological, vertical stacking patterns, framework sandstone composition, and paleontological (pollen-spore-dinoflagellate, foraminifera, macrofossils content) data were analyzed for a total of 21 wells using electric logs, cores and cuttings. Three composite stratigraphic sections on the Llanos foothills and axial zone of the Eastern Cordillera were constructed to link depositional systems between the Llanos foothills and Llanos basin. One thousand three hundred fifty two palynological samples from wells and outcrops were analyzed to support stratal correlations (Table 1; see details for construction of the Cenozoic palynological zonation in Jaramillo & Rueda 2004; Jaramillo, Muñoz, Cogollo, & Parra, 2005). All the above data, in conjunction with the vertical arrangement of lithofacies, provide the support for the interpretation of depositional environments.

Major unconformities and Miocene flooding surfaces were selected mainly as stratigraphic datums for stratigraphic correlations presented in Figures 2 to 4. Stratigraphic descriptions focus on intervals of change in lithology/stacking patterns. From base to top these intervals are: the Barco-Cuervos contact, the Cuervos-Mirador contact, the Mirador-Carbonera contact, lower and upper contacts of basal Carbonera sandstones in the Llanos basin, and changes across Lower and Middle Miocene flooding surfaces. In order to understand the

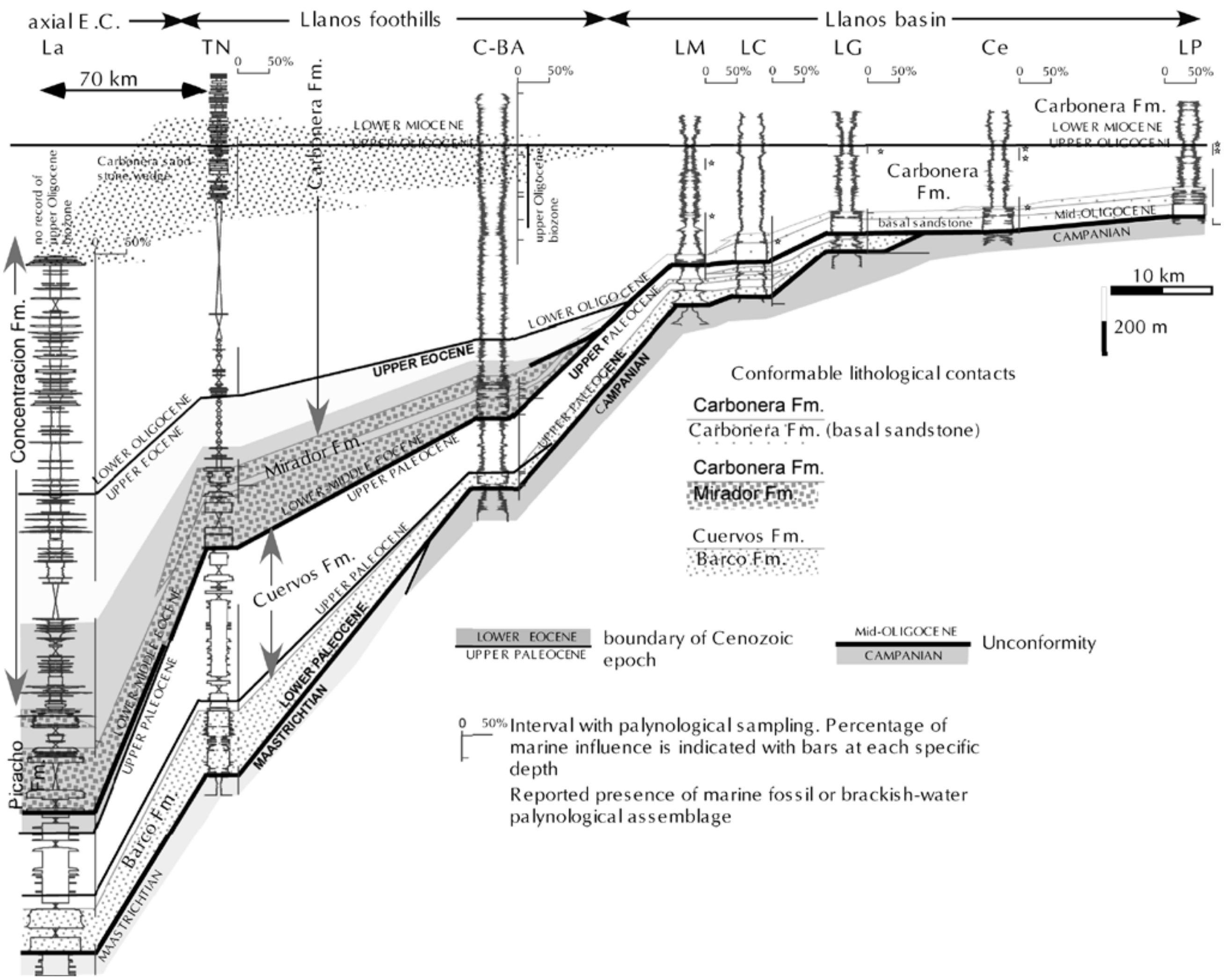

Figure 3. Correlation of Paleocene to Oligocene strata along the central SLC. See Figure 1 for location and code definition of sections. Note change of scale to the west of the Llanos foothills. Datum is uppermost oligocene strata. gamma-ray profiles or grain-size trends are duplicated for each section/well. There are no Eocene strata in the Llanos basin, whereas in the axial zone of the EC the thickness reaches approximately 900 m. Basal sandstone beds of the Carbonera Formation on the Llanos basin correlate with thick fine-grained strata of the Carbonera Formation in the Llanos foothills. See Figure 8 for chronostratigraphic correlation

diachronism of changes in lithology/stacking patterns within the Paleocene-middle Miocene succession, we used our palynological control as a guide to the placement Cenozoic epoch boundaries (e.g. lower Paleocene/ upper Paleocene; Oligocene/Miocene), as precisely as age resolution allowed.

Barco-Cuervos and Cuervos-Mirador contacts

Distribution and age. The Barco and Cuervos formations (or Lower Socha-Upper Socha formations in the axial zone of the Eastern Cordillera) comprise the lowermost nonmarine foreland succession in the Llanos foothills and Llanos basin. The Barco Formation unconformably overlies fine-grained strata of the Colon-Mito Juan Formation (or Guaduas Formation in the axial zone of the Eastern Cordillera). The Barco-Cuervos succession is recorded in the northern and central SLC, but coeval strata are truncated 10 - 30 km north of the southern SLC. The Barco-Cuervos succession thins eastward and forms an eastward-stepping stratal package onlapping the basal Cenozoic unconformity in the western Llanos basin. Strata beneath the unconformity are older toward the craton, whereas strata above the unconformity are younger cratonward. The age of the Barco Formation is lower Paleocene in the central SLC and mostly upper Paleocene in the northern SLC. The Upper Paleocene Cuervos Formation correlates eastward in the Llanos basin with the Barco Formation (Figures 2 and 3). Lower Mirador beds accumulated earlier in the Llanos foothills than equivalent sandstones beds in the axial zone of the Eastern Cordillera (Figures 2 and 3).

