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ABSTRACT
The Piedemonte Llanero is a wedge duplex zone in the Llanos foothills on the eastern flank of the Eastern Cordillera of Colombia. It is located northeast of the Cusiana and Cupiagua hydrocarbon fields. The area is characterized by a series of moderate to high-angle duplexes with east-southeast verging thin-skinned and thick-skinned tectonics. We present a structural model constrained by 2-D and 3-D seismic reflection data, surface geology, and well data. The structural analysis is based on backward modeling (kinematic restoration) and forward modeling using transfer-flexural slip and fault slip fold algorithms. The structures are significantly tighter in the northern segment compared to the southern segment of the over-thrust trend. We estimate approximately 17 km of shortening in the northern duplex zone, and about 26 km total shortening for the southern duplex zone. We propose that thin-skinned in-sequence imbricate thrust stack deformation produced most of the shortening. The main Andean deformation (80% of the total shortening) commenced in the Piedemonte area about 6 Ma with rapid shortening and uplift in the area resulting in the development of an active-roof duplex structure as the cover was bulldozed forward by a horse block (Monterralo anticline) ramping up to a detachment at the base of C2, then ramping to the surface as the Yopal thrust. Later the horse blocks in the wedge rose, underthrusting the cover in a passive-roof duplex triangle zone. This was followed by an out-of-sequence Laramide-style thick-skinned basement-uplift of the range which produced much of the structural relief of the Eastern Cordillera. Cenozoic deformation in the Eastern Cordillera has been primarily range-normal, but has involved an increasing component of mountain-parallel right-lateral shear in the last 2 Ma.

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1. Introduction

The Piedemonte Llanero in the central Llanos foothills is a broad zone covering the area of Fig. 1 and containing a triangle zone. The NE–SW trending central Llanos foothills form the frontal thrust zone along the eastern flank of the Eastern Cordillera of Colombia. The central Llanos foothills are bordered by the Yopal thrust fault system and the Llanos basin to the east, and by the Guacaramo fault system and the Eastern Cordillera to the west. The foothills are divided into three main structural domains that exhibit increasing structural complexity northeastward along the mountain front (Villamil et al., 2004; Martinez, 2006) (Fig. 2): a frontal inverted normal fault domain (Cusiana), a transition bedding plane thrust domain (Cupiagua), and a wedge duplex domain (Piedemonte). Within the Piedemonte Llanero, the main surficial structures are the Nunchia syncline that folds outcropping Oligocene to Recent age rocks, and the Monterralo anticline, that folds outcropping Cretaceous to Oligocene age rocks (Fig. 1). The main hydrocarbon accumulations in the Piedemonte Llanero are in the sandy units of the Late Cretaceous Guadalupe Group, Eocene Mirador Formation and Paleocene Barco Formation within the Floreña, Pauto, Dele, and Volcanera structures (Figs. 3–7). These wedge zone structures hold considerable hydrocarbon reserves due to the duplication of reservoirs in the duplexes.

Exploration in the Piedemonte Llanero began in the early 1990s with the acquisition of 2-D seismic reflection lines and the drilling of several exploratory wells. Well data reveals tight asymmetric folds with high dip angles (usually exceeding 50°). The quality of the 2-D seismic images is generally poor due to the complexity of the subsurface structures, rugged terrain, and the poor acoustic properties of the Mesozoic rocks, resulting in low signal-to-noise ratio in the acquired seismic data. Recent 3-D seismic reflection data have improved on the seismic image quality.

This work offers new insight into the 3-dimensional structure and kinematics of the Piedemonte Llanero. We present the first...
interpretation with multiple geologic profiles of the wedge duplex zone constrained by previously unpublished 2-D and 3-D seismic reflection data, well data, and detailed surface geology. The structural analysis is based on kinematic restoration and forward modeling using Transfer-flexural slip and Fault slip fold algorithms in Paradigm GeoSec®. We propose a thin-skinned in-sequence imbricate thrust stack deformation for the Piedemonte Llanero followed by thick-skinned out-of-sequence thrusting and uplift. We present the first published shortening estimates for the Piedemonte Llanero wedge duplex zone. The main Andean deformation (80% of the total shortening) commenced in the Piedemonte area about 6 Ma with rapid shortening and uplift in the area resulting in the development of an active-roof duplex structure as the cover ramped to the surface as the Yopal thrust. Our multiple profiles of the Piedemonte Llanero show that structures are significantly tighter with less shortening in the northern segment compared to the southern segment of the wedge duplex. Unlike previous interpretations, we recognize the importance of fault-propagation folding in the formation of the wedge duplex structures. We also note, for the first time in the foothills, evidence for trishear fault-propagation folding, in which decreased displacement along the blind El Moro fault is accommodated by heterogeneous shear in a triangular zone radiating outward from the fault tip. We also propose an increasing component of mountain-parallel right-lateral shear in the last 2 Ma.

2. Regional geologic setting

The Eastern Cordillera represents the leading edge of deformation in the northern Andes (Corredor, 2003). It is interpreted as a wide extensional basin that evolved into a foreland basin and was
inverted during the Cenozoic Andean orogeny (Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995; Roeder and Chamberlain, 1995; Mora et al., 2006). The inversion of pre-existing extensional structures has been reported for numerous other orogens (for example, Coward et al., 1989; Grier et al., 1991; Lowell, 1995).

