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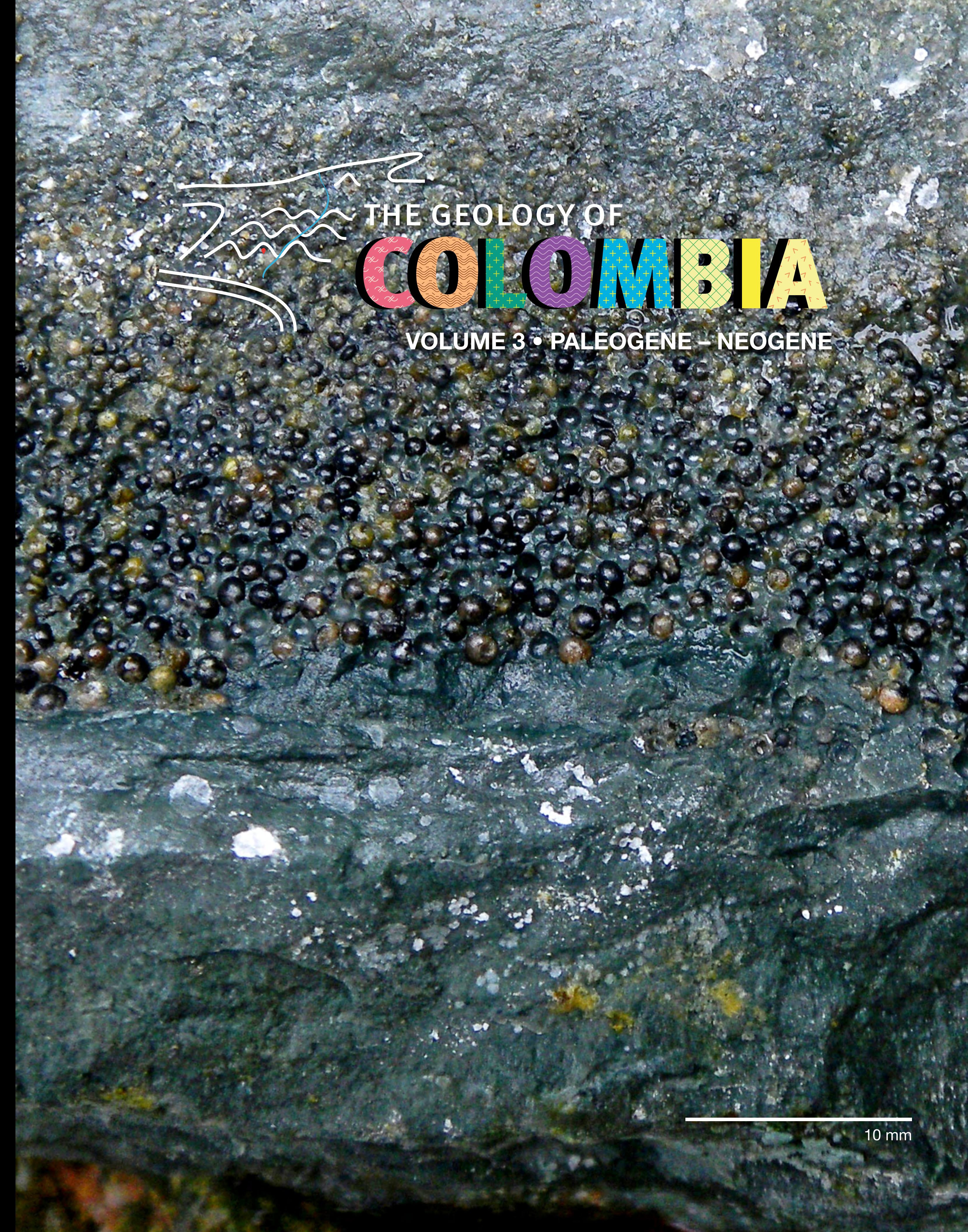

Chapter 5

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The Eastern Foothills of Colombia

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Abstract In this chapter, we summarize for the first time the structural geometry and evolution of the Eastern Foothills of Colombia based on new and previously published cross–sections. We compare shortening records of the Caguán–Putumayo and Llanos Foothills as two different end–members for thick– and thin–skinned foothill deformation along the Andean deformation front. The Caguán–Putumayo area involves thick–skinned deformation and broad basement uplifts, such as the Garzón Massif, with a simple frontal monoclinal structure expressed in folded and faulted basement rocks, similar to broad thrust–related uplifts in the eastern Rocky Mountains of North America. In contrast, the Llanos Foothills have a more complex array of structural styles, from tightly folded frontal basement structures to thin–skinned antiforms of faulted detachment folds. The main factor controlling the style of basement deformation appears to be basement composition, which is igneous/metamorphic crystalline in the Caguán–Putumayo area and low–grade metasedimentary in the Llanos Foothills, prompting tighter basement folds. The main factors in determining thin– versus thick–skinned deformation appear to be the thickness of the Mesozoic – Cenozoic stratigraphic units and the presence or absence of detachment horizons. The Andean Foothills of Colombia record a geometric evolution that started in the Oligocene, with similar structural styles across all segments at that time. However, the deformation styles diverged rapidly during the Miocene to recent shortening, where rapid deposition of thick fluvial sedimentary units drove source rocks into the oil window and helped form efficient detachment horizons for thin–skinned deformation in deeper sectors of the basin.

Keywords: *thin–skinned, thick skinned, basement, detachments.*

Resumen En este capítulo se sintetiza por primeva vez la geometría estructural y evolución del piedemonte oriental de Colombia a partir de secciones estructurales nuevas y otras ya publicadas. Se compara la evolución del acortamiento de los piedemontes del Caguán–Putumayo y Llanos como dos miembros extremos de deformación de piedemonte con y sin basamento implicado a lo largo del frente de deformación andino. El área del Caguán–Putumayo involucra deformación con basamento involucrado y amplios antiformes de basamento, como el Macizo de Garzón, con una estructura monoclinal frontal simple expresada en un basamento plegado y fallado, similar a los *thrust–uplifts* en las Montañas Rocosas de Norteamérica. En contraste, el piedemonte llanero presenta un arreglo más complejo de estilos estructurales, desde estructuras

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de basamento frontales con plegamientos apretados hasta estructuras despegadas de basamento en apilamientos antiformes con pliegues de despegue fallados. El principal control en el estilo de deformación del basamento parece ser su composición, la cual es cristalina ígnea/metamórfica en la región del Caguán–Putumayo y metasedimentaria en el piedemonte llanero propiciando así la presencia de pliegues de basamento más apretados. Los principales factores que determinan la presencia de deformación despegada del basamento o deformación con basamento involucrado parecen ser el espesor de las unidades estratigráficas mesozoicas y cenozoicas y la presencia o ausencia de horizontes de despegue. Los piedemontes andinos de Colombia registran una evolución geométrica que empezó en el Oligoceno, con estilos estructurales similares a lo largo de todos los segmentos de ese tiempo. Sin embargo, los estilos de deformación divergieron rápidamente durante el acortamiento mioceno al reciente, en el cual un rápido depósito de unidades sedimentarias fluviales espesas hizo que las rocas generadoras del piedemonte entraran en la ventana de generación de petróleo y ayudó a la formación de horizontes de despegue eficientes para la deformación sin basamento implicado en los sectores más profundos de la cuenca.

