Thick-skin orogen–foreland interactions and their controlling factors, Northern Andes of Colombia

S. HERMESTON1 & M. NEMČOK2,3*

1Remora Energy, 1400 Post Oak Blvd., Suite 350, Houston, TX 77056, USA
2Energy and Geoscience Institute at University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, UT 84108, USA
3Energy and Geoscience Laboratory at Geological Institute of Slovak Academy of Sciences, Dúbravská cesta 9, SK-840 05 Bratislava, Slovakia

*Corresponding author (e-mail: mnemcok@egi.utah.edu)

Abstract: The study draws from reflection seismic, in-situ stress and low-temperature geochronology data on the Eastern Cordillera–Llanos foreland basin system of Colombia, which is an example of the retro-wedge of the orogen with an advancing subduction zone. The system was obliquely converging during deposition of the Lower Oligocene–Lower Miocene Carbonera to recent Guayabo formations, recording it by the northeastward depocentre shift in the proximal Llanos Basin. While the southern portion of the foreland did not flex and undergo flexural normal faulting after Carbonera deposition, the northern portion did. The earthquake data indicate that the northern Eastern Cordillera undergoes strengthening by internal deformation, while the southern segment is already strong enough to undergo significant displacements dominantly along its bounding fault systems. Furthermore, the southern segment initiated detachment of the first thick-skin blocks from the proximal Llanos Basin. Such co-existence of different convergence maturity stages along the orogen strike allows unravelling of its development starting with internal deformation and foreland flexure, followed by mountain building and large-scale boundary fault displacements, to the large-scale foreland deformation. The onset of new foreland accretion seems to be controlled by the resistance of the foreland plate to flexing, given that the orogenic engine continues to drive convergence.

Supplementary material: Discussion of evidences for dextral transpression in the Eastern Cordillera, data on exhumation history of the Eastern Cordillera and colour versions of Figures 4–6 are available at http://www.geolsoc.org.uk/SUP18629

Many thick-skin regions occur in retro-wedge settings, associated with advancing subduction zones (see Nemčok et al. this volume, in press), as documented by examples from the Rocky Mountains and eastern Northern Andes (e.g. Oldow et al. 1989; Baby et al. 2013; Jimenez et al. this volume, in press; Mora et al. 2013a; Silva et al. this volume, in press; Tesón et al. this volume, in press). Among those listed, the Eastern Cordillera–Llanos foreland basin system of Colombia (Figs 1 & 2) represents a unique case, because it is currently seismoactive and earthquakes are distributed both inside and along the two opposite boundaries of the Eastern Cordillera (see figure 7 in Nemčok et al. this volume, in press). Furthermore, both plate movement vector patterns in the region (Cortés & Angelier 2005a) and σ1 stress trajectories (Arcila et al. 2000) indicate that the system is experiencing oblique convergence, which should allow us to see different shortening stages of the system along its strike. Such a study area should contain data on the factors controlling thick-skin orogen–foreland interaction through time. In an attempt to unravel this interaction, the study draws from the data on exhumation history, in-situ stress data from earthquakes and reflection seismic images.

Existing knowledge of exhumation history of the Eastern Cordillera

For the purpose of the following text, the Eastern Cordillera will be divided into five strike-parallel zones:

1. the axial zone, including points 1b, c, 4a, b, 5a, b and 5e from Figure 3, and being roughly as wide as the Sabana de Bogotá Plateau shown in Figure 2a;
2. the western flank, including points 1a and 6c, d from Figure 3, and being located between the axial zone and Bituima and La Salina faults shown in Figure 2a;
3. the thin-skinned thrustbelt to the west of the Bituima and La Salina faults;
Modelling of apatite fission track data constrained by vitrinite reflectance data from the Los Cobardes Anticline (Parra et al. 2012) indicates that the first signs of inversion or perhaps basement uplift activity come from the NW corner of the Eastern Cordillera (Fig. 3, point 1a), where they have a Paleocene–Eocene age. Evidence for orogenic activity older than Paleocene comes from the region to the west of the Eastern Cordillera (e.g. Cooper et al. 1995; Gómez et al. 2003, 2005; Ramon & Rosero 2006; Villagomez et al. 2011). However, strictly speaking, the evidence for deformation older than Paleocene comes only from the Central Cordillera. No strong evidence of pre-Paleocene deformation is reported for the Middle Magdalena Valley, where only a single indication comes from the study of Jaimes & DeFreitas (2006).

Apart from the low-temperature thermochronology data, the late Paleocene–middle Eocene initiation of the deformation along the western fold-and-thrust belt is constrained by areally extensive angular unconformity located at the base of the middle Eocene terrestrial formations (Gómez et al. 2003; Restrepo-Pace et al. 2004).

The Eocene orogenic activity has been documented by low-temperature thermochronological methods in both the NW corner (Fig. 3 – points 1a, 1b, 1c; Duddy et al. 2009; Parra et al. 2012) and the axial zone of the Eastern Cordillera, roughly in its middle portion (Fig. 3 – point 4a; Parra et al. 2009; Mora et al. 2010; Saylor et al. 2012a, b). The timing of the basement uplift of the hanging wall of the Vetas Fault (point 1b) and the timing of its internal thrust deformation (point 1c) has been
constrained by apatite fission track data (Duddy et al. 2009). Hanging-wall movement of the Pesca Fault (points 4a, 4c and 5f) has been determined from modelling of the apatite fission track and vitrinite reflectance data (Parra et al. 2009; Ramirez-Arias et al. 2012).

Apart from the low-temperature thermochronology data, the middle Eocene–early Oligocene deformation is indicated by growth strata thinning in the Guaduas Syncline in the direction towards the Villeta Anticlinorium (Gómez et al. 2003) and provenance data based on both conventional sandstone petrology and U–Pb chronology carried out on detrital zircons (Bayona et al. 2008; Nie et al. 2010, 2012; Moreno et al. 2011; Saylor et al. 2011; Saylor et al. 2012a, b). The same deformation timing is indicated by growth strata located to the south of the Sabana de Bogotá Plateau, in the central zone of the Eastern Cordillera (Julivert 1963; Gómez et al. 2005).

The Oligocene orogenic activity has spread from the axial zone of the Eastern Cordillera to both its flanks. The activity remaining in the axial zone was documented at points 4b and 5a, e in Figure 3. The activity reaching the western flank was documented at locations 6c, d in Figure 3. The activity reaching the eastern flank was indicated at locations 1d, 2a, 5c, d and 7a, b in Figure 3.