During the Mesozoic era, the area of the modern Eastern Cordillera was an extensional basin. Northwestern South America...
was affected by rifting related to the break up of Pangea and the eventual separation of North and South America (Pindell and Dewey, 1982; Ross and Scotese, 1988; Cediel et al., 2003). Westward propagating intracontinental rifting between Yucatan and northern South America led to the proto-Caribbean seaway. However, since synrift continental clastic sediments are difficult to date, the exact timing of the onset of rifting is not well constrained, and basin geometries are still uncertain. Rifting in Colombia established depocenters throughout the Eastern Cordillera area. Pre-rift units include Lower—Upper Paleozoic rocks. The Quetame Group, made up of possible Precambrian or Cambrian—Ordovician phyllitic rocks with a minimum thickness of 915 m (Campbell, 1962) represents the lower unit of the pre-rift metamorphic rocks. An alternative mechanism for the rifting is back-arc extension due to subduction rollback, with which the South American craton did not keep pace (Maze, 1984; Pindell and Erikson, 1993; Pindell and Tabbutt, 1995).

By the Early Cretaceous, considerable accommodation was created in the Eastern Cordillera. Late Jurassic to Early Cretaceous rifting generated basaltic intrusions, thinning of the lithosphere, and shallowing of the mantle (Ojeda, 1996). The rifting phase was followed by thermal subsidence throughout the Cretaceous period (Pindell and Tabbutt, 1995; Ojeda, 1996).

From the Early Cretaceous to Late Cretaceous period, deposition in the Eastern Cordillera area was almost entirely marine. The Ure Formation (Fig. 3) was deposited from Early Cretaceous until the Cenomanian and is composed of sandstones deposited in shallow marine conditions (Cooper et al., 1995; Linares et al., 2009). It is considerably thicker in the foothills and thins eastward in the Llanos basin. In the Late Cretaceous, global sea level rise (Haq et al., 1987) combined with anoxic upwelling, created a favorable environment for deposition of the marine mudstones, cherts, and phosphates that make up the Gacheta Formation, a prolific source rock that is contemporaneous with La Luna Formation (Villamil and Kauffman, 1993; Pindell and Tabbutt, 1995). A drop in sea level during the Campanian—Maastrichtian accompanied the deposition of the Guadalupe Group on a shallow marine shelf (Linares et al., 2009). The Guadalupe Group is predominantly a progradational sandstone unit that progressively thins toward the east. Late Cretaceous subsidence in the Eastern Cordillera area was mostly driven by lithospheric cooling, with additional input from water loading associated with eustatic sea level rise, and horizontal compressional stresses resulting from the collision of oceanic terranes in western Colombia (Sarmiento-Rojas et al., 2006).

Deformation resulting from the accretion of the oceanic terranes of the Western Cordillera from Late Cretaceous to early Paleocene marked a significant change from a shallow marine to continental depositional environment in an incipient foreland basin (Van der Hammen, 1961; Sarmiento-Rojas et al., 2006). This foreland basin likely developed as a result of the topographic load of the Central Cordillera, a volcanic arc that formed as part of the Farallon plate subduction complex along the west coast of Colombia (Cooper et al., 1995). Starting in the middle Paleocene, the Barco Formation, a sandstone rich fluvial to estuarine deposit that is sourced from the Guayana shield was deposited (Cooper et al., 1995). In the late Paleocene, the Los Cuervos Formation, which is mostly shale with intercalations of sandstones, siltstones, and coal beds (Linares et al., 2009), was deposited in a regressive mud dominated coastal plain setting (Cooper et al., 1995).

In the Eocene, the Mirador Formation was deposited in two stages interrupted by a regional unconformity (Martinez, 2006), with tidal channel sandstones overlapping fluvial channel sandstones (Linares et al., 2009). The Carbonera Group (C8—C1), a cyclic sequence of continental to transitional sandstones and marine shales, was deposited in the late Eocene to late Miocene. A global rise in sea level following the deposition of the Carbonera Group in the middle Miocene (Haq et al., 1987) led to the deposition of the Leon Formation shales.

Based on detrital-zircon ages from the Carbonera Group in the eastern foothills of the Eastern Cordillera, Horton et al. (2010) concluded that uplift-induced recycling of basin fill was well under way by the latest Oligocene to early Miocene (26—23 Ma). However paleobotanical data (Wijninga, 1996; Gregory-Wodzicki, 2000) and apatite fission-track ages and low  T thermochronology (Mora, 2007; Parra et al., 2009b; Mora et al., 2010b) indicate that most of the shortening and uplift in the central and eastern flank of the Eastern Cordillera occurred in the last 6 Ma. Paleobotanical data imply rapid uplift at a rate on the order of 0.6—3 mm/ a (Gregory-Wodzicki, 2000).