Lithology and stacking patterns. The Barco Formation rests upon a regional disconformity (Figures 2 and 3). This unit consists of amalgamated quartzose sandstones with sedimentary structures that change upsection from (1) cross-bedded fine- to coarse-grained fining-upward sandstones that are locally conglomeratic in Cocuy (south of northern SLC in Figure 1; Fabre 1981) to (2) interbeds of fining-upward sandstone and mudstone beds, and to (3) bidirectional cross-bedded and bioturbated heterolithic laminated sandstones at the top with organic rich mudstones and coal beds in the Llanos foothills. In the Llanos basin, the Barco Formation changes from aggraded fine-to-coarse-grained sandstones to fining-upward sandstones at the top.

The contact between the Barco and Cuervos formations in the northern and central SLC is marked by an increase of fine-grained lithologies with a dominant aggradational stacking pattern. Lower beds of the Cuervos Formation consist mainly of laminated to locally bioturbated dark-gray organic-rich claystones and mudstones with thin coal seams and pass upsection to fining- and coarsening-upward successions with cross-bedded, ripple and wavy laminated sandstones.

Amalgamated sandstones of the Mirador Formation (or Picacho Formation in the axial zone of the Eastern Cordillera) disconformably overlie mudstones and litharenites of the Cuervos Formation. Sandstone beds are fine- to medium-grained and locally conglomeratic. Sedimentary structures are massive, cross-bedded and wavy-laminated to the top. Thin-to medium-bedded lenses of gray massive sandy mudstones are locally preserved.

Sandstone composition. An upward increase in polycrystalline quartz and unstable lithic fragments has been documented from quartzarenites to sublitharenites in the Barco - Lower Socha units, and to litharenites in the Cuervos - Upper Socha formations (Fabre, 1981; Jaramillo, Roa, & Torres, 1993; Céspedes & Peña, 1995; Vergara & Rodríguez, 1996; Mesa, 1997, 2003, 2004). Lithic fragments comprise up to the 33% of the framework grains and include mainly sedimentary fragments (siltstones, chert) and a minor component of metamorphic (gneiss, schist, phyllite), and igneous rock fragments. Quartzarenite composition dominates in lower Mirador Formation sandstone beds (Mesa, 1997, 2004), but Cretaceous foraminifera fragments occur locally in the matrix of conglomerates (Céspedes & Peña, 1995) and chert, argillaceous, gneiss, schist and igneous fragments (Mesa, 1997, 2004) have been reported.

Palynological association. In the axial zone of the EC, the Lower Socha Formation includes continental palynofloras (angiosperms, mostly palms) (Pardo, 2004). In the Llanos foothills, palynofloras in the Barco Formation are dominated by very few species, with Nypa pollen (a brackish-water palm) as the most common element. Few dinoflagellates grains were reported in the Llanos foothills of the central SLC near the top of the Barco Formation (well C&BA in Figure 3). Lower beds of Cuervos and Upper Socha formations are dominated by a low-diversity assemblage composed mainly of palms, Araceaea, Proteaceae, Bombacacae and legumes suggesting a forest with tropical affinities. At the Lower Socha-Upper Socha contact, the pollen content increases significantly (Pardo, 2004), whereas morphospecies diversity increases at the Cuervos-Mirador contact (Jaramillo *et al*., 2006).

Depositional environment. The vertical arrangement of lithofacies and palynological association of the Barco-Cuervos-Mirador succession has been interpreted as product of deposition in fluvial systems. The uppermost Barco sandstones show more fluvial influence in the axial Eastern Cordillera than in the Llanos foothills; in the latter area, bi-directional cross beds, heterolithic lamination (Cazier *et al*., 1995; Reyes, 1996) and few dinoflagellate grains suggest more tidally-influenced deposition. The Cuervos-Upper Socha accumulated in coastal plains with more estuarine influence toward the Llanos foothills. The excellent pollen recovery in lower beds of the Cuervos and Upper Socha units suggest a very humid environment with small fluctuations of the water table that was near the surface (Pardo, 2004).

Summary. The Barco-Cuervos succession comprises a conformable fluvial-coastal plain package bounded by two disconformities (or abrupt decrease of accommodation/sediment supply rate). This succession is an eastward-stepping stratal package onlapping the basal Cenozoic unconformity. Amalgamated quartzose sandstone beds overlie the lower (Barco Formation) and upper (Mirador Formation) disconformities, but Barco sandstones are younger eastward, whereas Mirador sandstones are younger westward. The Barco-Cuervos contact is younger cratonward and records (1) an abrupt increase of accommodation space, and (2) input of sedimentary and metamorphic lithic fragments to the coastal plain system. The Barco-Cuervos contact records the lateral migration of depositional environments, whereas the Cuervos-Mirador contact records an abrupt decrease of accommodation/sediment supply rate within a continental setting.

Mirador-Carbonera contact in the Llanos foothills; lower and upper contacts of the basal Carbonera sandstones in the Llanos basin

Distribution and age. Strata of lower and middle Eocene age (Mirador and Picacho formations) are reported only to the west of the Llanos foothills (Jaramillo *et al*., 2007) (Figure 3). Upper Eocene strata include the contact between the Mirador-Carbonera formations in the Llanos foothills (or the Picacho-Concentracion formations in the axial Eastern Cordillera). In the Llanos basin, either a basal sandstone or fine-grained successions of the Carbonera Formation unconformably cover Paleocene and Campanian beds in the northern and central SLC (Figures 2 and 3), and Upper Cretaceous and Paleozoic beds in the southern SLC (Figure 4). The age of lower Carbonera strata is younger northward and eastward and varies from late Eocene to mid-Oligocene. Oligocene foreland deposits of the Carbonera Formation formed a wedge-like basin geometry; the thickness of Oligocene strata in the Llanos basin is at least half of the thickness preserved in the Llanos foothills (Figures 3 and 4). Upper Oligocene strata completely covered the Llanos basin with exception of distal uplifted blocks in the southern Llanos basin (Figure 4).