The activity timing in the axial zone was indicated by:

1. apatite fission track and apatite (U–Th)/He methods constrained by vitrinite reflectance data in the hanging wall of the Chameza Fault (Parra et al. 2009; Ramirez-Arias et al. 2012; point 4b); and
2. apatite fission track data in the hanging wall of the Macheta Fault (Parra et al. 2009; point 5a); and
3. zircon (U–Th)/He data in the western limb of the Arcabuco Anticline (Mora et al. 2013a; point 5e).

Furthermore, the late Oligocene–early Miocene exhumation of the Floresta Massif is indicated by the apatite fission track data (Toro 1990; Toro et al. 2004; Saylor et al. 2012a, b).

The activity reaching the western flank was suggested by:

1. zircon fission track data in the Villeta Anticlinorium (Parra et al. 2009; point 6c); and
2. apatite fission track data constrained by vitrinite reflectance data in the western limb of the Guaduas Syncline (Gómez et al. 2003; Parra et al. 2009; point 6d).

Further evidence for the activity along the western flank during the late Oligocene–early Miocene time period comes from the growth strata thinning of the upper Oligocene–lower Miocene Upper Mugrosa and Colorado formations on flanks of the Nuevo Mundo Syncline (Gómez 2001; Gómez, et al. 2005).

The activity reaching the eastern flank was suggested by:

1. apatite fission track data in the footwall of the Los Yopos Fault (Mora et al. 2010; point 1d); and
2. apatite fission track data in the hanging wall of the Guaicaramo Fault (Mora et al. 2010; point 2a); and
3. zircon fission track methods (Parra et al. 2009; point 5c) and zircon (U–Th)/He method (Mora et al. 2013a, b) in the hanging wall of the Servitá Fault;
4. zircon (U–Th)/He data in the hanging wall of the Tesalia Fault (Mora et al. 2013a; point 5d); and
5. apatite and zircon fission track data, apatite and zircon (U–Th)/He data constrained by vitrinite fission track data in the eastern limb of the Farallones Anticline (Parra et al. 2009; Mora et al. 2013a; point 7a); and
6. zircon (U–Th)/He data in the hanging wall of the Mirador Fault (Mora et al. 2013a, b; point 7b).

Apart from the low-temperature thermochronology data, the evidence for the activity along the eastern flank comes from detailed palynological data documenting a late Oligocene increase in subsidence rates in the Medina basin (Parra et al. 2009).

Some early Miocene orogenic activity remained in the axial zone of the Eastern Cordillera (points 4b and 5b in Fig. 3), while most of the activity resided along its eastern flank (points 1d, 2a, 5c and 7a, b in Fig. 3).

The activity timing in the axial zone was indicated by:

1. apatite fission track (Parra et al. 2009; point 4b) and apatite and zircon (U–Th)/He methods (Ramirez-Arias et al. 2012) constrained by vitrinite reflectance data in the hanging wall of the Chameza Fault; and
2. apatite fission track data in the hanging wall of the Macheta Fault (Parra et al. 2009; point 5d); and
3. zircon and apatite fission track data in the hanging wall of the Servitá Fault (Parra et al. 2009; point 5b).

The activity extending to and/or residing in the eastern flank was suggested by:

1. apatite fission track data in the footwall of the Los Yopos Fault (Mora et al. 2010; point 1d); and
2. apatite fission track data in the hanging wall of the Guaicaramo Fault (Mora et al. 2010; point 2a); and
3. zircon and apatite fission track data in the hanging wall of the Servitá Fault (Parra et al. 2009; point 5c);
apatite and zircon fission track data, apatite and zircon (U–Th)/He data constrained by vitrinite fission track data in the eastern limb of the Farallones Anticline (Parra et al. 2009; Mora et al. 2013; point 7a); and

zircon (U–Th)/He data in the hanging wall of the Mirador Fault (Mora et al. 2013a, b; point 7b).

Some middle Miocene orogenic activity remained in the axial zone of the Eastern Cordillera (point 4b Fig. 3), some along the eastern flank (points 1d and 6a in Fig. 3) and some took place in the NW corner (points 1b, c in Fig. 3).

The activity timing in the axial zone was indicated by the apatite fission track and (U–Th)/He data constrained by vitrinite reflectance data in the hanging wall of the Chameza Fault (Parra et al. 2009; Ramirez-Arias et al. 2012; point 4b).

The activity along the eastern flank was suggested by:

1. apatite fission track data in the footwall of the Los Yopos Fault (Mora et al. 2010; point 1d); and
2. zircon fission track data in the footwall of the San Juanito Fault (Parra et al. 2009; point 6a).

The activity in the NW corner was documented by:

1. apatite fission track and zircon (U–Th)/He data in the hanging wall of the Vetas Fault (Duddy et al. 2009; point 1b); and
2. apatite fission track and zircon (U–Th)/He data in the footwall of the Vetas Fault (Parra et al. 2012; point 1c).

No late Miocene orogenic activity resided in the majority of the axial zone of the Eastern Cordillera, while both eastern and western flanks were active. Actually, a lack of orogenic activity in the present-day Sabana de Bogota region can be inferred from the presence of late Miocene–Holocene deposition in this region. However, the intervening ridges in the axial zone may have been active (see Mora et al. 2010 presenting the late Miocene AFT ages from the Boyaca Fault), albeit with slower uplift/exhumation rates than those at the flanks of this region. Overall, the thermochronology data
requires the cooling in the axial zone to be much slower than that to the east and west of it.

The activity along the eastern flank was indicated by:

1. apatite fission track data in the footwall of the Los Yopos Fault (Mora et al. 2010; point 1d in Fig. 3); and
2. apatite fission track data in the hanging wall of the Guaicaramo Fault (Mora et al. 2010; point 2a in Fig. 3).

The activity along the western flank was suggested by:

1. apatite fission track and zircon (U–Th)/He data in the hanging wall of the Vetas Fault (Duddy et al. 2009; point 1b in Fig. 3); and
2. apatite fission track data modelling constrained by vitrinite reflectance data in the footwall of the Vetas Fault (Duddy et al. 2009; point 1c); and
3. apatite fission track data in the Villeta Anticlinorium (Gómez et al. 2003; point 6c).

Furthermore, La Salina Fault at western margin of the cordillera cuts the Upper Miocene strata (Mora et al. 2010). The same deformation timing can be seen at Peña de Oro and Opon anticlines (Mora et al. 2010).