By late Oligocene to early Miocene, the Farallon plate had broken up into the Nazca and Cocos plates and a new spreading center formed, resulting in increased convergence rates at the Middle and South American trenches (Wortel and Cloetingh, 1981; Wortel, 1984; Lonsdale, 2005). About 12 Ma the Panama arc began colliding with the northern Andes, leading to the uplift of the Eastern Cordillera, which became a sediment source (Gregory-Wodzicki, 2000). The timing, direction, and magnitude of shortening indicate that the Panama arc collision was the probable cause of the Andean orogeny in the Eastern Cordillera. The thin lithosphere and relatively ductile sediments of the Eastern Cordillera and the foothills were caught in a vice between the rigid South American backstop and the rigid Panama arc indenter. The collision initiated the inversion of Mesozoic extensional structures, uplift of the Eastern Cordillera and development of east-verging compressional structures in the Llanos foothills (Van der Hammen, 1961;
Lateral changes in Mesozoic stratigraphic thicknesses suggest that the thrust faults that now define the eastern and western borders of the Eastern Cordillera were originally normal faults (Sarmiento-Rojas et al., 2006; Mora et al., 2006, 2009).

Deformation and uplift in the Eastern Cordillera is still ongoing today, resulting in earthquakes mainly in the foothills area. Recent erosion of the Eastern Cordillera is evident from the coarse grained continental clastics of the Guayabo formation in the Llanos foothills and Llanos basin (Cooper et al., 1995). GPS studies show that Panama is actively colliding with South America at an average rate of 25 mm/a (Trenkamp et al., 2002). However, present-day shortening in the Eastern Cordillera appears to have slowed to at most $12 \pm 4$ mm/a and on the east flank of the Cordillera to only $4 \pm 2$ mm/a (Trenkamp et al., 2002).

Approximately 2 Ma, the aseismic Carnegie ridge, which was formed by the Galapagos hotspot at the Cocos–Nazca spreading center, arrived at the Colombia–Ecuador trench (Egbue and Kellogg, 2010). Increased coupling in the trench due to the subduction of the buoyant aseismic Carnegie ridge is driving the present-day northeastward tectonic escape of the northern Andes. GPS results show that the northern Andes are escaping toward the northeast at a rate of about 6 mm/a (Trenkamp et al., 2002).

Geologic estimates indicate that slip rates of 4–10 mm/a continued back to about 2 Ma (Egbue and Kellogg, 2010). In the Eastern Cordillera area, the rate of range-normal shortening still exceeds the rate of escape, but range-parallel right-lateral shear has become increasingly important in the last 2 Ma (Egbue and Kellogg, 2010).

3. Structure of the Eastern Cordillera

The Eastern Cordillera of Colombia is an asymmetrical bivergent fan of thrusts toward the Middle Magdalena Valley basins and the Llanos basin, containing a thick Jurassic and lower Cretaceous depocenter (Campbell and Burgl, 1965; Julivert, 1970; Campbell, 1974; Cooper et al., 1995). Thickness estimates for the Cretaceous section in the Eastern Cordillera are not well controlled and vary widely. Restrepo-Pace (1989) estimated the thickness of the total Cretaceous section as approximately 5 km, based on structural and biostratigraphic analysis of the lower Cretaceous rocks along the eastern flank of the Cordillera. On the western flank of the Cordillera, Cardozo (1988) measured the Cretaceous section as about 8 km. Campbell and Burgl (1965) estimated the thickness of the total Cretaceous stratigraphic column as over 11 km near Bogotá. It is important to note that thicknesses measured from outcrops in the Eastern Cordillera are likely exaggerated due to structural repetition as demonstrated by Restrepo-Pace (1989).

Numerous structural models have been proposed for the Eastern Cordillera. Based on a retrodeformed cross-section through the Eastern Cordillera, Colletta et al. (1990) proposed that the Cordillera was formed by the inversion of two deep Upper Jurassic–Lower Cretaceous basins during Miocene–Pliocene times. In this model, the structure is controlled by low angle thrusts and reactivated normal faults that constitute frontal ramps. They estimated a total shortening of at least 105 km with a decollement at a depth of about 20 km. Dengo and Covey (1993) proposed that basement-detached (“thin-skinned”) shortening was followed by uplift on high-angle basement-involved reverse faults (“thick-skinned”) deformation and estimated approximately 150 km of shortening (40%) from a regional retrodeformable cross-section. Cooper et al. (1995) proposed that deformation in the Llanos foothills was predominantly inversion of pre-existing extensional faults by basement-involved “thick-skinned” listric reverse faults. They estimated only 68 km of shortening.

Martinez (2006) proposed two main phases of Cenozoic deformation in the Llanos foothills, incipient shortening during the deposition of the Lower Carbonera (C8–C6) and the main Andean orogeny, starting around 7–5 Ma. He proposed an overthrust
most recent exposed thrust and the frontal syncline in the foreland leading edges of fold and thrust belt systems, located between the oroclines (Couzens-Schultz et al., 2003). The Piedemonte Llanero has been interpreted as an active-roof duplex and “triangle zone” by Martinez (2006). Some authors, however, restrict the use of the term “triangle zone” to passive-roof duplexes only (e.g., Jones, 1996).

4. Triangle zones, passive and active-roof duplexes

Triangle zones are a common structural feature found at the leading edges of fold and thrust belt systems, located between the most recent exposed thrust and the frontal syncline in the foreland (Boyer and Elliott, 1982; Jones, 1982; Banks and Warburton, 1986; Vann et al., 1986; Álvarez-Marrón et al., 1993; Valderrama et al., 1996). The Piedemonte Llanero has been interpreted as an active-roof duplex and “triangle zone” by Martinez (2006). Some authors, however, restrict the use of the term “triangle zone” to passive-roof duplexes only (e.g., Jones, 1996).