Lithology and stacking patterns. Lithofacies associations of the upper Mirador Formation vary along the Llanos foothills. In the northern SLC, the upper Mirador sandstones show complete fining-upward successions and coal interbeds (Reyes, 2004). In the Llanos foothills of the central SLC, fine to medium-grained quartzarenites have more interbeds of organic mudstones with plant remains that show evidence of deposition in a brackish-water environment, including: (1) a diverse ichnofacies association (Ophiomorpha, Thalassionoides, Psilonichnus and Diplocraterion; Pulham, Mitchell, MacDonald, & Daly, 1997), (2) couplets in foreset laminations, and (3) wavy and flaser lamination. Overlying Carbonera strata in the Llanos foothills of the northern and central SLC consist dominantly of 250 m-thick dark green and gray laminated and poorly bioturbated mudstones (Jaramillo, 1999; Jaramillo & Dilcher, 2001; Mora & Parra, 2004) grading to coarsening-upward successions (Figure 3).

In the Llanos basin, the basal sandstone of the Carbonera Formation consists of amalgamated to fining-upward successions of fine- to coarse-grained quartzarenites, locally conglomeratic. In the central SLC, both the thickness of this basal sandstone and the thickness of the sandstone-mudstone transition increase eastward (Figure 3). In the southern SLC, the thickness increases eastward up to >100 m (wells F1 and Ca-1 in Figure 4), and decreases farther east. The thickness changes are attributed to the filling of incised valleys or onlap over structural highs (e.g., Las Brujas high). Dark-colored mudstones, shales and thin coal interbeds diachronously overlie these basal sandstones. At the western segment of the southern SLC, this fine-grained interval is followed by a fining-upward succession, which is not present in any other area.

Sandstone composition. Sandstone of the Mirador Formation and the basal sandstones of the Carbonera are quartzarenites (Mesa, 1997, 2004). The lower half of the Carbonera Formation is comprised of quartzarenites and sublitharenites (Fabre 1981; Moreno & Velásquez 1993; Cardona & Gutiérrrez 1995). In the axial zone of the Eastern Cordillera, conglomerate beds of the Concentracion Formation contain chert and fossiliferous limestones of Cretaceous age (Reyes & Valentino 1976).

Palynological association. Palynoflora assemblages of the upper Mirador and lower Carbonera in the Llanos foothills are very similar to each other. The Eocene-Oligocene boundary is well documented by a large extinction of palynomorphs (Jaramillo *et al*., 2006). Palynological samples from the Upper Mirador

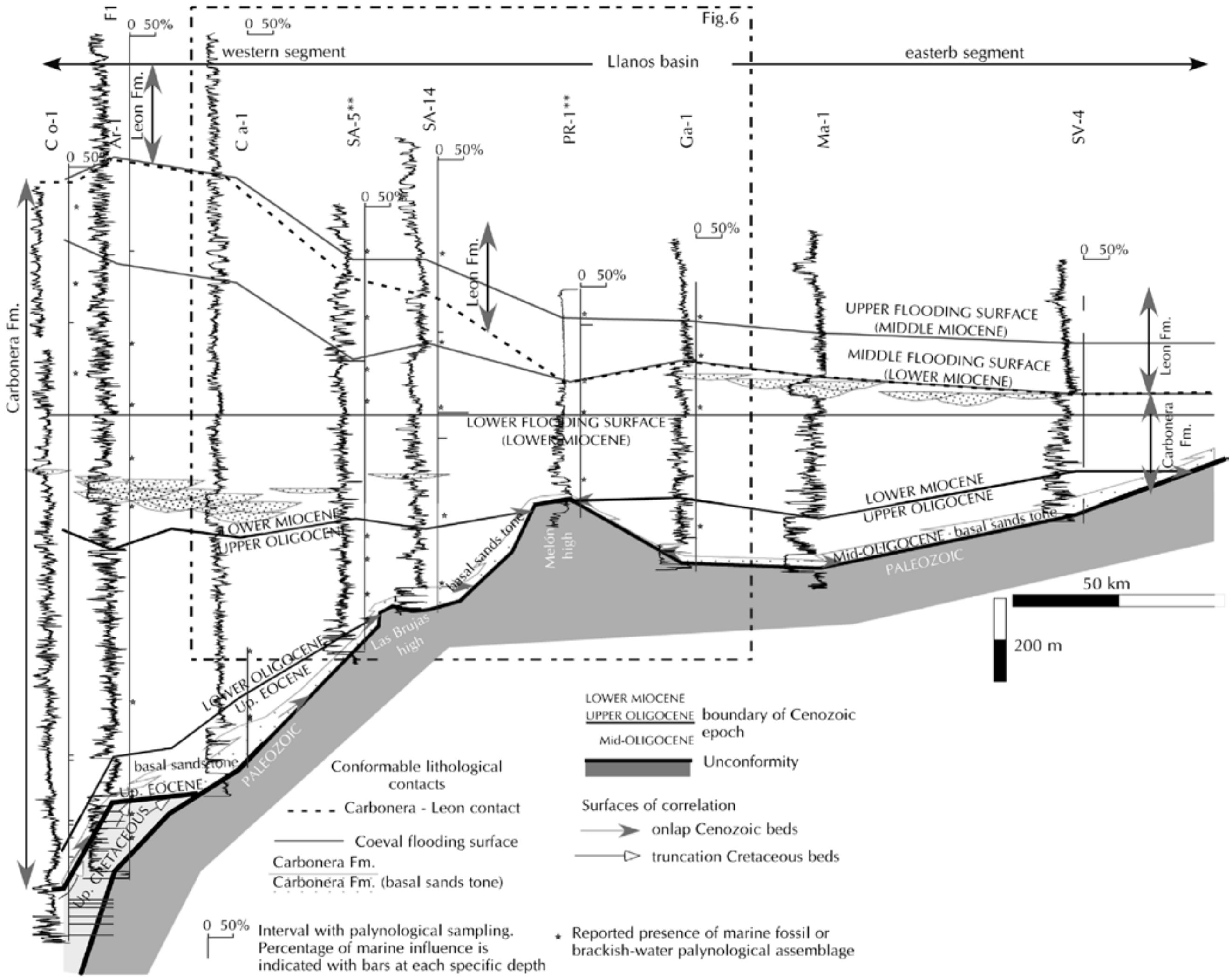

Figure 4. Schematic correlation of upper Eocene - middle Miocene strata using 10 wells projected along the southern SLC (**wells SA-5 and PR-1 are more than 40 km from SLC and are used only for reference). See Figure 1 for section locations and codes. Datum is the lower marine flooding surface of early Miocene age. Gamma-ray profiles are shown for each well, except for PR-1 which shows the spontaneous potential profile and F1 which shows a resistivity log. Basal sandstone beds of the Carbonera Formation on the eastern segment correlate with thick fine-grained strata of the Carbonera Formation in the western segment. Note lateral change of gamma-ray profiles in the correlation of the flooding surface

in the central SLC indicate a marine influence that ranges from 10 to 30%. Samples from the lowermost Carbonera Formation in the western side of the southern SLC (wells Co-1 and Ar-1), in the axial zone of the Eastern Cordillera and Llanos foothills of the central SLC (sections La and TN) and in the Llanos foothills of the northern SLC (well G1&G2) indicate marine influence of 10% or less. In the Llanos basin there are only isolated occurrences of brackish-water palynological assemblages to the top of the basal sandstone and algae colonies in the southern Llanos basin.