The Pliocene–Quaternary orogenic activity is characterized by its lack in the axial zone, presence along the western flank (Fig. 3; points 1b, c and 6c) and dominating presence along the eastern flank (Fig. 3; points 2a, 5c, 6b and 7a–c).

The activity along the western flank was documented by:

1. apatite fission track and zircon (U–Th)/He data in the hanging wall of the Vetas Fault (Duddy et al. 2009; point 1b); and
2. apatite fission track data modelling constrained by vitrinite reflectance data in the footwall of the Vetas Fault (Duddy et al. 2009; point 1c); and
3. apatite fission track data in the Villeta Anticlinorium (Gómez et al. 2003; point 6c).
The activity along the eastern flank was indicated by:

1. Apatite fission track data in the hanging wall of the Guaicaramo Fault (Mora et al. 2010; point 2a);
2. Apatite fission track and zircon (U–Th)/He data in the hanging wall of the Servita Fault (Mora et al. 2008; Parra et al. 2009; point 5c);
3. Apatite fission track data in the hanging wall of the San Juanito Fault (Mora et al. 2008; point 6b);
4. Apatite fission track and (U–Th)/He data combined with vitrinite reflectance data in the eastern limb of the Farallones Anticline (Parra et al. 2009; Mora et al. 2013a; point 7a);
5. Zircon (U–Th)/He and apatite fission track data in the hanging wall of the Mirador Fault (Mora et al. 2008, 2010; point 7b); and
6. Apatite fission track and vitrinite reflectance data in the hanging wall of the Boa Thrust (Mora et al. 2008; point 7c).

Furthermore, the Late Miocene–Recent deformation evidence comes from strata truncations by Guaicaramo and Yopal faults (Mora et al. 2010).

Methods

Modern σ3 stress trends were taken from literature (Arcila et al. 2000; Fig. 1). Furthermore, an earthquake focal mechanism database for eight swaths (see swath location in Fig. 3) was taken from the National Earthquake Catalogue of Colombia (INGEOMINAS 2009). Focal mechanism locations were plotted on top of topographic profiles through the Magdalena Valley–Eastern Cordillera–Llanos foreland basin system. Topographic profiles clearly allow one to see both the western and eastern boundaries of the Eastern Cordillera by a change of rugged orogenic relief to sub-horizontal topography.

Reflection seismic and well data from the Llanos foreland basin were interpreted to evaluate the timing of the oblique collision of the Eastern Cordillera with its foreland, coming from the south to the north. The seismic data included about 20 000 km of 2D data and 14 three-dimensional...
seismic volumes. Abundant well data provided stratigraphic ties for the seismic data mapping. Because neither seismic nor well data can be located for confidentiality reasons, their approximate locations will be shown as locations in one of the nine provinces (see Fig. 1 for province location).

Nine seismic horizons were mapped across the basin, including tops of the crystalline basement, Palaeozoic section, Guadalupe Formation, Members 7 and 1 of the Carbonera Formation, León Formation, and sub-units 4, 3 and 2 of the Guayabo Formation. Their division was based on their regional identification and different character of seismostratigraphic units bounded by them. The seismostratigraphic units can be characterized as (Fig. 4):

1. The crystalline basement rocks have their upper surface imaged as a strong peak, which is commonly associated with onlapping reflectors imaging either Palaeozoic or younger sediments. Their image is relatively reflective and patchy.
2. The Palaeozoic sedimentary section has an image characterized by a strong peak representing its top. It is commonly associated

Fig. 4. Dip-oriented profile through the Oropendola Province showing most of the mapped seismostratigraphies. The profile is vertically exaggerated. Note well-imaged reflector truncations at upper surface of the C1 Member of the Carbonera Formation. This local unconformity is onlapped by the León Formation. The local erosional unconformity indicates the location of the western flank of the forebulge during end-C1 time in this area. Note evidence of distinct young flexing.
with onlapping reflectors representing either Cretaceous or younger sediments. The underlying events could be conformable, truncated or absent owing to erosion. If present, the seismic stratigraphic unit varies in the basin from being relatively reflective and layered to being unlayered and pale.

3) The Guadalupe Formation has its top represented by a strong peak with common erosional truncation of the underlying events as the top horizon represents regional unconformity across the basin. The seismic stratigraphic unit itself is characterized by a moderate reflectivity and layered character.

4) The C7 Member of the Carbonera Formation has its top associated with a weak peak with variable strength. Along the central and eastern area the event merges with other underlying events as the thickness and sediment character change. The horizon lies underneath the second lowest and above the lowest pale layers of the Carbonera Formation. The seismic image of the C7 Member is relatively reflective and layered.

5) The C1 Member of the Carbonera Formation has its top imaged as a strong peak overlying a repetitive series of high- and low-amplitude peaks and troughs of the Carbonera sequence. Its low-strength seismic character is correlated to the shale-prone C2, C4 and C6 members and its high-strength seismic character is representative of the C1, C3 and C5 sand-prone members. The top surface of the C1 Member lies above a

Fig. 5. Earthquake data of the swath 1 projected into topographic profile 1 (INGEOMINAS 2009). (b) Earthquake data of the swath 2 projected into topographic profile 2 (INGEOMINAS 2009). (c) Earthquake data of the swath 4 projected into topographic profile 4 (INGEOMINAS 2009). (d) Earthquake data of the swath 5 projected into topographic profile 5 (INGEOMINAS 2009).
regionally extensive layer with a pale and not typically layered character.

(6) The top of the León Formation has a seismic character characterized by a weak peak underlying the high-amplitude character of the base of the Guayabo Formation. The León interval is a thick interval of low-amplitude peaks and troughs indicative of the shale character of the formation.

(7) The top horizon of the sub-unit 4 of the Guayabo Formation can be mapped in reflection seismic data as a strong peak at the top of a highly reflective package correlated to a thick sand sequence in wells. The base of the sub-unit 4 grades into the León Formation and the top grades into a thin shale break between the sub-unit of the Guayabo Formation and overlying base of the sub-unit 3 of the Guayabo Formation.

(8) The top horizon of the sub-unit 3 of the Guayabo Formation is imaged as a strong peak at the top of a highly reflective package correlated to a thick sand sequence in wells. The base of the sub-unit 3 and the top grades into a shale break between the sub-unit 2 and overlying sub-unit 1 of the Guayabo Formation, represented by more-or-less recent sediments bounded by the ground surface of the basin from the top.