Palabras clave: *deformación sin basamento involucrado, deformación con basamento involucrado, basamento, despegues.*

1. Introduction

Foothill belts in contractional orogens normally represent the youngest deformation front, which usually accommodates active shortening in modern mountain belts (Banks & Warburton, 1986; Cooper, 1996; Morley, 1986). The structural geometries and evolution of foothill belts are related to several mechanical factors, including tectonic inheritance, thickness of the stratigraphic succession, and the presence or absence of suitable detachment horizons. Some studies have further suggested that erosion could be a factor controlling the geometry and evolution of foothills (e.g., Horton, 1999; Malavieille, 2010; Mora et al., 2008). Understanding the geometry and evolution of active foothill systems is fundamental for the exploration of hydrocarbon resources (e.g., Cooper et al., 1995; Dengo & Covey, 1993), active tectonics (Veloza et al., 2012), and the general evolution of mountain belts. Regarding mountain building and orogenic evolution, foothill structural systems provide an essential record in understanding deformation patterns within fold–thrust belts and in extrapolating structural geometries and styles from well–known areas to less studied ones, in both surface and subsurface settings (Nemčok et al., 2013).

There are several recent studies related to fold and thrust belts in Colombia (e.g., Anderson et al., 2014; Caballero et al., 2010, 2013a, 2013b; Saylor et al., 2012; Teixell et al., 2015). However, the Eastern Foothills of Colombia have been studied in even greater detail due to a significant effort primarily from the oil industry (e.g., Carrillo et al., 2016; Jimenez et al., 2013; Martinez, 2006; Mora et al., 2010a; Támara et al., 2015). In this contribution, we summarize previous studies and expand upon them by investigating the lesser known Caguán–Putumayo Foothills. Here, we present various observations that help us reach conclusions regarding the evolution of foothill belts in other Andean provinces and worldwide.

The Eastern Cordillera of Colombia contains several important basement boundaries (e.g., Algeciras Fault; Figure 1; Velandia et al., 2005). We interpret these boundaries as the potential margins of a Precambrian – early Paleozoic mobile belt against the Precambrian Guiana Shield. The fundamental boundaries considered in this contribution include the Algeciras, Tesalia–Servitá, and Pajarito Faults. For example, the Algeciras Fault defines the boundary of known outcrops of lower Paleozoic sedimentary rocks in the Eastern Cordillera south of 4° N (Figure 1). Such Paleozoic rocks are absent east of the Algeciras Fault, where pre–Cretaceous rocks correspond to the Neoproterozoic basement of the Garzón Massif. This configuration also characterizes the pre–Cretaceous substrate farther east in the Caguán Basin (Ibañez–Mejia et al., 2011). Boundaries such as the Algeciras Fault later served as an important boundary for extensional domains characterized by syn–rift Cretaceous and potentially lower Paleozoic rocks (Figure 2). In contrast, in the north, the Tesalia–Servitá and Pajarito Faults are not well documented basement boundaries (i.e., boundaries of different pre–Mesozoic units that also uplift and expose the basement rocks) but rather graben–bounding Cretaceous master faults (Mora et al., 2013a; Tesón et al., 2013). However, and as we document in this contribution, the Algeciras, Servitá, and Pajarito Faults are fundamental pre–existing structural elements that largely controlled the Neogene evolution and geometry of the foothill belts in Colombia.

The foothills of the Caguán and Putumayo Basin display surface exposures of basement (i.e., crystalline igneous or metamorphic rocks), including either Precambrian crystalline or Jurassic igneous (volcanic or intrusive) rocks. In the subsurface,

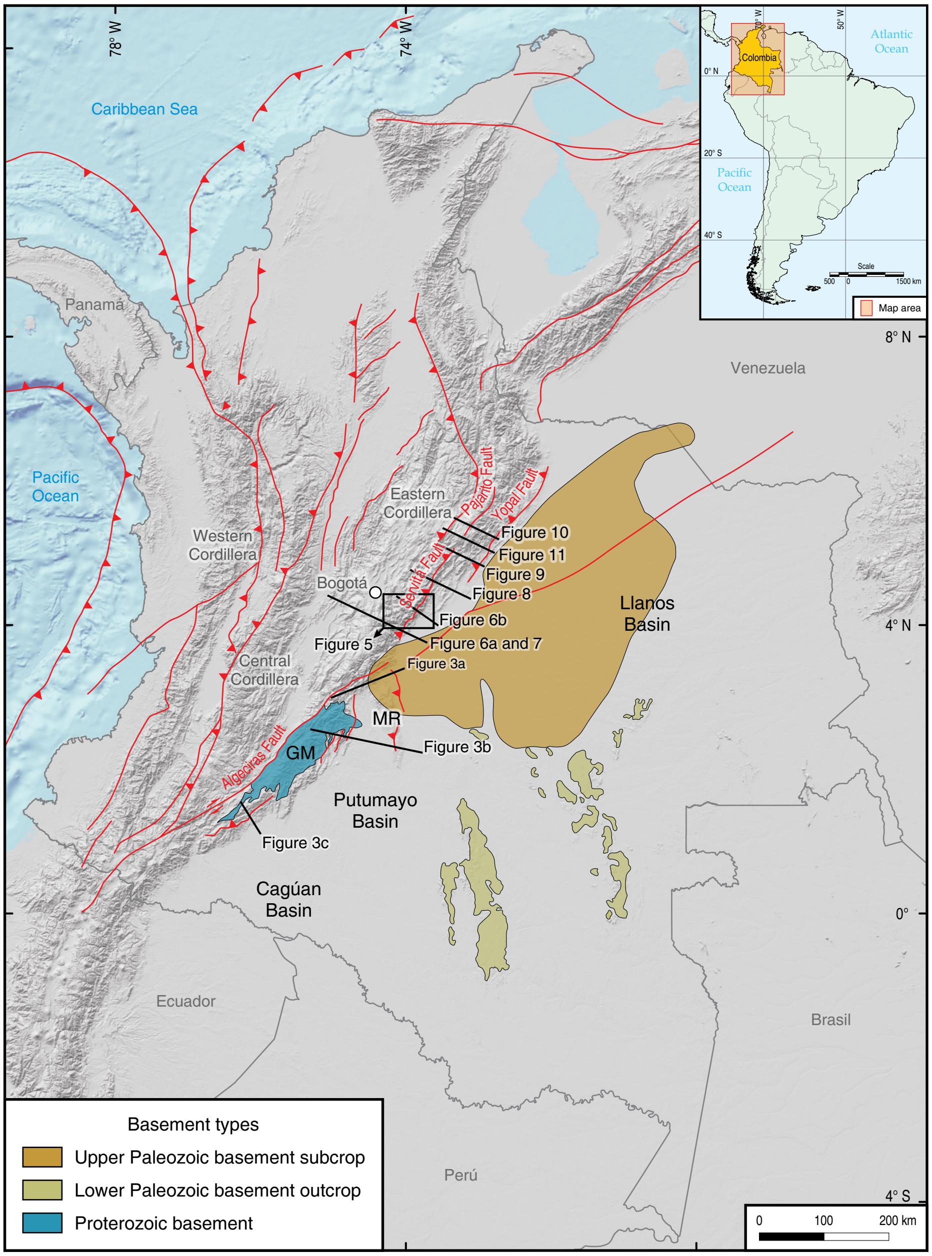

Figure 1. Shaded relief image of Colombia with the location of the figures and cross–sections discussed in the text. The different sub-cropping and outcropping basement types are also shown. The location of the Guaicáramo Fault (which is a fault shown in Figures 10 and 11) can be inferred in this figure because it is the unnamed fault located between the Yopal and the Pajarito Faults. (GM) Garzón Massif, (MR) Macarena Range.

the foreland basin also consists of basement rocks with local occurrences of Paleozoic sedimentary rocks (Figure 1). This configuration contrasts sharply with that of the Llanos Foothills and Llanos Basin. In the Eastern Foothills of the Llanos province, the exposed rocks include Cenozoic, Cretaceous, or subordinate Paleozoic sedimentary rocks, with local metasedimentary rocks. In the Llanos Basin east of the foothills, the absence of documented crystalline basement rocks is significant, and pre–Cretaceous rocks mostly consist of Paleozoic sedimentary rocks (Delgado et al., 2012; Moreno–Lopez & Escalona, 2015; Reyes–Harker et al., 2015). Whereas Paleozoic rocks have been documented in different wells in the subsurface of the Llanos Basin, they are absent in western portions of the Caguán Basin (Ibañez–Mejia et al., 2011).