Depositional Environment. Upper Mirador sandstones have been interpreted as fluvial channels and mouth-bar sands deposited on a coastal plain in the central Llanos foothills (Cazier *et al*., 1995; Fajardo, 1995; Warren & Pulham, 2001), with more continental influence in the northern Llanos foothills (Reyes, 2004). Lithological associations of lowermost Carbonera beds in the Llanos basin have been interpreted as a change from channel-fill processes in fluvial systems to tidally-influenced coastal plains and delta bays to the top of the basal sandstones (Fajardo *et al*., 2000).

Summary. Quartzose sandstones of the Mirador Formation in the Llanos foothills and the basal sandstones of the Carbonera Formation in the Llanos basin overlie two different stratigraphic surfaces. The former unit disconformably overlies Paleocene strata, whereas the latter is an eastward-stepping stratal package that onlap the basal Cenozoic unconformity in the Llanos basin. The nature of the upper contacts of these sandstone units also differ. The Carbonera-Mirador contact in the Llanos foothills area shows evidence of a late Eocene marine transgression, as documented by ichnofossils and paleontological data. In contrast, the upper contact of the basal sandstones in the Llanos basin is more transitional, and the overlying fine-grained strata only show evidence of eastward and northward migration of coastal-plain environments.

Lower and Middle Miocene flooding surfaces of the upper Carbonera-Leon formations

Distribution and age. Strata deposited during early and middle Miocene time correspond to the upper Carbonera and Leon formations in the Llanos foothills and Llanos basin. Sandstones of the upper Carbonera record the last pulses of pre-Andean deformation, whereas shales of the Leon Formation record a basin-wide flooding event during the Middle Miocene. The Carbonera-Leon contact is defined by the onset of fine-grained deposition that occurred earlier in the eastern Llanos basin than in the Llanos foothills (Figure 4).

Lithology and stacking patterns. In the Llanos foothills of the northern and central SLC, lower Miocene Carbonera strata consist of coarsening-upward successions that begin with laminated mudstones grading to tabular and wavy laminated, locally bioturbated, fine-grained sandstones (Fajardo *et al*., 2000). In the central Llanos foothills, these successions include coal interbeds, feldspar-bearing fine-grained muddy sandstones and locally conglomeratic massive to cross-bedded sandstones (Mora & Parra, 2004).

In the northern and central Llanos basin, fining- and coarsening-upward successions constitute the Carbonera Formation. This unit grades eastward to a finer-grained succession. In the southern SLC, upper Carbonera strata change from coarsening-upward successions, which include calcareous mudstones to the south and east, to variable grain-size trends toward the western margin (Figure 4).

Lower strata of the Leon Formation consist of wavy laminated, bioturbated, and varicolored mudstones interbedded with tabular-bedded, bioturbated quartzarenites (Geoestratos-Dunia, 2003) in the Llanos foothills. In the Llanos basin, lower Leon strata consist of a thick interval of dark-colored laminated mudstones and shales. Sandstone interbeds in the Leon Formation increase northward and westward (Cooper *et al*., 1995; Fajardo *et al*., 2000).

Sandstone composition. Compositional analysis of well cuttings indicates an increment of feldspar and lithic fragments, and the sandstones at the western margin of the Llanos basin are compositionally more immature than sandstones at the eastern margin of the basin.

Palynological association. Poaceae and Mauritia (monostand palms commonly found of riparian forests) dominate the assemblage in upper Oligocene strata, suggesting development of savannas. Lower-middle Miocene palynofloras have a lower diversity than Eocene-lower Oligocene palynofloras. In some fine-grained intervals in the upper Carbonera and at the Carbonera-Leon contact, fresh-water (lacustrine algae), but also brackish-water palynological associations, dinoflagellate cysts and foraminifera test linings are observed (Figure 4), and contributed to the evidence for defining flooding events in the lower-middle Miocene strata. Samples from these levels have been analysed for foraminifera and thecamoebians content, showing strong evidences of alternating fresh to brackish-water conditions (Flavia Fiorini, STRI post-doctoral fellow, personal communication, 2007). Therefore, flooding surfaces were identified in wells on the basis of biostratigraphic data and the shale signature at the base of coarsening-upward successions in gamma-ray profiles.

Depositional Environment. The northward and eastward lateral change of depositional patterns in the upper Carbonera Formation supports an interpretation of an eastward-prograding fluvial-dominated delta plain that developed into a coastal plain (or savannas) and a coeval shallow lacustrine system in the Llanos basin to the east (Mora & Parra, 2004). The lacustrine system was bounded on the east by a fluvial system draining the Guyana craton, and it eventually has an influx of brackish-waters. The change of pattern of deposition and depositional environments from Carbonera to Leon beds indicates a westward flooding of a broad fluvial-deltaic system followed by regional onset and establishment of fresh shallow-water (lacustrine) environments with less estuarine influence than that reported in Eocene strata.

Summary. Fluvial-deltaic depositional systems of the lower Miocene Carbonera formation advanced eastward, transporting synorogenic detritus toward shallow lacustrine environments. Fluvial systems draining the Guyana craton also supplied detritus into the lacustrine setting. Westward-stepping and encroaching of fine-grained lacustrine deposits indicate a decreasing influx of synorogenic detritus and an increase of accommodation space in the Llanos basin.

SEISMIC IMAGES OF STRATIGRAPHIC SURFACES

Seismic facies, unconformity surfaces, and onlap/truncations of reflectors were identified on 2D seismic reflection profiles. Unconformities, abrupt changes in lithology/stacking patterns and flooding events identified in wells were tied to seismic reflectors and traced regionally along composite seismic lines. Upper Paleocene Barco-Cuervos strata in the northern SLC are defined as discontinuous seismic reflectors onlapping onto an unconformity toward the eastward trend (Figure 5). The unconformity underlying Carbonera strata in the Llanos basin is identified by truncation of seismic reflectors (Figure 5).