4.1. Passive-roof duplex

In a passive-roof duplex (Fig. 4a), the cover is underthrust by the horse blocks, most of the shortening is accommodated by delaminating the cover and no significant displacement is transmitted forelandward of the duplex leading edge (Jones, 1982; McMechan, 1985; Banks and Warburton, 1986). The cover is “passively uplifted by thrust wedging beneath (Jones, 1996) and may be folded or thrust to accommodate shortening above the roof thrust. The Foothills in Alberta, Canada is an example of a passive-roof duplex triangle zone.

4.2. Active-roof duplex

In an active-roof duplex (Fig. 4b; Couzens-Schultz et al., 2003) the cover is bulldozed forward by the horse blocks. An important amount of shortening is transferred to the cover and accommodated by structures forelandward from the duplex leading edge (no significant delamination occurs). Active-roof duplex zones are found in the southern Pyrenees, Spain and the Virginia Appalachians (Couzens-Schultz et al., 2003).

Duplex zones produce multiple trapping configurations, but are difficult to image seismically because of steep bedding and fault dip angles. Exploration in these areas has therefore, relied heavily on structural models, and drilling usually reveals structural surprises. The Piedemonte Llanero duplex zone is bounded by the Guacaramo thrust fault to the west, the bedding plane detachment of the Nunchia syncline above and to the east, and the Yopal fault at the base (Fig. 7; Martinez, 2006). Based on seismic reflection profiles and well data from the Piedemonte, we propose that the structure developed as an active-roof duplex during the Pleistocene—Pleistocene, followed by passive-roof delamination and uplift of the cover over the thrust wedge.

5. Data & Methodology

For this research, we used a recent 3-D seismic reflection dataset provided by BP Exploration Company Colombia. The migrated 3-D data has a lateral coverage of 17 × 37 km with 939 NW-SE inlines and 850 NE-SW cross-lines. The survey configuration consisted of 17 shots per km² in a subsurface cell of 20 × 40 m, with a nominal 48-fold multiplicity and 60,000 traces per km². For the source, 5–10 kg of dynamite was used in a 17 m deep single hole with a total of 17 shot points per km². The data was processed by CGG Veritas Argentina for BP Exploration Company Colombia.

BP Exploration Company Colombia also provided the authors with several 2-D seismic reflection lines that were acquired in the 1990s. For this study, we selected seismic line PT90-379 (Line 7b in Fig. 1) that traverses the triangle zone. The location of this seismic line allows us to constrain our interpretation using well data from two deviated wells located adjacent to the profile (Fig. 1) and extend the interpretation outside the area covered by the 3-D seismic survey. Some of the limitations of the 2-D seismic reflection data related to the difficulty in imaging complex subsurface structures and low signal-to-noise ratio are resolved with the new 3-D data (Fig. 5). Depth slices through the 3-D volume (Fig. 6) illustrate three structures in map view.

Fig. 6. Depth slices through the Piedemonte showing the major structural features at (a) 2270 m, El Morro anticline, (b) 4300 m, Floreña anticline, and (c) 5280 m, Pauto anticline.
The following interpretations are constrained by a detailed surface geology map of the Llanos foothills and well data (bedding dips and formation tops. Bedding dips are from Stratigraphic High-resolution Dipmeter Tool (SHDT), Ultrasonic Borehole Imager (UBI), Fullbore Formation MicroImager (FMI), surface geology, and seismic profiles. Where two wells penetrate clearly imaged seismic reflectors in the Nunchia Syncline (Fig. 7b and c), the dipmeter data correlates well with the dips of the depth-corrected seismic reflectors. This correlation supports the reliability of the dipmeter data to reflect true bedding dips with errors of a few degrees. Time-to-depth conversion of the migrated 3-D and 2-D seismic reflection data was performed using Hampson-Russell Strata/C210. The velocity model used for the depth conversion was built using P-wave velocities from eight deviated wells in the study area. Preliminary interpretations of the seismic depth sections were then developed using Schlumberger Petrel/C210. Balanced cross-section construction, structural analyses, and modeling were performed using Paradigm GeoSec 2D and 3-D Canvas. Transfer-flexural slip and Fault slip fold algorithms were used for the kinematic restoration and forward modeling in GeoSec 2D.

5.1. Data preparation

Selected inlines were extracted from the 3-D seismic volume using Schlumberger Petrel. They were then exported as 2-D SEGY files. The exported inlines 201 (Fig. 1, line 7a) and 608 (line 7c) and 2-D line (PT90-379; line 7b) and adjacent deviated wells with formation tops and dipmeter data were then imported into GeoSec 2D. Following this, well data (trajectory, formation tops, and bedding dips) were projected onto adjacent seismic cross-sections. The program automatically converts the true dip measurements associated with the well data into apparent dips on the section plane, and the 3-D deviated boreholes are projected into a 2-D deviated borehole trace. We created a stratigraphic column for the Piedemonte Llanero in GeoSec 2D. The thicknesses assigned to each stratigraphic unit were based on data from BP Exploration Company Colombia and Bayona et al. (2008). Ground elevation and surface geologic information (strike and dip measurements, geologic contacts, and fault traces) for the Piedemonte were entered into GeoSec 2D and projected onto the cross-sections.