(9) The top horizon of the sub-unit 2 of the Guayabo Formation correlates with a strong peak at the top of a highly reflective package correlated to a thick sand sequence in wells. The base of the sequence grades into the sub-unit 3 and the top grades into a shale break between the sub-unit 2 and overlying sub-unit 1 of the Guayabo Formation, represented by more-or-less recent sediments bounded by the ground surface of the basin from the top.

Fig. 5. Continued.
The described division of the Guayabo Formation into four sub-units differs from division in earlier studies, which only recognized two sub-units: Upper and Lower Guayabo formations (e.g. James & van Houten 1979; Parra 2009). It is based on their character in seismic images being different from each other and recognition of their boundaries in wells and seismic images, both of which can be mapped in the entire Llanos Basin. The division was done in order to reach finer stratigraphic control of the foreland basin fill, which helps to determine the depositional history of the Llanos Basin in detail.

All units were mapped in time-migrated images. Subsequently, horizons bounding the Carbonera Formation, León Formation and four sub-units of the Guayabo Formation were regionally depth-converted and used for construction of the sediment thickness maps. The seismic interpretation represents the original research done for this paper. The remaining data came from public sources.

Data

The $\sigma_1$ stress trajectories determined from the regional set of earthquake focal mechanisms taken from Arcila et al. (2000; Fig. 1) indicate an important change in $\sigma_1$ trend along the strike of the Eastern Cordillera–Llanos Basin system. While the Servitá recess of the Eastern Cordillera, roughly to the south of 4.5° N latitude, has its foreland loaded by the east–west-trending $\sigma_1$ stress, the region to the north of this latitude, transitioning from the Servitá recess to the Guaiacarno salient, has its foreland loaded by NW–SE trending $\sigma_1$ stress (Fig. 1).

Earthquake locations, which were taken from the focal mechanism database of INGEOMINAS (2009), document important variations in earthquake pattern along the strike of the Eastern Cordillera. To advance through this dataset towards the region exhibiting most mature results of the mountain building, we can start slicing from north to south.

Profile 1 through the Eastern Cordillera contains a relatively small amount of earthquakes. They only form 32% of the average amount of earthquakes per swath. They are also relatively homogeneously distributed in all parts of the Eastern Cordillera. The profile does not show any earthquake focusing along the western and eastern boundary fault systems of the Eastern Cordillera (Fig. 5a).

Profile 2 contains more earthquakes than the first one (Fig. 5b). They form 96% of the average amount of earthquakes per swath. The internal portion of the cordillera along this profile also exhibits earthquakes, although they are somewhat less scattered than those in Profile 1 (compare Fig. 5a & b).

Profile 3 contains the second largest amount of earthquakes per swath (figure 7 in Nemcok et al. this volume, in press). They form 131% of the average amount of earthquakes per swath. The profile still has numerous internal the Eastern Cordillera earthquakes, but large earthquake clusters are already present as more-or-less focused on the boundary fault systems. Out of 45 focal mechanisms, 25 are distributed roughly along the western flank of the Eastern Cordillera, nine are distributed roughly along the eastern flank and 11 occupy an internal location.

Profile 4 contains numerous earthquakes. They form 116% of the average amount of earthquakes per swath. The profile already contains very few internal Eastern Cordillera earthquakes and displays a clear earthquake focusing on both boundary fault systems (Fig. 5c). Out of 40 focal mechanisms, nine are distributed roughly along the western flank of the Eastern Cordillera, 28 are distributed roughly along the eastern flank and three occupy an internal position.

Profile 5 contains 73% of the average amount of earthquakes per swath. It does not have the internal Eastern Cordillera earthquakes anymore, having all of them focused on boundary fault systems (Fig. 5d). Out of 25 focal mechanisms, 14 are distributed roughly along the western flank of the Eastern Cordillera and 11 are distributed roughly along the eastern flank.

The remaining profiles 6–8 have their earthquake distributions analogous to that of profile 5. They all have strongly asymmetric topographic profiles of the Eastern Cordillera, with the eastern side being the highest and containing a record of distinct exhumation.

Reflection seismic data in dip-oriented profiles document important geometrical changes in the Llanos foreland basin fill from south to north along the strike. Most of the images through the Castilla–Chichimene province show no flexure of the foreland plate (Fig. 6a). All mapped horizons are sub-horizontal along the profile and seism stratigraphies among them show no thickening towards the Eastern Cordillera for stratigraphic units younger than Carbonera Formation. The youngest stratigraphies deposited in the foreland basin are Guayabo 4, 3 and 2 sub-units, the last one being very thin. Furthermore, the Palaeozoic section is deformed by important normal faults controlling half-grabens. However, none of them show indications of subsequent normal fault reactivation during Cenozoic flexing of the foreland plate.

Reflection seismic images through a specific portion of the Castilla–Chichimene province document very young thrusting, which apparently
detaches into the crystalline basement (Fig. 6b). It is located in front of the Eastern Cordillera frontal thrust, which is mapped in the surface geological map. The seismic image in Figure 6b shows that this new front is buried. Its controlling ramp did not propagate all the way to the surface where the deformation is taken up by folding. The Carbonera Formation incorporated in the buried anticline thickens towards the Eastern Cordillera.

An important change in the geometry of the Llanos foreland basin fill comes as one leaves the Castilla–Chichimene province and enters the Santiago province further to the NE. Reflection seismic images here document a prominent foreland plate down-flexing in a northwesterly direction (Fig. 6c). This is the first province northwards along the strike, which contains the youngest sub-unit 1 of the Guayabo Formation. While the Carbonera Formation does not display any distinct thickening towards the orogen, both León and Guayabo formations do. Furthermore, the image documents a system of normal faults. Most of them cut the top of the crystalline basement and die out undetached inside the basement. They propagate upwards, usually, into the sub-units 3 and 2 of the Guayabo Formation.

The northern neighbour, the Stacked Pay province, also shows an important flexure of the foreland plate (Fig. 6d). In this province even the León Formation does not show an important thickening towards the orogen. It is the Guayabo Formation, and namely its sub-units 3 and 2, which do. The flexed top surface of the crystalline basement has an important kink in this province. Its location coincides with the densest spacing of the normal faults, while their spacing increases in direction away from it. The upper propagation tips of normal faults are located in sub-units 3 and 2 of the Guayabo Formation. The lower ones reside in the crystalline basement, without any detachment.