Strong seismic reflectors in the southern SLC can be traced for several tens of kilometers, providing op-

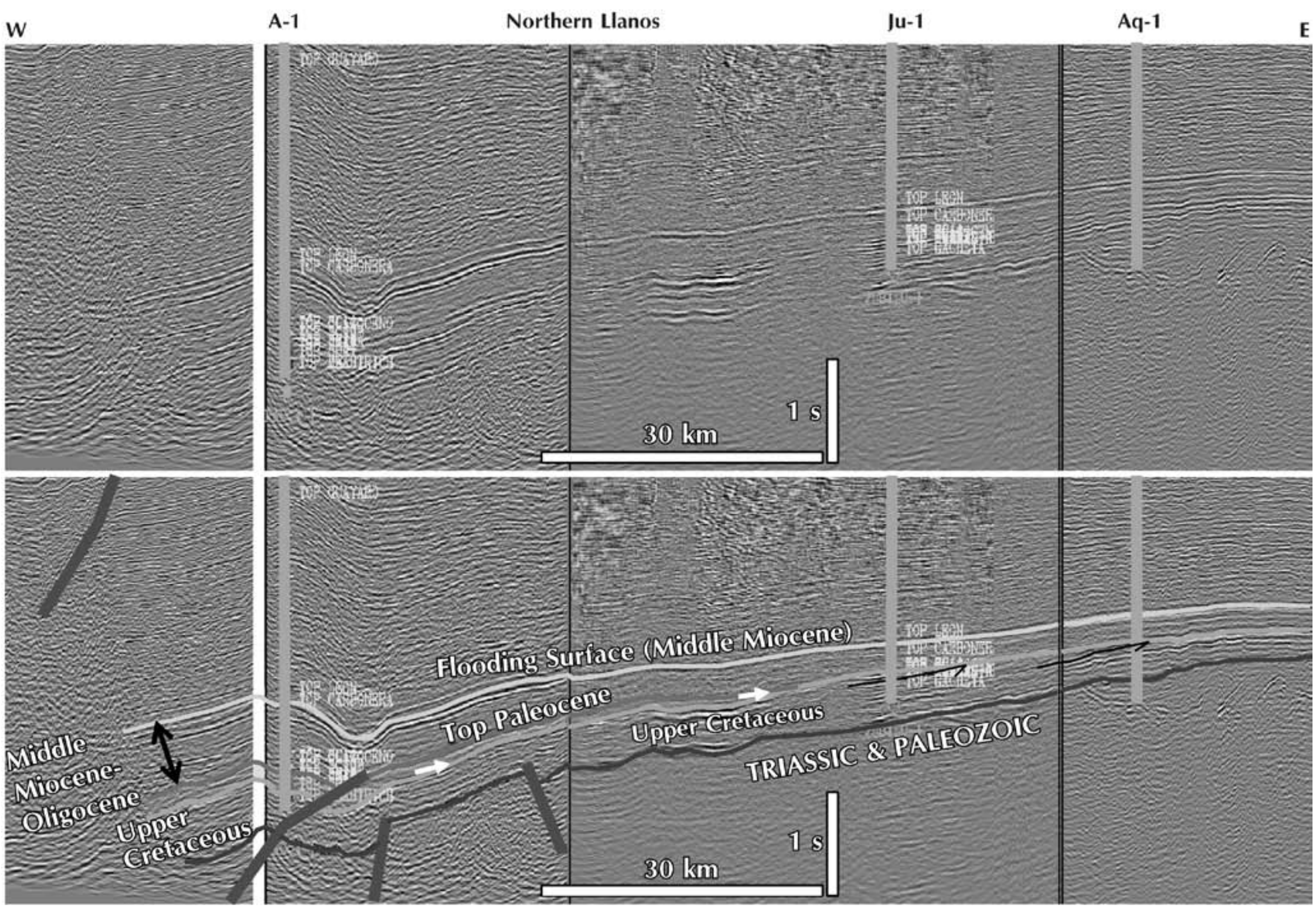

Figure 5. Composite seismic line along the northern SLC. See Figure 1 for location and code definition of sections. These seismic images show the onlap of upper Paleocene strata, truncation of upper Cretaceous beds, and the lateral continuity of the middle Miocene flooding surface (top of the Carbonera Formation)