The basement arch of the Caguán Basin, called the Vaupés swell (Mora et al., 2010b), is a significant crystalline basement feature where the entire Phanerozoic sedimentary section is either condensed or absent (Figure 1). This contrast is particularly relevant in comparison to the Llanos Basin, which forms a deeper basin with a thicker sedimentary fill.

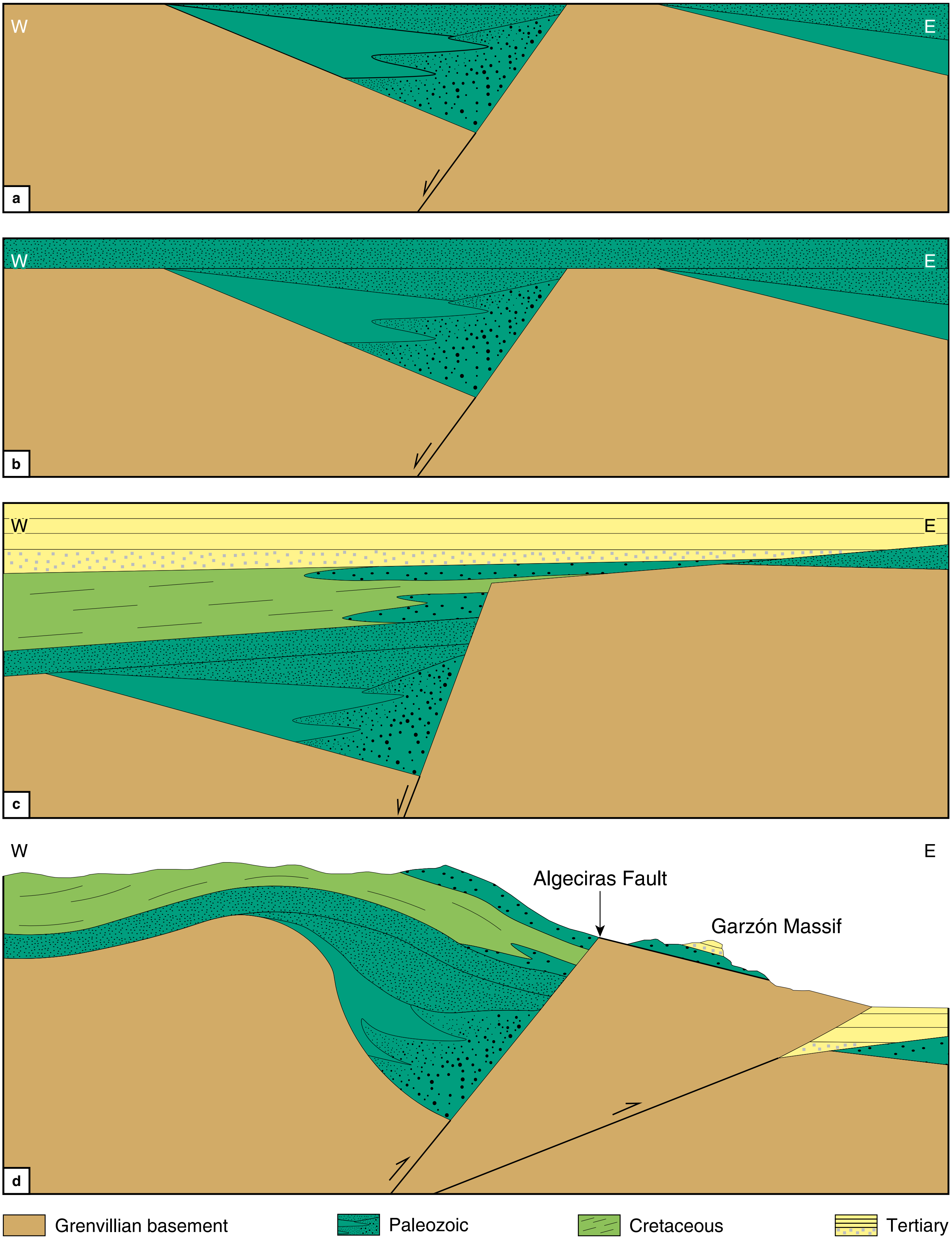
W
E
a
W
E
b
W
E
c
W
E
Algeciras Fault
Garzón Massif
d
Grenvillian basement
Paleozoic
Cretaceous
Tertiary

Figure 2. Generalized illustration showing the proposed evolution of the Algeciras Fault as a crustal boundary with lower Paleozoic rocks to the west and Neoproterozoic basement to the east. In this context the uplifted Neoproterozoic basement blocks of the Garzón Massif correspond to footwall shortcuts (Huyghe & Mugnier, 1995) branched from the Algeciras inverted normal fault. The evolutionary steps are not related to precise geological times, they only intend to summarize the geometric evolution of the different crustal domains.

2. Methods

In this chapter, we review the structural styles and evolution of the Eastern Foothills of Colombia, from the Putumayo Basin to the Llanos Basin, using previously published (e.g., Jimenez et al., 2013; Martinez, 2006; Mora et al., 2010a) and new structural cross–sections. Our new cross–sections are mostly from the Caguán–Putumayo Basin and were constructed based on available surface geological maps as well as subsurface information. From these datasets, we discuss folding mechanisms and controlling factors, and we then compare them with brief observations from other foothills segments of comparable fold and thrust belts.

3. Results

3.1. Caguán Foothills

Recent work and our new cross–sections confirm that the southern ends of the Andean deformation front in the Caguán Basin and in the Putumayo Basin (Figure 3) are simple basement uplifts in which the frontal segments are folded and locally disrupted by reverse faults with minor displacement. Wolaver et al. (2015) suggest that this could resemble basement–involved contractional wedges (e.g., Mount et al., 2011), which include a backthrust dipping to the east. However, in our southernmost cross–section in the Caguán Basin (Figure 3), we observed a simple east–dipping monoclinal panel, lacking well documented backthrusts, whose dip never exceeds 45°. This style resembles more that of classical foreland basement–involved structures (Mitra & Mount, 1998; Narr & Suppe, 1994). Recent work (e.g., Saeid et al., 2017) shows that this structural style continues along strike southward into the Putumayo Basin, where local, steeply dipping forelimbs exceed 60°. This structural style has also been interpreted in northern Ecuador in the Napo Uplift area (e.g., Baby et al., 2013). In these domains, the foreland regions east of this deformation zone are consistently undeformed and flat lying.

In the northernmost Caguán Basin (see Figure 3), although shortening is limited, the basement is faulted with one or multiple basement faults delimiting the Andean deformation front. In general, folding in the hanging wall of the basement faults is minor except in the case of the Macarena foreland basement uplift (Figure 3), where both the hanging wall and footwall display east–dipping folded panels.