The eastern neighbour of the Stacked Pay province, the Oropendola province, contains seismic images, which are also characterized by a flexed foreland plate (Fig. 4). The dip of the basin floor is lower than that of the provinces along the orogen front, but still recognizable. The León Formation and sub-unit 4 of the Guayabo Formation in the profile show no thickness changes, while the younger Guayabo sub-units thicken in a northwesterly direction. The comparison of the western row of provinces with the eastern one shows that it is in the eastern provinces where the seismic images typically document important erosion-controlled truncations of some horizons and onlaps of their immediate overburdens. For example, Figure 4 contains the top Carbonera Formation, Member C1, with truncations and onlapping León Formation. Similarly, the profiles through the Jaqueyes province document the truncations inside the Carbonera Formation, Member 7, and onlap of the younger sediments.

Important observations can also be made from strike-oriented seismic images, coming from south to north. The image through the Castilla–Chichimene province shows a distinct tilt of the basin fill toward the NE (Fig. 7a). The only sediments indicating northeastward thickening are those in sub-unit 3 of the Guayabo Formation. Sub-units 2 and 1 are missing. The NE neighbour province shows a similar character, although it contains sub-unit 2 of the Guayabo Formation, which also thickens northeastward, together with sub-units 4 and 3, and the León Formation thickens in the opposite, southwest direction, (Fig. 7b). Further northeastward, the Stacked Pay province shows the Carbonera and León formations and sub-units 4 and 3 of the Guayabo Formation without any thickness changes and only sub-units 2 and 1 thicken towards the NE (Fig. 7c). Further north, the Trinidad province even shows a northeastward thinning of the Carbonera and León formations and sub-unit 4 of the Guayabo Formation (Fig. 7d). Sub-unit 3 shows no thickness changes. Sub-unit 2 thickens in a northeast direction while sub-unit 1 has no thickness change and shows no northeastward tilt.

Discussed observations made in reflection seismic images are easier to understand in 3D from thickness distribution maps (Fig. 8a–e). Starting from the Carbonera Formation time slice and finishing with sub-unit 2 of the Guayabo Formation time slice, each of them contains a distinct thickness maximum, representing a depocentre for the respective time. The Carbonera Formation depocentre is a small local one and occurs in the central Castilla–Chichimene province (Fig. 8a). The León Formation depocentre is also small and resides in the northern Castilla–Chichimene and southern Santiago provinces (Fig. 8b). The Guayabo 4 depocentre is a relatively long one in orogen strike-parallel dimension, for the first time (Fig. 8c). It is located in the Santiago and Stacked Pay provinces. The depocentre expresses one more character relatively well that the previous two time slices did not express very well. It is its distinct asymmetry, characterized by the relatively abrupt thinning of the associated thickness maximum in the northeastern direction and long-distance thinning in southwest direction.

The migrating Guayabo Formation depocentre makes it for the first time to the front of the Guaiacamo orogenic salient during the deposition time of sub-unit 2 (Fig. 8d). This is also the first time when the depocentre is not a single local depression. On the contrary, the depocentre has complex geometry, comprising three local depressions. As
a result, its overall asymmetry is gone. The first of the local depocentres lies isolated in the north Santiago and Stacked Pay provinces. The other two twin depocentres occur in the northern Trinidad and Arauco Graben provinces, separated by an area with an only slightly thinned fill.

The Guayabo 2 depocentre more or less remains in front of the Guaicaramo salient, only its geometry was rearranged to two twin depocentres (Fig. 8e). They are about 60 km apart, separated by an area with distinct fill thinning. The southern twin lies in the northern Trinidad and Arauco Graben provinces. The northern one is outside of the study area.

The exhumation timing dataset has been described in the section on ‘Existing knowledge of the exhumation history of the Eastern Cordillera’.

**Interpretation**

The depocentre shift along the strike of the Llanos foreland basin from the Early Miocene to the present, based on a comparison with such a shift.
in obliquely closing convergent settings (e.g. Meulenkamp et al. 1996), indicates its control by oblique convergence. Such oblique convergence can be determined from palaeostress calculations from the fault-striae data from the Guaduas Syncline–Apulo region and Sabana de Bogotá Plateau carried out by Cortés & Angelier (2005b), who recognized the following palaeostress fields acting during the time between the Late Cretaceous and present. The first, Cretaceous–Eocene, event was characterized by an east–west to WSW–ENE trending $\sigma_1$-stress. This $\sigma_1$ stress direction subsequently changed to a NW–SE one, and finally became WNW–ESE trending during the Oligocene–Pliocene.

A close inspection of the palaeostress dataset allows one to imply that the eastern portion of the northern Andes of Colombia was controlled by dextral transpression to compression during the Cenozoic time interval. It is entirely possible that two tectonic phases, which have been separated as based on characteristics of controlling palaeostress regimes, are in fact two snapshots of the same long-lasting dextral transpression mechanism, which involved significant stress deflection and dextral material rotation in its eastern zone,
analogous to deflection and rotation recognized in transpressional orogens (e.g. Nemčok 1993; Gayer et al. 1998). Such dextral transpression would also be in accordance with the northeastward shift in the depocentre location in the Llanos foreland basin. Such dextral transpression, lasting until the present day, is in accordance with the distribution of motion vectors of all involved plates (Cortés & Angelier 2005a). While the Cocos plate moves northeastward at a rate of 71 mm a\(^{-1}\), the Nazca plate near Colombia, central Peru and northern Chile moves eastward, east-northeastward and east-northeastward at rates of 54, 22 and 32 mm a\(^{-1}\), respectively. Bayona (2011, pers. comm.) characterizes the Colombian segment of the Nazca plate also by east-northeastward movement. These plate movements are opposed by an absolute westward drift of the South American plate, which is
responsible for significant resistance against eastward orogenic advance. The drift is characterized by WSW-directed movement rates of 47 and 48 mm a\(^{-1}\) in central Peru and northern Chile, respectively (Moretti 2011, pers. comm.). It is related to the intra-middle Miocene increase in Mid-Atlantic ridge sea-floor spreading rate (Cobbold 2011, pers. comm.). The increased rate controls a large-scale buckling recognized in platform areas of the South American plate, which is under horizontal loading (Moretti 2011, pers. comm.). The horizontal loading is well expressed by earthquakes, the focal mechanisms of which allowed us to determine \(\sigma_3\) stress trajectories as east–west-oriented in the Servita\' recess and WNW–ESE to NW–SE-oriented in the Guaicaramo salient (see Arcila et al. 2000; Fig. 1). Similarly to the West Carpathians and the South Wales segment of the Variscan orogen (see Nemc\'ok 1993; Gayer et al. 1998), the long-lasting transpression in the Eastern Cordillera–Llanos foreland basin system should involve significant stress deflection and clockwise material rotation in the Guaicaramo salient, characterized by the reduced resistance of the foreland plate against the eastward orogenic advance, and reduced deflection and rotation in the Servita\' recess, characterized by the increased resistance of the foreland plate against the eastward orogenic advance.