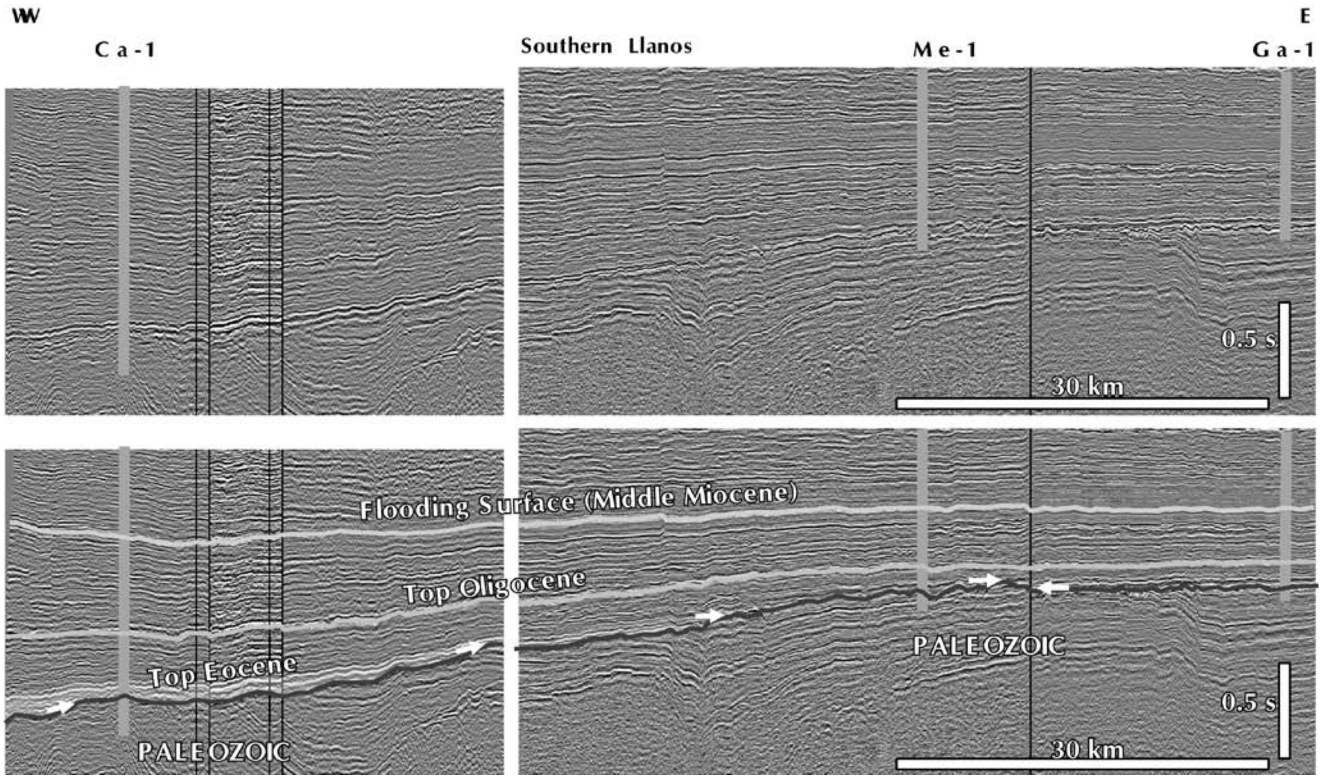

Figure 6. Composite seismic line along the southern SLC. See Figure 1 for location and code definition of sections. These seismic images show the onlap of upper Eocene and Oligocene strata, Paleozoic structures beneath the unconformity (no interpreted here), eastward thinning of synorogenic strata, and the lateral continuity of seismic reflectors corresponding to lower and middle Miocene strata. Only two surfaces are shown for simplicity, the first at the top of the Oligocene, and the other at the middle Miocene flooding surface of Figure 4. Note the lateral change of seismic facies above and below the middle Miocene flooding surface

portunities to decipher onlap of seismic reflectors and lateral continuity of seismic facies. The eastward onlap of reflectors of the diachronous basal sandstone and mudstones of the lower Carbonera Formation can be traced laterally for several tens of kilometers (Figure 6). In the eastern side of Figure 6, reflectors corresponding to lower Miocene strata tend to be more continuous. The uppermost continuous reflector corresponds to the Carbonera-Leon contact that separates a seismic stratigraphy facies of several continuous reflectors from a facies with fewer and more discontinuous reflectors. The former represents the sandstone-mudstone successions of the Carbonera Formation and the latter represents the dominance of fine-grained lithologies of similar acoustic impedance of the Leon Formation. However, when the top of the Carbonera Formation reflector is traced westward, the equivalent reflector on the western side of Figure 6 corresponds to reflectors within the Carbonera Formation.

ONE DIMENSIONAL SUBSIDENCE ANALYSIS AND EUSTASY

Backstripping techniques were used to decompact the measured stratigraphic thickness of each section to define a relation between changes in lithology/stacking pattern and slope configurations of tectonic subsidence curves. We followed the methods specified in Allen and Allen (1992) for construction of tectonic subsidence curves, and we used first-order sea-level curve of Haq, Hardenbol, and Vail (1987) for correction of eustasy.

The results of our one-dimensional backstripping indicate that in most cases the tectonic subsidence curves are not straight lines, suggesting changes in their tectonic subsidence history. The Barco-Cuervos and Mirador-Carbonera contacts do not necessarily coincide with the point of an abrupt increase of tectonic subsidence (Figure 7). The increase of tectonic subsidence