5.2. Cross-section construction

Our interpretations of the seismic reflection cross-sections are constrained by well data and surface geology. Constant bedding thicknesses and layer parallel slip, the initial structural approximations, were modified as needed. Uniform dip domain boundaries and consistent dip domain geometries were chosen wherever possible. The simplest structural solutions with the minimum amount of shortening consistent with the data were selected. The greatest sources of error in the interpretations were the poor seismic resolution and limited well control for the cross-sections. As mentioned previously, the lack of resolution is due to the complex structural geometry, the high dip angles, and low signal-to-noise ratio. After constructing the cross-sections, we built a 2.5-D model of our interpretation of seismic line PT90-379 (line 7b) using Paradigm 3D Canvas.

5.3. Kinematic restoration

Following our interpretation and cross-section construction, we restored line PT90-39 using the Transfer-Flexural slip module in GeoSec 2D to test the feasibility of our structural model. The Transfer-Flexural Slip algorithm folds rocks along sliding surfaces that are parallel, or close to parallel, to bedding. The section was kinematically restored to the top of the Eocene Mirador Formation. We chose line 2D PT90-379 (line 7b) for restoration because, unlike inlines 201 (7a) and 608 (7c), this profile clearly images the relatively undeformed footwall block (Llanos basin). The footwall block provides us with a pre-deformation reference and target surfaces for retrodeformation. Finally the restored section was forward modeled using Transfer-flexural slip and Fault slip fold algorithms until the present-day deformation was duplicated.

Fig. 7. Geologic cross-sections through the Piedemonte Llanero with the seismic reflection profiles, well data, and surface geology used to constrain the interpretations. Cross-sections were constructed using Paradigm GeoSec 2D. (a) 3-D Inline 201, (b) 2-D Line PT90-379, and (c) 3-D Inline 608. Locations of the cross-sections are shown in Fig. 1.
6. Structural interpretation

In order to better understand the structural geometry and along strike variations in the Piedemonte Llanero triangle zone, we interpreted three NW–SE dip seismic cross-sections from the northern and southern segments of the overthrust trend (Fig. 7). The cross-sections traverse the Guaiacarito fault and the Nunchia syncline and are constrained by detailed surface geology, well data, and 3-D and 2-D seismic reflection profiles. Line PT90–379 (Fig. 7b) is 21 km long and based on a 2-D reflection profile that extends into the Llanos basin. In-lines 201 (Fig. 7a) and 608 (Fig. 7c) are both about 17 km long, and are from the 3-D volume. Given the seismic ambiguities, the availability of well control was key in determining which seismic lines were selected for interpretation and modeling.

6.1. Northern cross-sections

6.1.1. Inline 201

This cross-section (Fig. 7a) is located in the northern segment of the Piedemonte Llanero (Fig. 1). It traverses a structural high in the northwestern corner that thrusts Cretaceous rocks over the Monterralo anticline along the NE-SW striking Chameza fault. It also traverses the Guaiacarito fault and extends into the Nunchia syncline. The main structural features in the cross-section are the east-verging Monterralo, El Morro, Floreña, and Pauto anticlines and the Nunchia syncline. Deformation in this cross-section involves sediments from the Lower Cretaceous (Fomque Formation and older) to the upper Miocene to Recent Guayabo Formation. The main fault detachments are in the shaly units of the basal Carbonera Group, the Gacheta Formation, and the Lower Cretaceous. There is seismic evidence for a number of major unconformities within the lower Carbonera Group, including an unconformity at the base of C5 in the Nunchia syncline. These unconformities are also observed in the wells. There is a pronounced lateral variation in the thicknesses of the lower members of the Carbonera Group, especially C7. The Cretaceous section is considerably thicker in the imbricated tectonic wedge than in the footwall block (Llanos basin). We interpret the Monterralo and El Morro anticlines as fault-propagation folds (Suppe and Medwedeff, 1984), while the Floreña and Pauto anticlines are interpreted as fault-bend folds (Suppe, 1983). Monterralo and El Morro are asymmetrically faulted anticlines with steep overturned forelimbs (up to 85°) and elongated backlimbs with estimated ramp dips of 40°–50°. The El Morro forelimb is overturned in the well. The overturned forelimbs suggest that the folds formed as the result of fault-propagation followed by forelimb breakthrough faulting. Monterralo and El Morro have been shortened approximately 5.5 km and 2.5 km, with about 4 km of vertical relief on each structure. The deeper structures, the Floreña and Pauto anticlines, are characterized by elongated moderately dipping forelimbs and shorter backlimbs. We estimate approximately 5 km and 4 km of shortening for Floreña and Pauto structures respectively with vertical reliefs of about 3 and 2 km. We estimated ramp dips of approximately 45° degrees for Floreña and 20° for Pauto. The minimum total shortening needed to produce the four imbricated anticlines in the cross-section is approximately 17 km. In addition there was at least 6–8 km of shortening on the Chameza fault plus a minimum of 4 km additional slip on the Yopal thrust (see Fig. 7b) from a bedding plane detachment at the base of C2 for a minimum total of 27 km. In Fig. 7a the Chameza fault is depicted as an out-of-sequence fault which cuts the core of the Monterralo anticline. However, the Chameza fault may be just as easily interpreted as an in-sequence fault that gently ramps up from a detachment at the base of C7 to a detachment at the base of C2 and was subsequently uplifted by the Monterralo anticline. The Yopal thrust bedding plane slip at the base of C2 postdated deposition of the lower Guayabo Formation. The base C2 slip formed a roof décollement for the duplex (Fig. 4) that may have been the upper flat for the Monterralo ramp anticline breakthrough fault. Approximately 3 km of the 11.5 km duplex zone shortening in the El Morro, Floreña and Pauto anticlines is taken up in the Yopal thrust. The remaining 8.5 km is predicted to have gone into a) displacement prior to the base C6 unconformity on the El Morro and Floreña breakthrough faults and b) backslip or passive-roof delamination on the base C6 backthrust at the roof of the triangle zone. The southeast dipping Lower Cretaceous unit in the lower northwest corner of the cross-section represents the predicted forelimb of an out-of-sequence basement-involved ramp anticline rooted deep in the lower crust below the Eastern Cordillera. The predicted deep southeast dipping forelimb is also shown in the regional interpretations of Deng and Covey (1993), Cortés et al. (2006), Bayona et al. (2008), and Mora et al. (2010a). Deng and Covey (1993) and Bayona et al. (2008) explain it as the forelimb of a mid crustal fault-bend fold similar to our model. The Cortés et al. (2006) and Mora et al. (2010a) listric reverse fault models provide a structural explanation for the uplift, but not for the southeast dipping limb. This late stage “thick-skinned” La Venta style uplift (Bayona et al., 2008; see De Toni and Kellogg, 1993 for “thick-skinned” deformation references and examples) provides 5–6 km of the structural relief for most of the Eastern Cordillera.