Having convergence vectors at an acute angle to the trends of rift zones of the failed Early Cretaceous rift system, the result of the dextral oblique closure of the foreland basin was the orogen advance towards the thicker portion of the underlying continental crust affected by rifting in the southern segment. The advance to a position with similarly thick crust took place later in the central segment and even later in the northern segment. It needs to be said at this point that our understanding

Fig. 6. Continued.
of the trends of the Early Cretaceous rift comes from strikes of uninverted or subsequently inverted rift-unit-controlling normal faults, which outcrop in the Eastern Cordillera. San Juanito, which is the example of the uninverted normal fault, and examples of inverted faults such as Bituima, La Salina, Soapaga, Lengupa, Servita and Guaicaramo faults (see Fig. 2a for location); they all have roughly NNE–SSW to NE–SW strikes. A lack of any major normal faults in more distant Eastern Cordilleran foreland indicates that the Early Cretaceous crustal thinning must have been responsible for the progressively thinner crust westward of the Guyana Shield.

Furthermore, it is important to note that normal fault strikes are at an acute angle (up to 20°) to the ramp strikes of the thin-skin thrustbelt located to the east of the Servita and Guaicaramo faults, indicating that the contraction controlling the Eastern Cordillera shortening was not perpendicular to the syn-rift architecture.

The thicker the foreland crust entering the convergence zone, the more buoyant it was. The increase in buoyancy correlated with an increase in resistance against the eastward orogen advance; that is, the decrease in ability of the foreland plate to flex. Eventually, the southernmost segment of the Eastern Cordillera was trying to advance...
towards the highly buoyant foreland, which was practically unable to flex. Because of this, the tectonic regime of the southern portion of the Eastern Cordillera, the Servitá recess, has the largest proportion of orogen-parallel dextral strike-slip faulting from the entire Eastern Cordillera area, as the orogenic material finds it easier to move laterally than to keep overriding the platform. The structural grain of the surface geological map of the southern portion of the eastern orogenic margin has more dextral strike-slip faults than the northern portion.
In contrast to the southern portion, it is the northernmost portion of the Eastern Cordillera, the Guaiacarimo salient, which finds it easiest to over-ride the foreland plate and contains the largest proportion of the orogen-perpendicular contraction.

The along-strike changing mechanism is further indicated by following observations from reflection seismic images. The southernmost profiles through the foreland basin, whose underlying plate does not flex anymore, show a sub-horizontal basin floor and sub-horizontally lying formations of the Carbonera to Guayabo sedimentary section (Fig. 6a). A lack of flexing is also indicated by missing flexure-driven normal faults, which are common in portions of the Llanos Basin further north, where it undergoes flexure. A little further north there are profiles that contain down-flexed basin floor and flexure-driven normal faults (Fig. 6c).

The exhumation patterns seem to correlate well with mountain building events, although the
mountain building clearly shows the following spatial and temporal activity pattern in the Eastern Cordillera (see Mora et al. 2010):

(1) the middle Eocene–early Oligocene time period characterized by the orogenic activity in the axial zone of the Eastern Cordillera only (i.e. Boyacá, Pesca and Soapaga faults);

(2) the Late Oligocene–Early Miocene time period characterized by the orogenic activity expansion westward as far as the Magdalena Thrust and the central portion of the La Salina Fault, located roughly at western Cordillera flank, and eastward as far as the Lengupa Thrust, Chameza Fault, Pajarito Fault and Cubugón Thrust, located roughly at the eastern Eastern Cordillera flank; and

(3) the late Miocene time period characterized by the orogenic activity expansion westward and eastward all the way to the present-day western and eastern fronts of the Eastern Cordillera.

A detailed study of low-temperature thermochronology data described in the section on ‘Existing knowledge of exhumation history of the Eastern Cordillera’ also allows one to see south-to-north spatial/temporal rearrangements of the orogenic activity. For example:

(1) The Carbonera Formation depocentre (see Fig. 8a for location) lies in front of points 7a, b (see Fig. 3 for location), which are the southernmost points in Figure 3, indicating...
orogenic activity during the deposition of the Carbonera Formation.

2) The León Formation depocentre (see Fig. 8b for location) lies in front of point 6a (see Fig. 3 for location). While the León depocentre moved along the strike of the Llanos foreland basin to the NE with respect to the Carbonera depocentre, the southern limit of the orogenic activity underwent the same northeastward shift during the deposition of the León Formation.

3) The depocentre of sub-unit 4 of the Guayabo Formation (see Fig. 8c for location) lies in front of point 5d (see Fig. 3 for location). While the Guayabo 4 depocentre moved along the strike of the Llanos foreland basin to the NE with respect to the León depocentre, the southern limit of the orogenic activity underwent the same northeastward shift during middle–late Miocene.

It needs to be said at this point that depocentre shifts between deposition times of sub-unit 4 and sub-unit 3 of the Guayabo Formation, and sub-unit 3 and sub-unit 2 of the Guayabo Formation do not correlate with any distinct south-to-north shifts in
orogenic activity patterns recorded in outcrops located by points in Figure 3. The first part of the problem may be that the late Miocene time period used for tracking the spatial and temporal trends in the orogenic activity roughly overlaps with the deposition period of Guayabo 3 sediments and the lower portion of Guayabo 2 sediments. This means that we are using less fine time calibration for the orogenic activity than that for the foreland basin depocentre migration. The second part of the problem may be a significant renewal of the orogenic activity along the eastern flank of the Eastern Cordillera that started in the later late Miocene and/or at the beginning of Pliocene. This widespread activity should mask any south-to-north shifts in the intensity of the orogenic activity. We believe that this widespread activity is a combination of two mechanisms:

1. The first is the south-to-north travelling main orogenic loading owing to overall dextral transpression along the strike of the Eastern Cordillera.
2. The second is the southern portion of the Eastern Cordillera undergoing local mountain building as the advancing orogen became stuck against the foreland plate having the largest resistance against the orogen advance from all areas along the strike of the Eastern Cordillera–Llanos Basin system.

Fig. 8. Continued.
Following an intense mountain building along the eastern flank of the southern segment of the Eastern Cordillera, the increasing convergence between orogen and foreland in the south of the convergent system started to initiate accretion of the new thick-skin block in front of the ancestral orogenic front, starting to deform the proximal Llanos Basin (Fig. 6b).