Comparable geometries have been described by Berg (1962) as thrust–related uplifts, where the rocks were first deformed by basement–involved folds that are potentially linked to deeper–level, foreland–directed contractional faults. In a subsequent evolutionary step, the main faults emerge and partition the east–dipping forelimb panel, stranding part of the former forelimb in the footwall and the remainder in the hanging wall (Figure 4a–c).

3.2. The Ariari–Guatiquía Region and Significant Features that Can Be Extrapolated

The structural style of the Ariari–Guatiquía region has recently been described by Mora & Parra (2008) using maps, cross–sections, and thermochronology data. The data described in Mora & Parra (2008) as well as in Mora et al. (2006) show that the hanging wall of the Servitá Fault has preserved a thick sequence (ca. 3 km) of Neocomian syn–rift sedimentary units that are absent or condensed in the fault blocks to the east. Data also show that the hanging wall has preserved a >4 km thickness of pre–rift upper Paleozoic units (e.g., Mora & Kammer, 1999), which are absent in the adjacent faulted block, where lower Paleozoic metasedimentary units underlie the condensed thickness of Cretaceous syn–rift rocks in those regions where they were deposited. Mora & Parra (2008) and Mora et al. (2006) also show that the Servitá Fault is an inverted rift–boundary master fault that bounds the principal topographic relief at this latitude along the Eastern Foothills (Figure 5a, 5b).

These features allowed Mora & Parra (2008) and Mora et al. (2006) to interpret the Servitá Fault as the main basin boundary fault inverted during the Cenozoic, but they also make it possible to interpret faults to the east, like the Mirador Fault, as footwall shortcuts.

The cross–section in Figure 6a shows the frontal shortcut faults having similar structural styles as those in the Caguán area. However, some deformation in the foreland domain is also visible. This is mostly related to splays departing from the most important shortcuts and to inverted normal faults. In a cross–section close to where the Anaconda well was drilled (Figure 6b; Mora et al., 2015a), the data from the well can be interpreted in terms of a highly deformed and folded hanging wall block of the Mirador Fault when compared to the regions we have shown to be present to the south. The projection of the fault surface trace and the same fault in the Anaconda well allows us to interpret the Mirador Fault plane as a shallowly dipping fault plane (ca. 20°). This behavior and the intense fold-

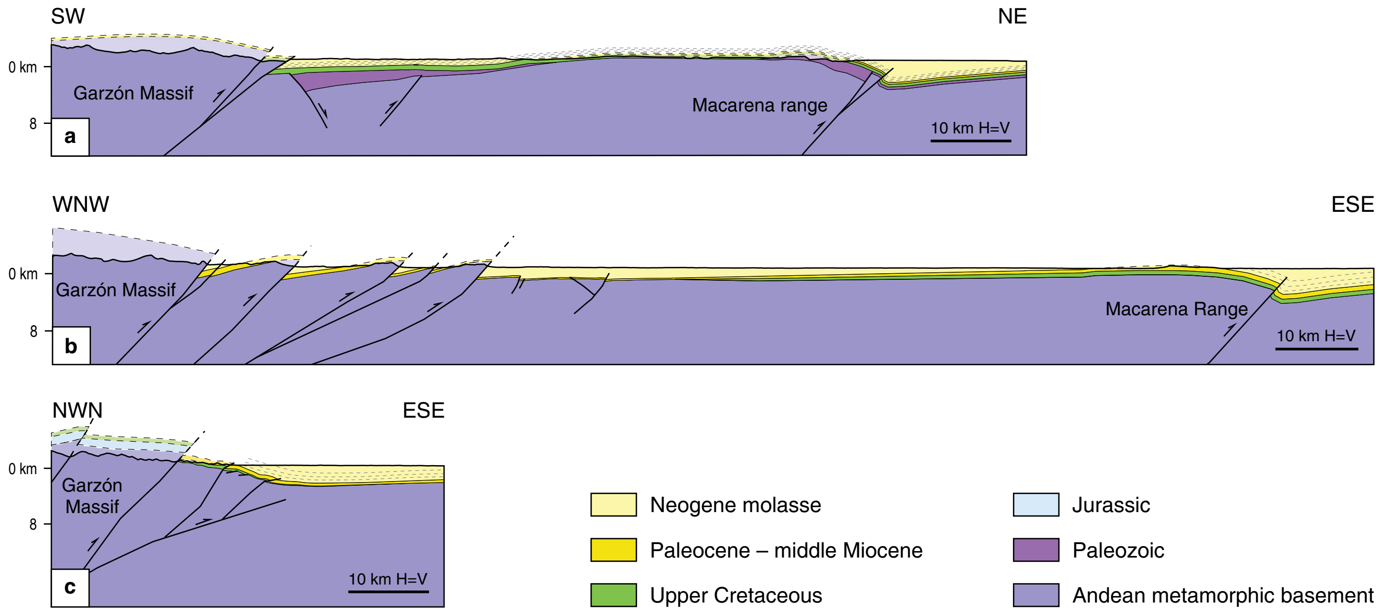

Figure 3. Cross–sections depicting the structural styles of the Caguán–Putumayo basement uplifts between the Garzón Massif and the Macarena range. See Figure 1 for location.

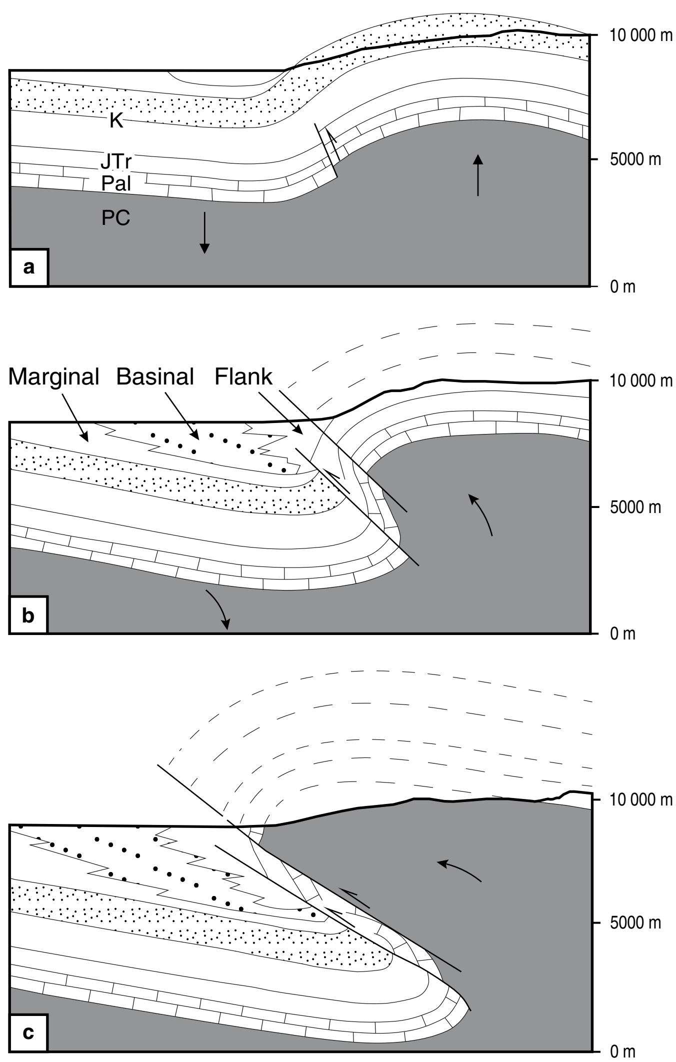

Figure 4. Geometric evolutionary model of thrust–uplifts after Berg (1962).

ing in the hanging wall block represent a significantly different structural style than is found in the foothills to the south. It is also worth noting the absence of Paleozoic sedimentary rocks in the faulted blocks of the Garzón Massif to the south (Figure 3) versus the faulted blocks to the north (Figures 6, 7). Moreover, the basement in cross–sections in Figures 6, 7 is not formed of crystalline basement rocks but instead of metasedimentary units, while the deformed basement rock units in the Garzón Massif in cross–sections in Figure 3 are actual crystalline Proterozoic rock units. These are important differences between the Ariari–Guatiquía (Figures 6, 7) and the Caguán (Figure 3) segments of the Colombian foothills.