6.1.2. Line PT90–379

This cross-section (Fig. 7b) is located in the northern segment of the Piedemonte Llanero south of inline 201. This is a 2-D seismic profile that extends beyond the 3-D survey volume, traversing the Yopal fault and extending into the Llanos basin. This cross-section has better well constraint than inline 201. In this cross-section, just like in inline 201, the Monterralo, El Morro, and Floreña anticlines are interpreted as fault-propagation folds, while the Pauto structure is interpreted as a fault-bend fold. The structure interpreted from two wells that penetrate the overturned forelimb of the El Morro anticline can be modeled by trishear fault-propagation folding (Ersliev, 1991; Shaw et al., 2005), in which decreased displacement along the fault is accommodated by heterogeneous shear in a triangular zone radiating outward from the fault tip. We estimate at least 2.6 km of shortening for the Monterralo structure, 3 km of shortening for the El Morro structure and about 4 km of vertical relief for each. We predict ramp dips of approximately 40°–50° for Monterralo and El Morro based primarily on surface dips exposed up plunge to the south southwest. The deeper Floreña structure is a tight fault-propagation fold with a breakthrough fault at the top of its overturned forelimb. We predict a ramp dip of about 50°, shortening of about 2.3 km, and vertical relief of over 2 km. Well data shows that the Pauto anticline is a gentle fold, probably produced by a fault-bend. The fold was faulted into two levels: Upper Pauto and Lower Pauto with a total vertical relief of about 1.3 km and 30°–40° ramp dip. The Upper Pauto has been shortened approximately 1.5 km and the Lower Pauto about 3.0 km. The beds in the Llanos basin are relatively undeformed and dip toward the northwest due to flexural loading of the lithosphere by the weight of the growing mountain belt (Salvador, 1991; Ojeda and Whitman, 2002). The Nunchia syncline is asymmetrical, formed by the Yopal ramp thrust to the southeast and the wedge of the triangle zone to the northwest. At least 4 km of the 6 km minimum slip on the Yopal fault, ramps up from a bedding plane detachment at the base of C2 in the Carbonera Group, which may have ramped up from the Monterralo breakthrough fault. The remaining 2 km of displacement on the Yopal fault ramps up from a detachment in the Lower Cretaceous.
rocks, inverting a Lower Cretaceous normal fault (Mora et al., 2010a). Of the 10 km wedge zone shortening in the El Morro, Floreña and Pauto anticlines, the remaining 8 km is predicted to have gone into (a) displacement prior to the base C6 unconformity and (b) backslip on the base C6 backthrust at the roof of the triangle zone. The Yopal fault trace marks the eastern edge of the Piedemonte Llanero, separating the Llanos foothills from the relatively undeformed Llanos basin. With 6 km of slip on the Chameza fault, we estimate minimum total shortening in the cross-section as 24.5 km. The southeast dipping Lower Cretaceous unit in the lower northwest corner of the cross-section is the predicted forelimb of a basement-involved ramp anticline uplifting the Eastern Cordillera 5–6 km (Dengo and Covey, 1993; Bayona et al., 2008).