**Discussion**

While the ‘Interpretation’ section focused on description of the orogen-foreland interaction, the ‘Discussion’ section discusses factors in its control. We use table 1 in Nemčok et al. (this volume, in press), which lists all potential factors, and discuss evidence for and against their presence in the study area, dividing the discussion according to three categories of factors.

**Main engine**

The main engine of the Eastern Cordillera–Llanos foreland basin system belongs to the retro-side of the orogen category characterized by subduction zone advance (see Doglioni 1993a, b). Movement rates of converging plates are rather high, including 71 mm a\(^{-1}\) of the northeastward-moving Cosos plate, 54 mm a\(^{-1}\) of the eastward-moving Nazca plate and about 47 mm a\(^{-1}\) of the west-southwestward-moving South American plate (Cortés &
The overall convergence is so strong that it drives large-scale intra-plate buckling in the South American platform regions (Moretti 2011, pers. comm.), which are loaded by horizontal $\sigma_1$ stress.

On a smaller scale, the convergence stage varies along the strike of the Eastern Cordillera–Llanos foreland basin system. The evidence on the initiation of deformation inside the proximal Llanos Basin in the southern end of the system (Fig. 6b) documents that convergence here is on a verge of accreting new foreland blocks into the orogen. The northern portion of the system is still in mountain building, as indicated by earthquake data (Fig. 5).

It is the earthquake data from eight NW–SE trending zones across the Eastern Cordillera–Llanos Basin system (Fig. 3) plotted into cross sections that allow us to see the difference in present-day convergence along the strike of the system. To advance through this dataset from the least to most developed system, we start slicing from the north to the south. Profile 1 does not show any earthquake focusing along the western and eastern boundary fault systems of the Eastern Cordillera (Fig. 5a), indicating that the cordillera still undergoes important internal strengthening by deformation before it can undertake large displacements along boundary faults. With regard to Profile 2, one can conclude that scattered...
earthquake distribution starts to indicate the very initiation of the clustering in broad regions with boundary fault systems inside (Fig. 5b). However, this profile can still be generally characterized as having no distinct earthquake focusing along the boundary fault systems. Profile 3 has large earthquake clusters present as more focused on boundary fault systems (figure 7 in Nemčok et al. this volume, in press). This figure allows one to conclude that all main faults on both sides of the Eastern Cordillera along this transect, including the Guayabito, La Salina, Boyacá, Soapaga and Guaicaramo faults, are active. Profile 4 displays clear earthquake focusing on western and eastern boundary fault systems and contains very small internal activity (Fig. 5c). Profile 5 has all earthquakes focused solely on boundary fault systems (Fig. 5d). The remaining profiles 6–8 are analogous to profile 5. They all have strongly asymmetric topographic profiles of the Eastern Cordillera, with the eastern side being the highest and containing a record of distinct exhumation.

The more advanced stage of the convergence in the south of the system also can be implied from exhumation data described in the section on ‘Existing knowledge of exhumation history of the Eastern Cordillera’ (see Fig. 3 for location), as it is the northern portion of the Eastern Cordillera that allows one to find the record of temporally different mountain building events, while the southern...
portion has most of the older record erased owing to the significant total erosion associated with the important Oligocene–early Miocene mountain building event and extreme total erosion associated with the prominent (late Miocene) Pliocene–Quaternary mountain-building event, especially on the eastern side of the Eastern Cordillera.

It needs to be emphasized that, despite the earthquakes indicating that internal strengthening is still active in the northern Eastern Cordillera, the present-day deposition of the Guayabo Formation indicates that the Llanos Basin is in its overfilled stage (Jordan 1995), that is, the sediment from the thrustbelt is transported almost as far as to the forebulge. The Guayabo Formation is the first stratigraphy in the Llanos foreland basin that does not react to prominent orogenic loading by the spread of the basin-axis facies (Flemings & Jordan 1990), which would be represented by the Leon Formation and four shale-dominated members of the Carbonera Formation, which are separated by four sandstone-dominated members (see Fig. 2b). On the contrary, it is the stratigraphy with coarse sediments coeval to major orogenic loading. Furthermore, the topographic maps of the Llanos Basin indicate the presence of NW–SE- to WNW–ESE-trending alluvial fans running down from the Eastern Cordillera to the Llanos Basin. The streams in this region are all transversal, feeding a longitudinal river, NE–SW-trending Meta River, the position of which is right next to the forebulge (Nemčok et al. 2009), indicating that the foreland basin is almost full.

Internal factors

It seems that there are several factors from the category of internal factors, which control the behaviour of the Eastern Cordillera–Llanos foreland basin system. Several of them, including rheologies of deformed layers, existence v. non-existence of potential detachment horizons, presence of basement buttresses, crustal thickness variations, inherited strength contrasts and pre-existing anisotropy, are all directly related to the fact that the orogen advances obliquely on the foreland containing pre-existing rift zones of the failed Early Cretaceous and Palaeozoic rift (see Fig. 4a) systems. The obliquity of the advance becomes very important in the case of crustal thickness variations in the NW–SE direction associated with Early Cretaceous thinning. As a result, the southern Eastern Cordillera reached the thickest crust first. Therefore, it is the southern part of the system where the foreland resistance against flexing and being overridden is largest. This is the regional trend. On the local scale, geometries of individual Early Cretaceous rift zones and their dividing high control more local strength contrasts, locations of basement buttresses and pre-existing anisotropy. The Palaeozoic rift grain adds to the complexity, as it further contributes to the final geometry and location of basement buttresses, areas with strength contrasts and pre-existing anisotropy.

Along its strike, the individual segments of the Eastern Cordillera respond to the progressively thicker foreland crust entering the convergence zone, as the Cordillera advances from the SW to NE, by solving the energy balance problem, choosing the minimum physical work to perform one of the following events:

1. **new fault propagation** events (occurring in the southernmost segment of the system, indicated by the seismically imaged newly propagating faults in the Castilla–Chichimene province; Fig. 6b);
2. **reactivation** events of pre-existing faults of the orogen (occurring in the southern more than two-thirds of the entire system, indicated by earthquake data in profiles 3–8 in Figs 3 & 5a–d and figure 7 in Nemčok et al. this volume, in press);
3. energy consumption events on opposing gravity by climbing hanging walls (occurring in the very southern portion and northern segment of the system; indicated by recent enhanced exhumation rates); and
4. **internal deformation** events of the orogen (occurring in the northern half of the system; indicated by earthquake data in profiles 1–4 in Figs 3 & 5a–c).