3.3. The Guavio and Tierranegra Segments

The Guavio segment displays a structural style that has steeply dipping beds in the hanging wall of the Servitá Fault (Tesalia) and an enormous frontal anticline. This frontal anticline, the Guavio Anticline, is in the hanging wall of the Guaicáramo Fault (Figure 8). Shortening associated with the Tesalia Fault (Figure 8) could be related to a thrust uplift style (Figure 4; Berg, 1962), as there is basement folding laterally evolving to a faulted monocline. However, the degree of folding compared to folding at the areas to the south is significantly larger.

In the Tierranegra segment farther north, the Servitá Fault is relayed by the Pajarito Fault as the main graben boundary

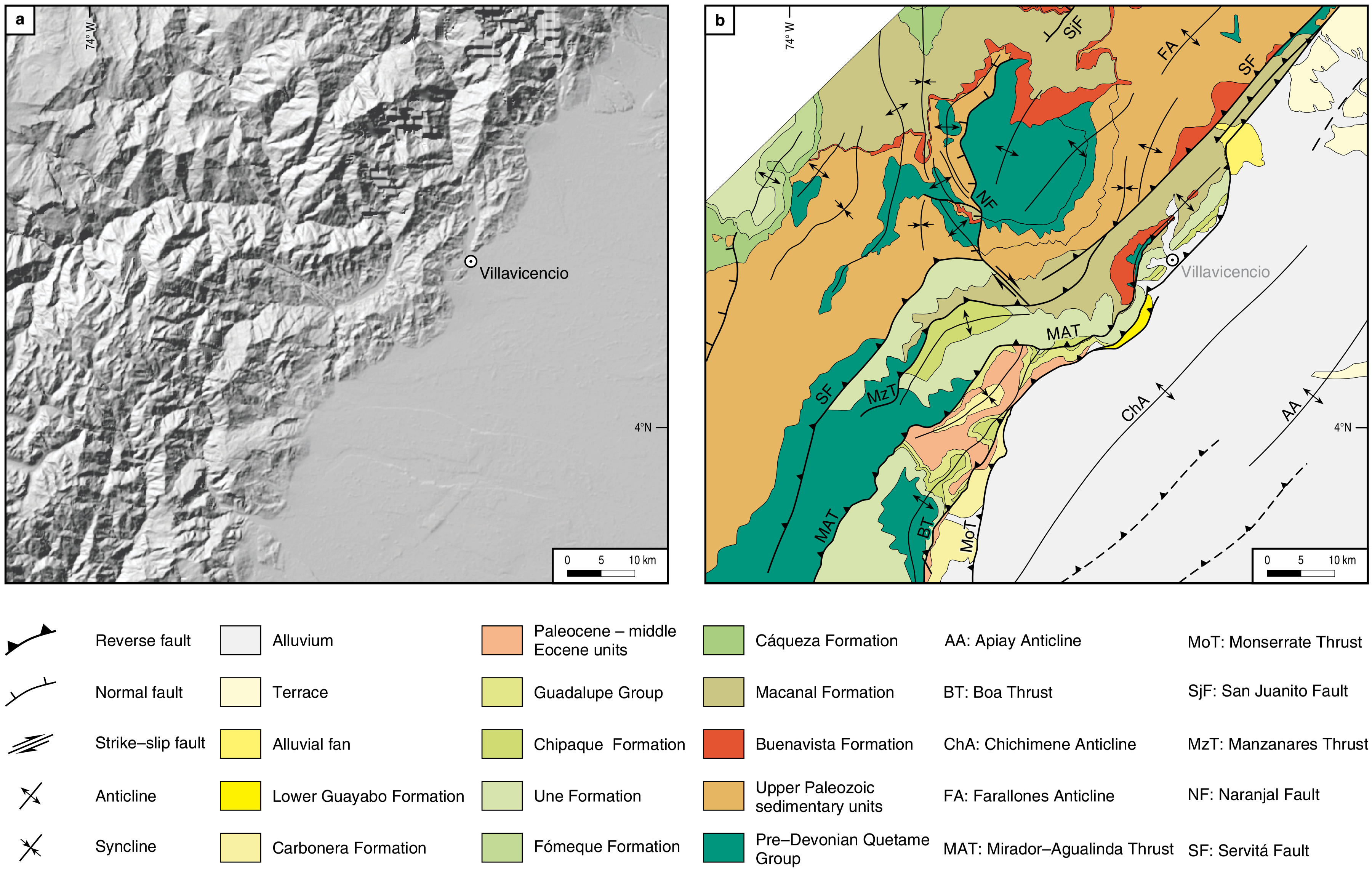

Figure 5. Geological map of the Ariari–Guatiquía region after Mora & Parra (2008). Notice that the Servitá Fault is the boundary for the preserved Paleozoic units observed only west of the Servitá Fault. Moreover, the units recording the onset of Cretaceous deposition are progressively younger to the east. See Figure 1 for their location and the text for further discussion.