6.2. Southern cross-section

6.2.1. Inline 608

This dip cross-section (Fig. 7c) is located in the southern segment of the Piedemonte Llanero and is parallel to inline 201. It is constrained by the 3-D seismic volume, surface geology, and well control of the Dele, Pauto, and Volcanera structures below the Nunchia syncline. This cross-section traverses a syncline on the hanging wall of the Chameza fault, the Monterralo anticline, the Floreña anticline, and the Nunchia syncline. The wells reveal that the basal members of the Carbonera Group (C7 and C8) thicken substantially northwestward. There is also evidence of an unconformity at the base of C5. Along this profile the Monterralo anticline is interpreted as a fault-bend fold with a forelimb breakthrough fault, and an estimated 30°–35° ramp dip. Structural shortening is estimated as approximately 6.5 km with about 5 km of vertical relief. Based on well data, the El Morro anticline is modeled as a fault-propagation fold, but it is not as tightly folded as in the two northern cross-sections. It has a ramp dip of about 30° and has been shortened approximately 6 km with 4–5 km of vertical relief. The Floreña structure dies out southward and does not extend into this cross-section. This section reveals two new structures: the Dele and Volcanera anticlines, with the Pauto structure sandwiched between them. These three deeper structures are modeled as gentle fault-bend folds characterized by elongated backlimbs and moderately dipping forelimbs. Dele has been shortened approximately 1.4 km on a 45° ramp producing about 1 km of vertical relief. Pauto has been shortened about 7 km on a 28° ramp producing 2 km of vertical uplift. Volcanera, the deepest structure, has a low angle 14° ramp dip, 1.3 km vertical relief, and about 5.5 km of shortening. Extrapolating from the middle profile, 4 km of bedding plane slip from the base of C2 is assumed for the Yopal thrust. The Yopal thrust is also displaced an additional 2 km from the underlying triangle zone. Of the 20 km wedge shortening in the El Morro, Dele, Pauto, and Volcanera anticlines, the remaining 18 km is predicted to have gone into a) displacement prior to the base C6 unconformity and b) backslip or passive-roof delamination on the base C6 backthrust at the roof of the triangle zone. With an estimated shortening of at least 5 km on the Chameza fault, total shortening for the section is over 35 km. This shortening estimate is significantly higher than the estimates for the northern cross-sections, but is highly dependent on relatively unconstrained models of footwall structures. As in the two northern cross-sections, the southeast dipping Lower Cretaceous unit in the lower northwest corner of the cross-section is the predicted forelimb of a lower crustal basement-involved ramp anticline (Dengo and Covey, 1993; Bayona et al., 2008). We interpret the Piedemonte duplex zone as a series of imbricated fault-propagation folds and fault-bend folds with steeply dipping, sometimes overturned forelimbs. Well data shows that stratigraphic units in the El Morro structure are inverted in the forelimbs with variable bedding thicknesses suggesting trishear deformation (Erslev, 1991; Shaw et al., 2005). Andean age deformation in the Piedemonte Llanero duplex zone began with a post-early Guayabo Fm (Pliocene-Pleistocene) active-roof duplex, as the cover was bulldozed forward by a horse block (Monterralo anticline) ramping up to a detachment at the base of C2 (not shown in Figs. 8 and 9), then ramping to the surface as the Yopal thrust. Later the horse blocks in the triangle zone rose, underthrusting the cover in a passive-roof duplex. The cover back thrust took place on a detachment at the base C6 unconformity. The complexity of the structures increases from the southern segment of the triangle zone (Fig. 7c) to the northern segment (Fig. 7a and b) with folding generally tighter in the northern cross-sections. The amount of shortening in the triangle zone appears to decrease from the south to the north, with more of the deformation in the northern segment going into folding and uplift. The basal members of the Carbonera Group (C7 and C8) thicken northwestward (Fig. 7c). This thickening might represent pre-C6 (Oligocene) foreland basin deposition and flexural loading to the west. This deposition was followed by folding observed under the base C6 angular unconformity in all three sections. The steep eastern flank of the Nunchia syncline is the hanging wall of the Yopal fault ramp, while the gentler western flank is the passive-roof of the duplex stack in the triangle zone.

Thin-skinned in-sequence imbricate thrust stack deformation produced most of the shortening in the Eastern Cordillera. Subsequent Laramide-style “thick-skinned” basement-uplift produced much of the structural relief in the range. The SE dipping units in the lower left corner of all three cross-sections compose the forelimb of a ramp anticline rooted deep in the crust. The basement reverse faulting uplifted the Eastern Cordillera and to a lesser extent the Monterralo anticline and triangle zone, as seen in the kinematic forward model of the Piedemonte Llanero (Fig. 9). Fig. 8 shows a simplified 2.5-D model for the northern segment of the Piedemonte Llanero based on cross-section PT90–379 (Fig. 7b). This perspective view for the top of the Mirador formation illustrates the horse block geometry within the duplex zone.

7. Cenozoic structural evolution

Fig. 9 shows the structural evolution of the Piedemonte triangle zone in the central Llanos foothills based on kinematic forward modeling of 2-D seismic line PT90–379. The Piedemonte Llanero and central Llanos foothills evolved through several
stages of major Cenozoic deformation, following the deposition of the basal members of the Carbonera Group (C8–C6) approximately 35 Ma.