It is the most mature southern portion of the system where the Eastern Cordillera:

1. finished internal strengthening;
2. underwent prominent mountain building and the largest orogenic strike-parallel tectonic transport component;
3. developed prominent orogen asymmetry with a higher eastern side and lower western side; and
4. initiated accretion of thick-skin blocks of the proximal Llanos Basin into the orogenic front.

In the meantime, its foreland plate:

1. is practically unthinned;
2. has high buoyancy;
3. is the most resistant against being overridden; and
4. is unable to flex under an orogenic load.

It is the least mature northern portion of the system where the Eastern Cordillera:

1. still undergoes its internal strengthening;
2. enters the time period of prominent mountain building;
has yet to develop a prominent orogen asymmetry; and

is still far from initiating the accretion of thick-skin blocks of the proximal Llanos Basin.

In the meantime, its foreland plate:

(1) is quite thinned;

(2) has relatively low buoyancy;

(3) is the least resistant against being overridden; and

(4) is able to flex under an orogenic load.

The impact of the Early Cretaceous and Palaeozoic rift (see Fig. 6a) systems on distribution of highs and lows of the Llanos Basin floor is important for the location of basement buttresses and potential shale-dominated detachment horizons. An example of the former comes from the Santiago high that prevents the Llanos plate from ‘elastic’ flexing (Love 1906, cited in Zoetemeijer 1993; Hetényi 1946; Turcotte & Schubert 1982). Instead, it gives it a ‘broken-plate’ flexural behaviour (Waschbusch & Royden 1992a, b; Zoetemeijer 1993), resulting in the magnification of flexural stresses at the summit of the basement high (see Fig. 6d). Figure 6d shows that the magnification is indicated by decreased flexural fault spacing at the maximum flexure point of the basement surface. Examples of the detachment horizon effect come from Palaeozoic lows with the highest likelihood of preserving a shale-dominated Palaeozoic section, which should have an important effect on stress transfer into the distal portions of the Llanos Basin fill.

External factors

Erosion rate variations seem to play an important role in affecting the deformation event choice in the energy balance problem described earlier. Although the mountain building and erosional acceleration are inter-related, the local climate-controlled erosion is apparently capable of driving reactivation (2) and opposing gravity (3) events from the energy balance problem mentioned earlier for little longer than would be in the case without erosion. Such an important climatic forcing, which was described by Mora et al. (2008) for the southern segment of the Eastern Cordillera–Llanos Basin system, is characterized by prominent orogenic asymmetry. Such enhanced erosion is capable of delaying the accretion of new blocks of the proximal Llanos Basin into the orogenic front by removing the gravity resistance and fault-friction resistance against choices (2) and (3); that is, favouring the reactivation (2) and opposing gravity (3) events from the energy balance problem.

The transport and deposition of sediment derived from the orogen complicates a ‘simple’ orogen loading–foreland flexing scenario by redistributing the load on the foreland plate. Although the maximum sediment thickness seems to respond by its location to the location of maximum orogenic load for stratigraphies such as Carbonera Formation, León Formation and sub-unit 4 of the Guayabo Formation (Fig. 8a–c), the younger stratigraphies may have been affected by the orogenic load being partially redistributed by a transversal stream system funnelling sediments southeastward to eastward and by longitudinal palaeo-Meta River, causing the northeastward redistribution. Effective filling of the foreland basin may speed up the onset of detachment propagation in its proximal portion.

Conclusions

(1) Migration of the Llanos foreland basin depocentres from Carbonera to Guayabo 2 snapshots from the SW to NE along the strike of the orogen indicates a dextral oblique convergence between the Eastern Cordillera and the Llanos foreland basin. The in-situ $\sigma_1$ stress trajectories are in accordance with this dynamic control, representing a regional dextral transpressional regime. This regime has a varying ratio of simple shear to pure shear along the orogenic strike. While the pure shear component becomes progressively more important from the south to the north, the simple shear component becomes more important from the north to the south. This variation results in dextral transpression with dominating orthogonal contraction in the north and dextral transpression with an important strike-slip component in the south.

(2) The convergence, which was oblique to the trend of failed Early Cretaceous rift zones, is characterized by progressively thicker foreland crust entering the convergence zone in the direction from SW to NE. While the southern segments of the Llanos foreland basin are characterized by a lack of flexure of its bottom, the northern segments have such flexure. An unflexed foreland plate does not contain any flexure-controlled normal faults. A flexed plate typically contains flexure-controlled normal faults.

(3) The presence of the basement highs in the flexed foreland plate has a tendency to reduce the spacing of the flexure-controlled normal faults over their summits. The spacing increases in a direction away from the summits.

(4) The thicker the foreland crust entering the convergence zone, the more buoyant it is. The
more buoyant the crust, the larger its resistance against being overridden by the Eastern Cordillera. The larger the foreland plate resistance, the larger the likelihood of significant mountain building in the adjacent segment of the Eastern Cordillera.

(5) While the northern portion of the Eastern Cordillera still undergoes strengthening by internal deformation coeval to movements along its bounding faults, which maintains a distribution of areas with the highest elevation in western, central and eastern zones of the Cordillera, the southern portion is already strong enough to undergo significant displacements mostly along its bounding fault systems. A particularly strong activity of the eastern boundary system results in its asymmetric topography represented by areas with the highest elevation located along the eastern side of the Cordillera.

(6) The southern portion of the Eastern Cordillera, which undergoes an important recent exhumation event, is the only portion that has initiated a detachment of the new basement-involved block in the proximal Llanos foreland basin. Being in the most mature convergence stage, the southern segment starts to deform the Llanos foreland basin, being strengthened earlier by significant internal deformation.

(7) The northern portion, which still has a ‘free’ interface to advance into along its northeastward advance trajectory, keeps developing the Guaiacaramo orogenic salient and still undergoes internal deformation.

(8) The presence of different convergence maturity stages along the strike of the Eastern Cordillera–Llanos foreland basin allows one to see several stages of its development history: proceeding from the internal deformation of the thick-skin orogen and flexure of its foreland, through the important mountain building and large-scale displacements along boundary faults of the thick-skin orogen and flexure of its foreland, to the detachment of new thick-skin blocks from the proximal portion of the foreland plate that refused to flex, being too buoyant to be overridden by the orogen. Thus, the onset of the new thick-skin event is triggered by the resistance of the foreland plate, given that the orogenic engine is strong enough to drive the convergence further.

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