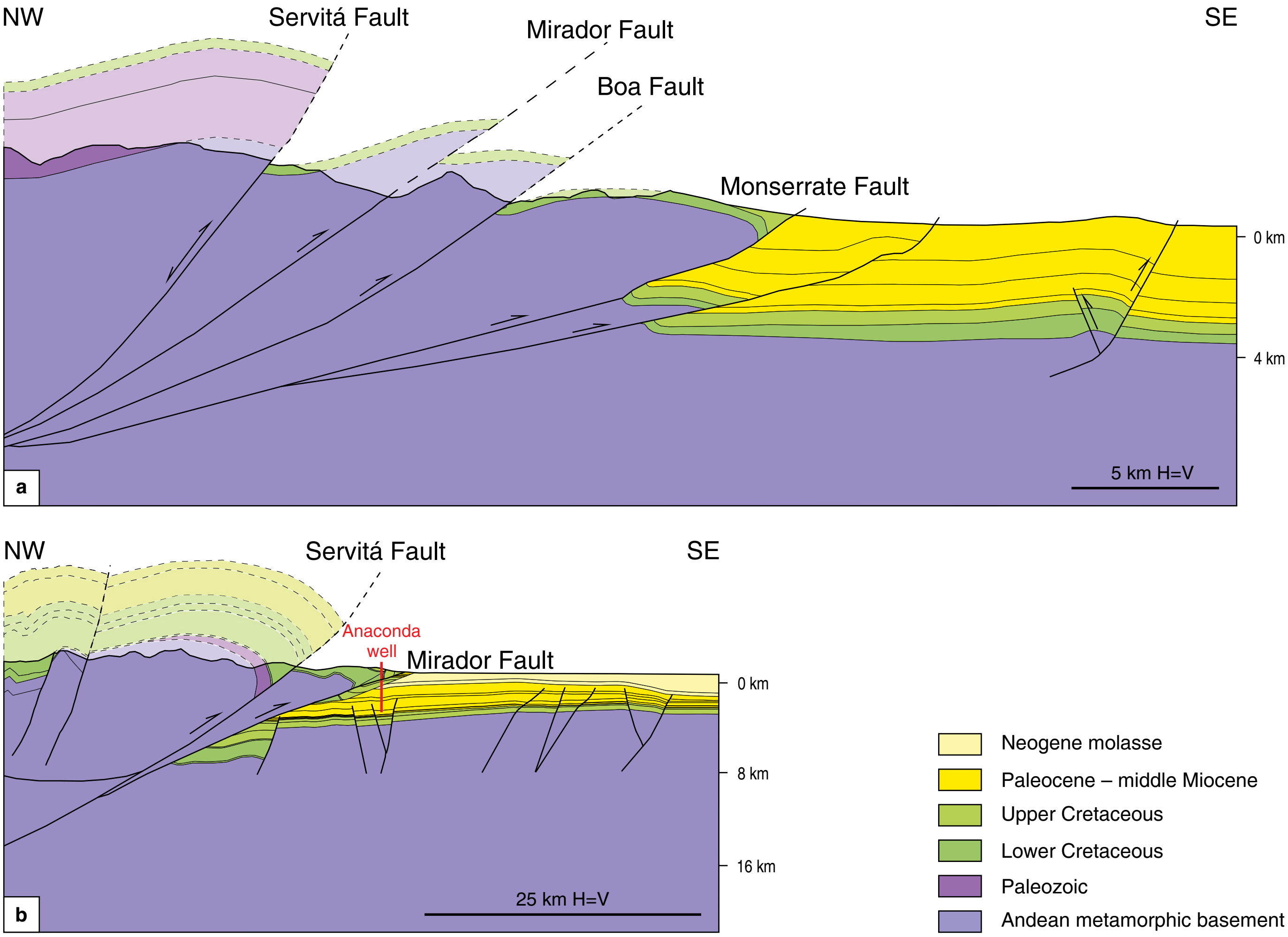

Figure 6. Representative cross–sections of the deformation front of the Ariari–Guatiquía segment. See Figure 1 for location.

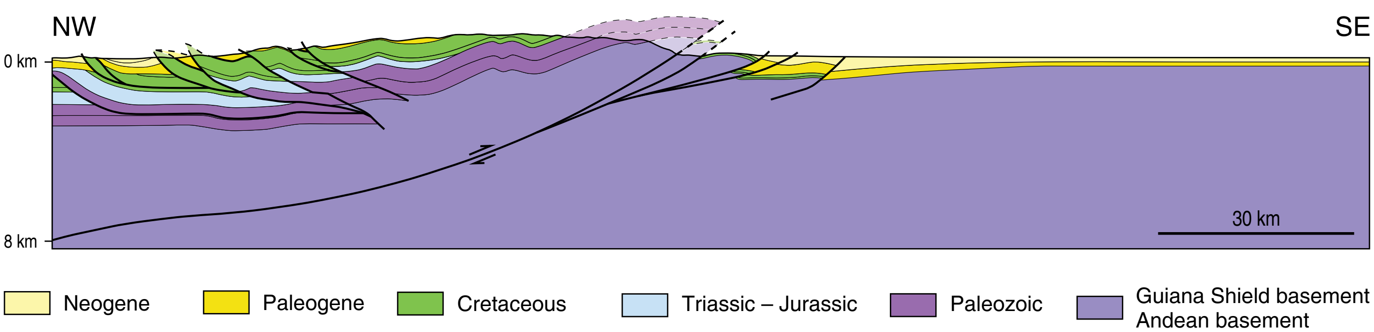

Figure 7. Regional cross–section of the Eastern Cordillera at the latitude of the Ariari–Guatiquía segment. See Figure 1 for location.

fault. Tight folding has also been documented in the frontal shortcut structures of the Guaicáramo Fault, together with subthrust anticlines (Figure 9). In this region, the Yopal and Cusiana Faults represent the most frontal foothill structures. The Yopal Fault is a low–angle thin–skinned fault with a detachment in the Cenozoic shales.

3.4. The Piedemonte Segment

The piedemonte segment is characterized by a stack of thrust sheets folded into tight anticlines (Figure 10), with trailing structures presumably detaching in Lower Cretaceous units and leading structures detaching in shaley units of the Upper

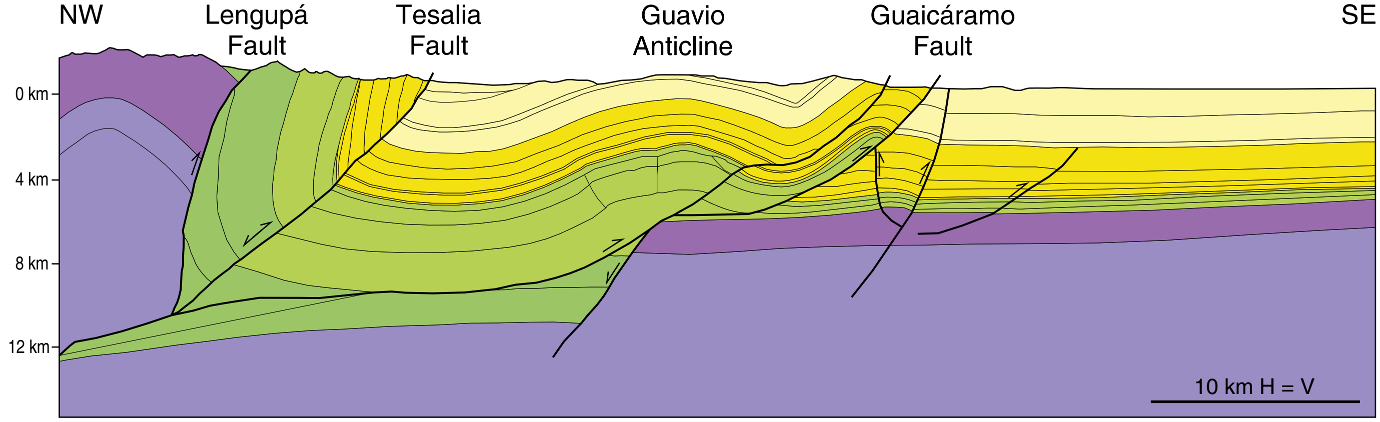

Figure 8. Representative cross–sections of the deformation front of the Guavio segment. See Figure 1 for location.