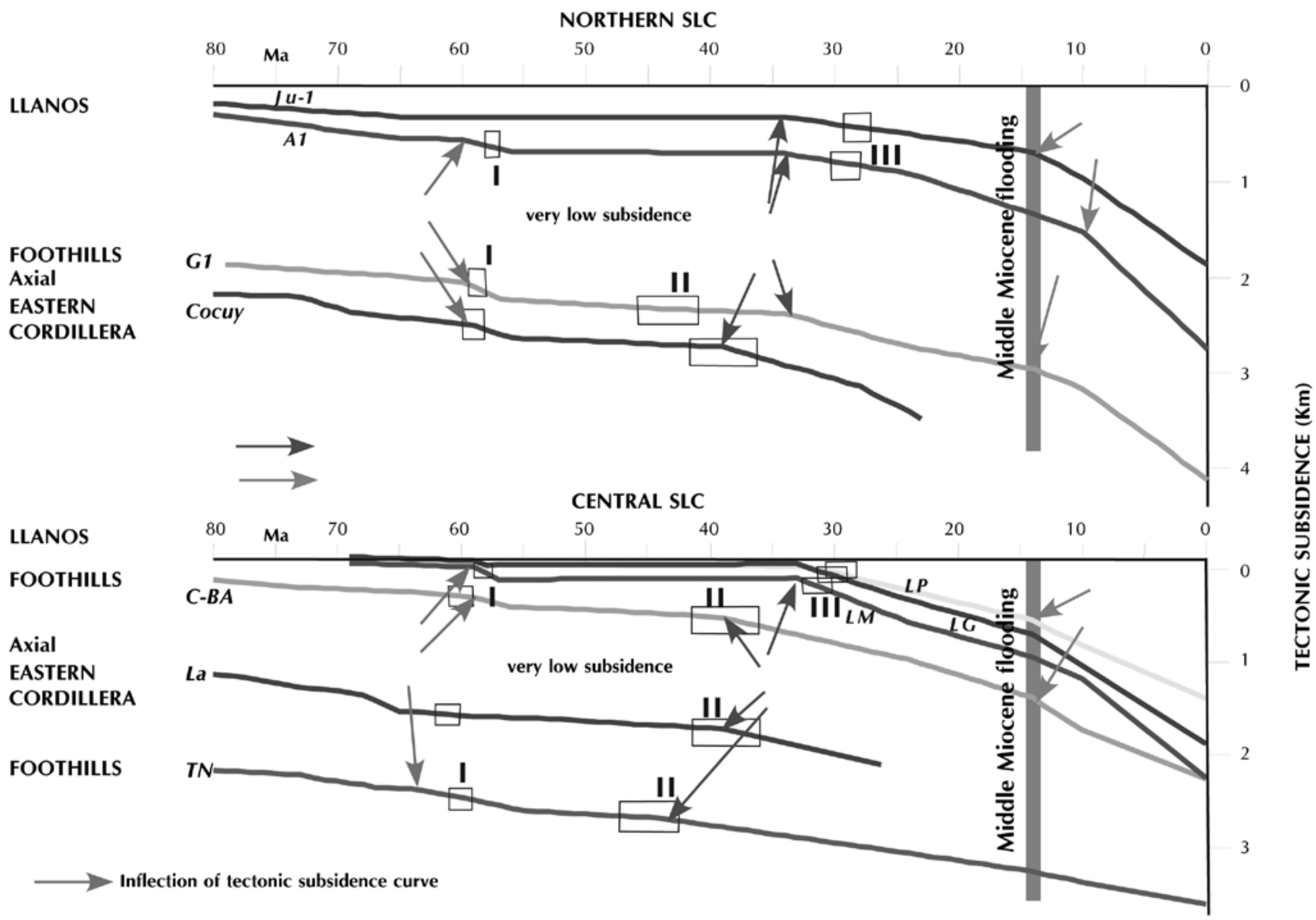

Figure 7. Tectonic subsidence curves for selected wells and sections in the northern and central SLC. Times of increases tectonic subsidence rate are indicated for each curve. Three conformable contacts overlying reservoir units are indicated by rectangles: I Barco-Cuervos contact; II Mirador-Carbonera contact in the llanos foothills and axial zone of the eastern Cordillera; III basal sandstones of the Carbonera Formation on the llanos basin. The width of each rectangle corresponds to the resolution of age for each contact. Note the relation between the event of middle Miocene flooding and the abrupt increase of tectonic subsidence rates

across the Barco-Cuervos contact occurred earlier in the Llanos foothills and axial Eastern Cordillera of the central SLC (59 - 62 my), then advanced to the northern SLC (58 - 60 my), and finally migrated to the Llanos basin at around 57 - 59 my.

The Late Eocene increase in tectonic subsidence and the onset of fine-grained Carbonera/Concentracion deposition become younger basinward. However, fine-grained deposition occurred slightly earlier in the Llanos foothills (Middle-Late Eocene; 41 - 47 my) than in the axial Eastern Cordillera and in the western side of the southern SLC (Late Eocene 36 - 42 my). In the central segment of the southern SLC and in the Llanos basin of the central SLC, fine-grained deposition began in early Oligocene (30 - 33 my), and reached structural highs on the northern and southern Llanos basins at the Oligocene-Miocene boundary (23 - 25 my). A slight increase in the rate of tectonic subsidence occurs nearly at the top of the Carbonera-Leon formations in the Llanos foothills and Llanos basin (aprox. 14 my), and the slope gently increases after 10 my.

DISCUSSION

The Barco and Mirador formations, the two main reservoir units in the Llanos foothills, are bounded at the base by an unconformity and at the top by abrupt changes in lithology/stacking patterns (or base-level turnarounds). Even though these surfaces can be recognized in outcrops, wells and seismic lines, our palynological data indicate that strata overlying those surfaces are diachronous. In addition, changes in stratal architecture and sandstone composition across these surfaces, and the eastward onlap of seismic reflectors on the unconformity may be explained by migration of a flexural basin.

The Paleocene Barco-Cuervos succession and Upper Eocene-Oligocene strata document the cratonward migration of depositional environments as the foredeep depozone migrated eastward. In both cases the onset of sandstone deposition is diachronous and becomes younger eastward (Figure 8). The onlap of seismic reflector on the unconformity and the quartzose composition of sandstone beds indicate accumulation adjacent to the forebulge. At the same time and toward the west, a conformable change from amalgamation of fluvial-estuarine sand bars (reservoir units) to deposition of fine-grained siliciclastic sediments on coastal and flood plains represent the abrupt change in lithology/stacking patterns of fine-grained strata (e.g., Cuervos Formation) overlying those quartzose units (e.g., Barco Formation). These changes are not flooding surfaces, since there is not a marine transgression or accumulation below a deep water column (i.e. a lake). Toward the western side of the foredeep depozone, sedimentary and metamorphic rock fragments in upper Paleocene Cuervos sandstones, and feldspar-bearing sandstones in Oligocene Carbonera strata accumulated adjacent to uplifted hinterland blocks (Bayona *et al*., 2006). Therefore, the Barco-Cuervos succession and the lower