7.1. Late Oligocene (25 Ma)

As noted earlier, based on detrital-zircon ages from the Carbonera Group in the eastern foothills of the Eastern Cordillera, Horton et al. (2010) concluded that uplift-induced recycling of basin fill was well under way by the latest Oligocene to early Miocene (26–23 Ma). Corredor (2003) estimated over 50 km of Oligocene ENE-WSW shortening in the northern Eastern Cordillera. The Oligocene age deformation is defined in the present eastern foothills area by the base C6 unconformity (Fig. 7), marking an important stage of Cenozoic crustal shortening in the pre-Eastern Cordillera foreland basin (Corredor, 2003). The base C6 unconformity is a striking feature apparent in all three profiles in Fig. 7 as a seismic angular unconformity, usually as a zone of abrupt changes in well dips, and by pronounced variations in thicknesses of C7. The late Oligocene folding and thrusting and subsequent erosion produced the observed C7 thickness variations in the study area. This period marks the earliest stages of deformation in the Monterralo, El Morro, and Floreña structures. This Oligocene deformation event is also recognized in the northern Eastern Cordillera by Corredor (2003) based on geologic mapping, seismic reflection profiles, and biostratigraphic data. Our evolutionary model is similar to that of Martinez (2006), but we attempt to quantify shortening and propose a structural explanation for the latest uplift of the Cordillera. Late Oligocene shortening in the Piedemonte Llanero is estimated as approximately 4 km, and represents about 15–20% of the total shortening in the area for the Cenozoic. Between 25 and 10 Ma there was very little tectonic activity in the area (e.g., Corredor, 2003). The upper members of the Carbonera Group and the Leon Formation were deposited during this period.

7.2. Late Miocene–Pleistocene Andean deformation (10 Ma to present)

The main Andean deformation commenced in the Piedemonte area about 6 Ma (Late Guayabo Formation age) with rapid shortening and uplift in the area resulting in the development of the duplex structures and folding of the roof thrust to create a frontal syncline in the foothills with the breakthrough of the Yopal thrust to the surface. The deformation age is demonstrated by the conformable folding of the lower Guayabo Fm with no evidence of syn-sedimentary deformation. As noted earlier, this deformation stage began with a bedding plane thrust at the base of C2 that ramped to the surface as the Yopal fault. This bedding plane thrust may have been the upper flat for the break through fault ramping up under the Monterralo fold (Fig. 7). Southeast of the Yopal fault, the Llanos basin remained largely undeformed with the Mesozoic normal faults inhibiting progradation along bedding plane detachments. During this stage of deformation, sediments of the Guayabo formation eroded from the rapidly uplifting Eastern Cordillera to the west were deposited in the developing Nunchia syncline and Llanos basin. Deposition of the Guayabo formation, shortening and uplift continued in the area throughout the Quaternary. The Pauto structure developed, and the Monterralo, El Morro, and Floreña folds became tighter. This section through the Piedemonte has undergone a minimum of 17 km (40%) shortening (not including 6 km slip on the Chameza fault) since the Late Eocene.
7.3. Basement block thick-skinned deformation

One of the latest structural events affecting the Piedemonte area during the Andean stage of deformation was the thick-skinned basement block uplift of the Eastern Cordillera. There is no direct evidence for this in the seismic cross-sections. This may be due to the lack of deep seismic image resolution underneath the imbricate thrust stack in the Piedemonte. The basement block crustal scale fault-bend fold is proposed as the most likely solution to explain the relatively uniform structural uplift of the entire mountain range to the northwest of the Foothills, similar to the solutions of Dengo and Covey (1993) and Bayona et al. (2008). We estimate that this uplift accounts for approximately 5–6 km of the total 10 km of structural uplift relative to the flanking basins. This structure is assumed to be a crustal scale ramp anticline analogous to the Wind River Range (Berg, 1962; Smithson et al., 1978) and the Venezuelan Merida Andes (Kellogg and Bonini, 1985; De Toni and Kellogg, 1993). The basement block listric fault models of Cortés et al. (2006) and Mora et al. (2010a) explain the uplift, but not postulate a blind wedge fault geometry similar to the Merida Andes (Kellogg and Bonini, 1985). There does not appear to be good evidence for an outcrop.

For a fault-bend fold with 5 km vertical relief, a forelimb dip of 23° and 12° upper ramp dip (Fig. 7b), the structure would require 10 km of additional late-stage shortening on a 29° lower ramp (Suppe, 1983). There does not appear to be good evidence for an outcrop.

8. Conclusion

The cross-sections and 3-D model presented here provides a new model for the kinematic evolution of structures in the duplex zone of the Piedemonte Llanero, based on new 3-D seismic and well data. The duplex zone is characterized by a series of as many as five east-verging stacked thrust sheets. To the northeast, the structures become tighter, developing steeper forelimbs, and in some instances they become overturned. We have modeled the Piedemonte duplex zone structures as fault-propagation folds and fault-bend folds characterized by back limbs truncated by ESE-dipping limbs which limit the predicted shortening. The deformation of the foothills occurred in several stages that controlled its evolution and present-day geometry. The main Andean deformation (80% of the total shortening) commenced about 10 Ma with rapid shortening and uplift in the area resulting in the development of an active-roof duplex structure. Later the horse blocks in the triangle zone rose, underthrusting the cover in a passive-roof duplex. The latest stage was an out-of-sequence Laramide-style “thick-skinned” basement-uplift of the range which provided most of the uplift in the area. The Piedemonte area has been shortened by over 40% since the late Eocene. In the last 2 Ma range-parallel right-lateral shear has become an increasingly important component of structural deformation in the Piedemonte. Further drilling will help to define the complex structural evolution of the wedge duplex zone, and further GPS measurements will map the present-day strain in the Piedemonte.

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