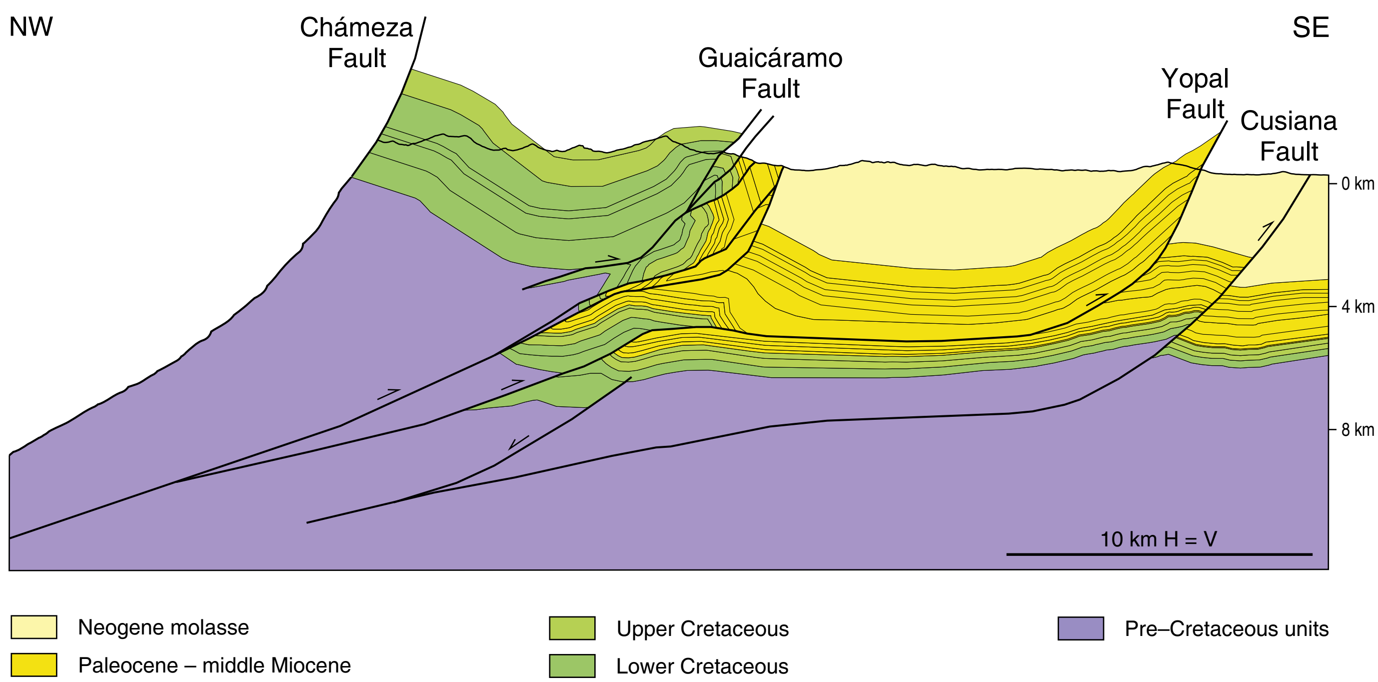

Figure 9. Representative cross–sections of the deformation front of the Tierranegra segment. See Figure 1 for location.

Cretaceous Chipaque Formation (Martinez, 2006). In addition, a rapid thinning of sedimentary units in the stacked anticlines has been documented in several wells, while Lower Cretaceous units are absent in the adjacent foreland. An analogous situation has been described by Castillo et al. (2016) and Gelvez et al. (2016) in the Ariari–Guatiquía area, where syn–rift sedimentary units have been exhumed. In the piedemonte segment, the Pajarito Fault to the west bounds the highest relief area in the foothills (Figure 1), with Lower Cretaceous grabbroic rocks along its fault plane (Vásquez & Altenberger, 2005) and over mature thick syn–rift Cretaceous sequences (Mora & Parra, 2008). This fault could be interpreted as an Early Cretaceous master rift boundary fault, while the structures at the front and to the east could be part of the uplifted foreland rock formations that lack Cretaceous syn–rift units. The difference then in the piedemonte region is that the exhumation associated with the main foothill structures is much less than in the Ariari–Guaitiquía segment.

4. Evolution

Recent studies have helped elucidate the evolution of foothill structures during the Cenozoic (e.g., Ramírez–Arias et al., 2012). Martinez (2006) showed that the presence of tight antiformal thrust structures below the relatively simple shape of the Nunchía Syncline (Figure 11a) proved that there was a late

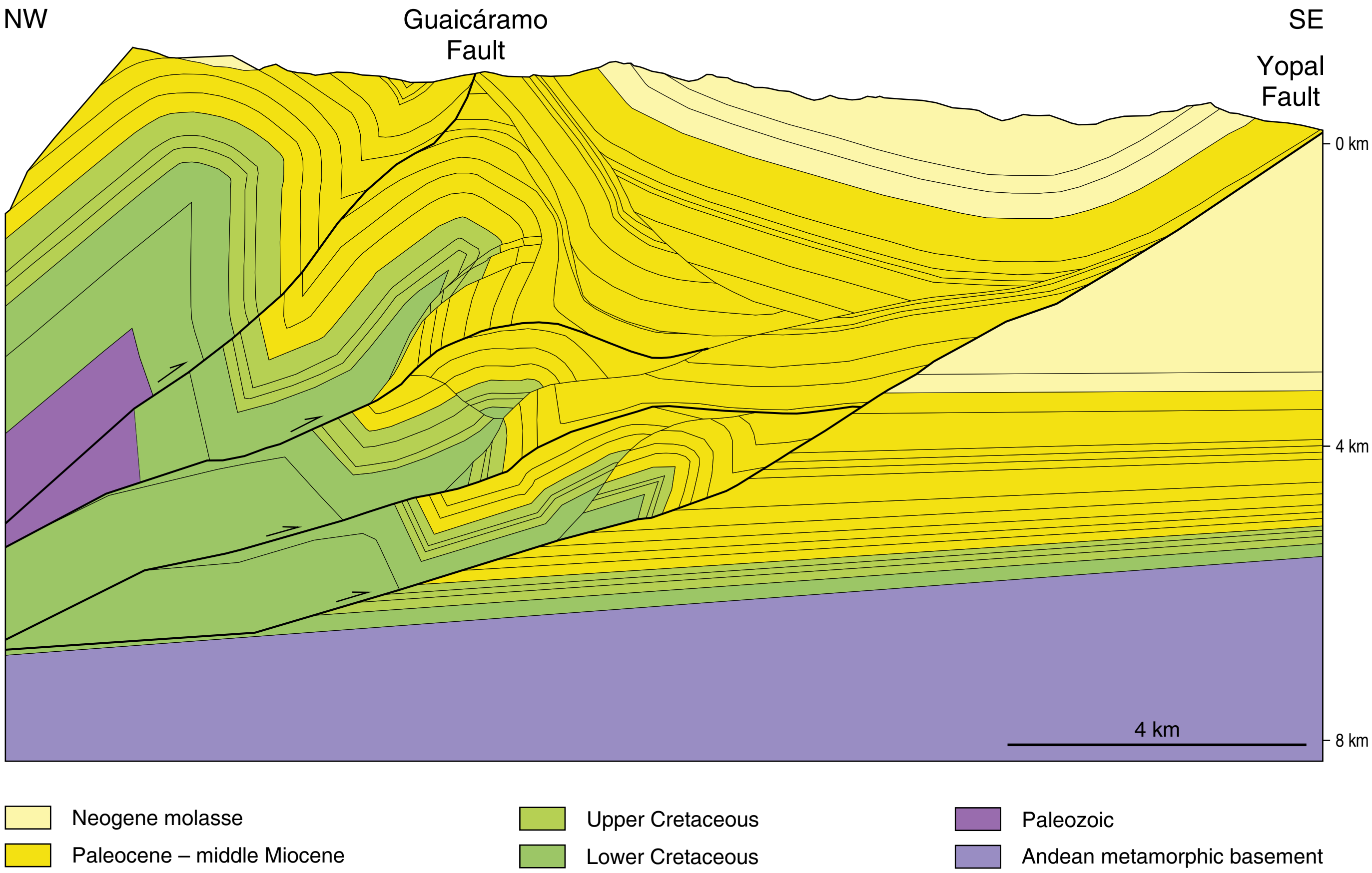

Figure 10. Representative cross–sections of the deformation front of the piedemonte segment. See Figure 1 for location.

Oligocene – early Miocene phase of detachment folding, with the detachment folds forming adjacent to one another. On top of those anticlines, there is the deposition of the Neogene sedimentary units. Thrust stacking of anticlines and a rather passive uplift of the Nunchía Syncline was a deformation event that occurred from the Miocene to Quaternary (Martinez, 2006).