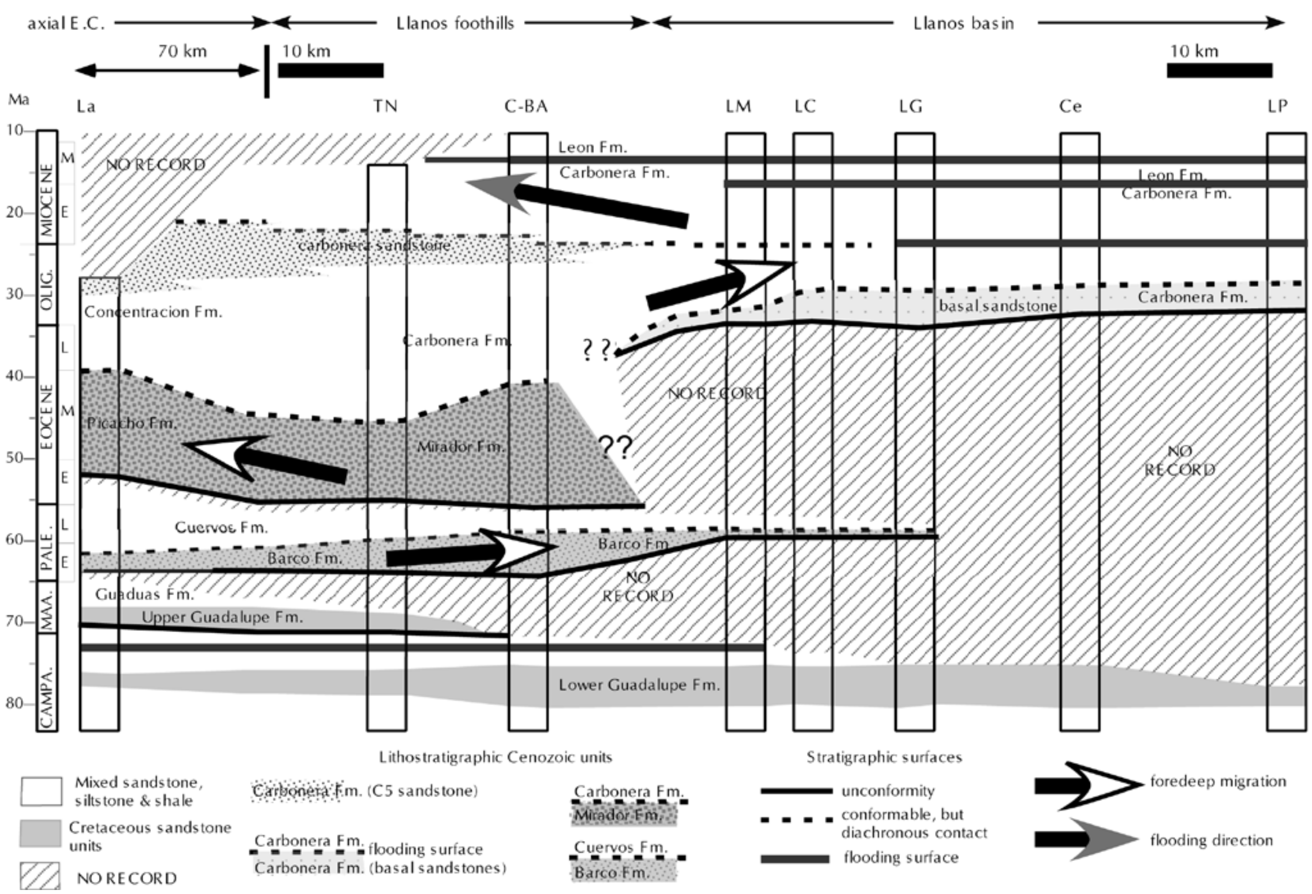

Figure 8. Chronostratigraphic correlation of Campanian - middle Miocene strata along the central SLC showing events of foredeep migration and the westward direction of lower-middle Miocene flooding event. See Figure 1 for section locations and codes. Note change of scale to the west of the Llanos foothills. Sandstones of the upper Paleocene Barco Formation and upper Eocene-Oligocene Carbonera Formation are younger eastward or basinward, whereas lower-middle Eocene mirador sandstones are younger westward. Lower-middle Miocene flooding surfaces may be considered as the surfaces with the least diachronism and the broadest lateral extension in the Paleocene-middle Miocene succession

beds of the Carbonera Formation record two episodes of eastward migration of the foreland basin (Figure 8), which are also coincident with events of increasing rates of tectonic subsidence.

The diachronous onset of Mirador and Carbonera deposition in the Llanos foothills and Eastern Cordillera indicate a period of westward migration of the foreland basin. Amalgamated quartzose sandstones of the Mirador and Picacho formations in the Llanos foothills and axial zone of the Eastern Cordillera accumulated in a period of very slow tectonic subsidence during early and middle Eocene time. The thick record of Eocene deposition in the axial zone of the Eastern Cordillera and the absence of Eocene strata in the Llanos basin support the westward migration of the flexural wave (Figure 8).

The westward encroaching of shallow-water deposition during early to middle Miocene time caused the flooding of the fluvial-deltaic system in the western part of the Llanos basin. Flooding events are well recognized across the Llanos basin, allowing a chronostratigraphic correlation in the foreland basin (Figures 6 and 8). This pattern of deposition suggests a regional transgression of a broad shallow-water lacustrine system, as reported in other South American basins. Miocene lacustrine and lagoonal deposits have been also documented in the Colombian Amazonas basin (Hoorn, Guerrero, Sarmiento, & Lorente, 1995), in southern Andean foreland basins (the Pebas sea of Marshall & Lundberg, 1996; Uba, Heubeck, & Hulka, 2005), and in the northern Magdalena Valley (Gómez *et al*., 2005a) as well as in sedimentary basins with other tectonic regimes such as in the 7 km-thick extensional Urumaco basin in northern Venezuela (Hambalek *et al*., 1994).

The extent of Miocene flooding events increases with time, reflecting either a major influence of eustasy or a change in scale of tectonic events. A first-order sea-level rise of less than 30 m during the early-middle Miocene (Haq *et al*., 1987) cannot explain an increase of accommodation space in the interior of the South America plate (e.g., Llanos basin). A shift from local uplift of internal massifs and other local blocks of the Eastern Cordillera since the Oligocene (Toro *et al*., 2004; Gómez *et al*. 2005a; Ojeda, Bayona, Pinilla, Cortés, & Gamba, 2006) to a regional Andean uplift in the Miocene (from Argentina to Venezuela; e.g., Cooper *et al*., 1995; Hoorn *et al*., 1995; Baby, Rochat, Mascle, & Herail, 1997; Audemard & Audemard 2002) may explain the broad increase of accommodation space in interior zones as a response to Andean loading. This shift in the scale of the orogen, as documented by geodynamic models (Ojeda *et al*., 2006), is related to the collision of the Panama arch with the northern South America plate in the middle to late Miocene (Coates, Collins, Aubry, & Berggren, 2004). During the Middle Miocene, it is probable that both eustasy and Andean-scale mountain-building processes influenced rates of generation of accommodation space in the continental foreland.

CONCLUSIONS

- The Paleocene-Oligocene succession between the axial zone of the Eastern Cordillera and the Llanos foreland basin of Colombia records three migration events of the foreland depozones that controlled the present geometry of reservoir units. Diachronous deposition of the Barco-Cuervos formation during the Paleocene recorded the eastward onlap of foreland deposits and the northward advance of synorogenic deposition. Later in Eocene time, westward migration of the foredeep depozone favored deposition of amalgamated quartzose sandstones of the Mirador Formation and bypass on the Llanos basin. In late Eocene to Oligocene time, the foredeep depozone advanced rapidly eastward, favoring thick fine-grained deposition in the Llanos foothills and diachronous onset of fluvial sandstone deposition on the Llanos basin.

- Unconformities that underlie amalgamated fluvial sandstones of the Barco and Mirador formations in the Llanos foothills should be considered only as the base of synorogenic successions, whereas the conformable contact between fluvial-estuarine sandstone and marginal mudstones should be used in a first instance to constrain the diachronous migration of the flexural wave.

- During the early and middle Miocene, the foreland basin recorded a westward-stepping transgression of shallow-water systems onto fluvial-deltaic systems. Lower to middle Miocene flooding surfaces are the most appropriate for strata correlation in the Llanos foreland basin because of the basinwide extension, seismic signature, and lack of significant diachronism of strata bounding those surfaces. Andean-scale mountain-building processes and rise of sea level in the Miocene interacted to generate the conditions for rapid and basinwide encroaching of a lacustrine-lagoonal system over a nonmarine foreland basin.

- Although lithology and vertical stacking patterns are fundamental for the understanding of stratal architecture, the success of correlation in a continental nonmarine foreland basin depends upon the integration of data from other techniques. The correlation relies primarily on recognition of the diachronism of potential key stratigraphic surfaces within a chronostratigraphic framework (Figure 8). Secondly, tectonic subsidence and provenance analyses supply important evidence to determine whether deposition took place during an episode of increasing tectonic subsidence and unroofing of new source areas. The tracing of key stratigraphic surfaces along seismic lines allows consideration lateral changes of lithofacies and strata stacking pattern within the basin. The integration of all these elements is fundamental to the determination of depositional sequences within a tectonically-active continental foreland basin.

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