Mora et al. (2010c) detected two cooling events in the same region using AFT (apatite fission tracks) data for samples from the crests of the uppermost anticlines located in the piedemonte antiform described by Martinez (2006) (Figure 11b). The documentation of such early deformation is based on the presence of two age populations (middle Miocene and younger in low–chlorine apatite grains and Oligocene to early Miocene in high–chlorine grains; Mora et al., 2010c). Subsequent thermochronology studies, fracture analysis, and microtectonic studies document a late Oligocene folding event in multiple folds in the Eastern Cordillera (e.g., Mora et al., 2013b). Late Oligocene growth strata in the Eastern Foothills, Magdalena Foothills, and Upper Magdalena Valley indicate that deformation of that age appears to be ubiquitous across the Eastern Cordillera (Mora et al., 2013a). Ramón & Rosero (2006) show evidence of important unconformities and growth strata of the same age in the Upper Magdalena Valley.

Southwards in the Ariari–Guatiquía area, several researchers have described the style of exhumation (e.g., Mora & Parra, 2008; Parra et al., 2009a, 2009b, 2010). It appears that graben–boundary master faults, like the Servitá Fault, started exhuming by the Oligocene while adjacent shortcuts possibly display minor exhumation or folding. Analogous behavior has been shown for the piedemonte segment (Bande et al., 2012).

Finally, Ketcham et al. (2016) provide detailed documentation of the exhumation history of the piedemonte antiform via thermochronology studies, in which the stacked thrust sheets were folded and potentially exhumed by the late Oligocene (Figure 11). A final out–of–sequence deformation event would then have been reactivated, faulting and stacking all the structures of the piedemonte antiform (e.g., Martinez, 2006). As indicated in Mora et al. (2015a), the final out–of–sequence deformation in the foothills was possibly more rapid, as deduced by thermokinematic modeling. Regarding the Garzón Massif, which is the geological province involved in the thick–skinned deformation of the Caguán–Putumayo Foothills, Anderson et al. (2016) suggest ongoing exhumation by the mid–Miocene, while Oligocene exhumation has not been documented so far in that area.

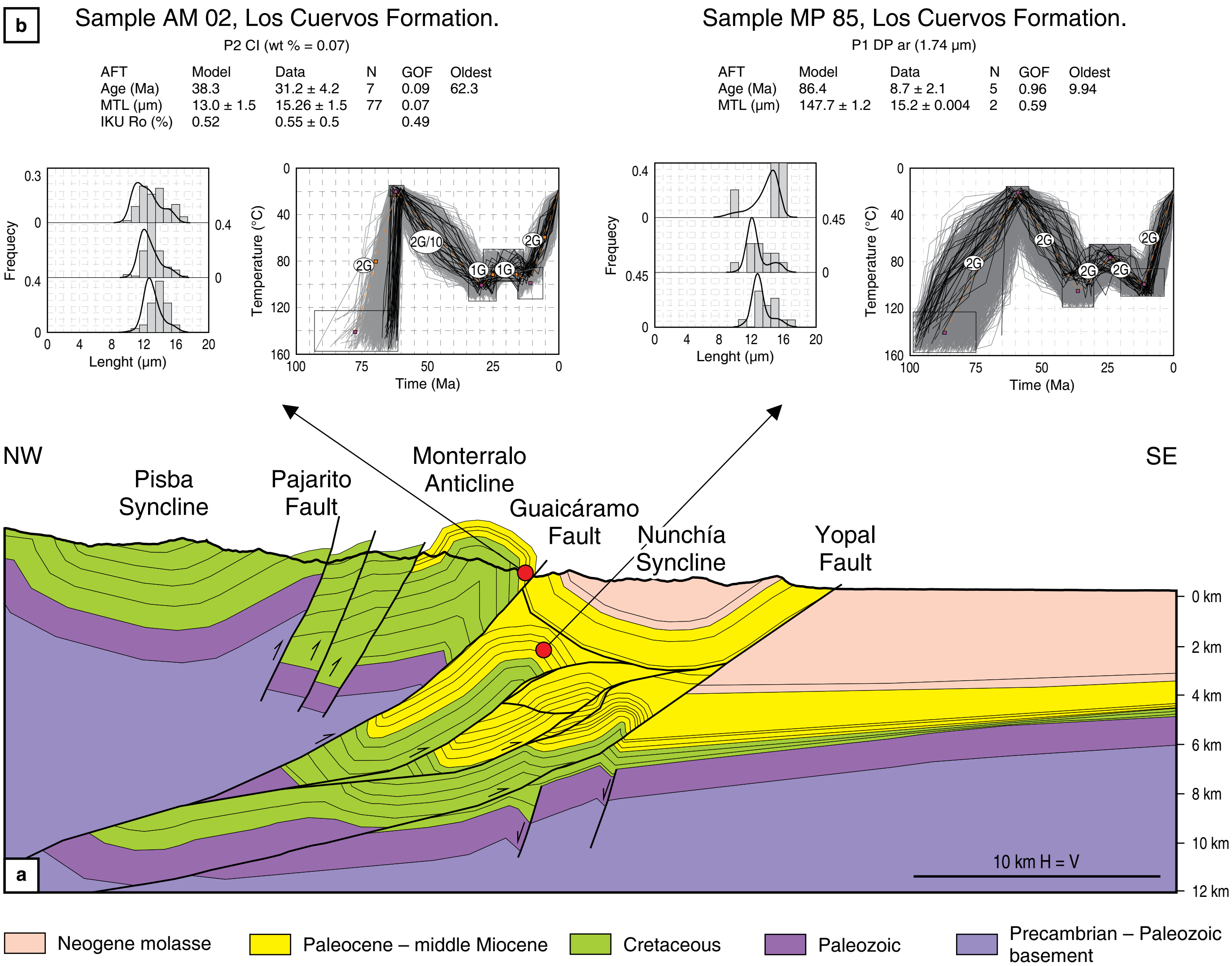

Figure 11. (a) Cross–section for the piedemonte segment and **(b)** high–resolution thermal solutions for anticlines in the same structure (after Mora et al., 2014). See Figure 1 for location.

5. Discussion

Thick–skin deformation has been documented in the southern Llanos Foothills as well as in the Caguán–Putumayo Foothills. Moreover, basement deformation at the frontal Eastern Foothills of Colombia appears to follow the pattern of thrust uplifts suggested by Berg (1962). However, there is a big difference that relates to the degree of folding of the basement rocks. The trishear mechanism of folding (Erslev, 1991; Hardy & Allmendinger, 2011; Hardy & Ford, 1997) can be used to effectively describe this change. Applying this trishear idea, the southern Llanos foothills along the Ariari–Guatiquía segment would be related to a higher propagation versus slip ratio, while the Caguán–Putumayo Foothills would be related to a lower propagation versus slip ratio. Further north in the Guavio and Tierranegra segments, intensely folded pre–Cretaceous rocks have been documented. Here we suggest that this major difference is related to the type of basement involved in the deformation. To the south, the Caguán–Putumayo Foothills are more related to the deformed crystalline basement rocks (Figure 1). To the north, basement–involved contractile deformation is related to the upper Paleozoic sedimentary units or the lower Paleozoic metasedimentary units, as documented by the Anaconda well. Tightly folded lower Paleozoic metasedimentary rocks of the Quetame Group are involved in an overturned fold, suggesting that the stratified anisotropies of the Paleozoic rocks may promote this behavior. A similar behavior has been suggested by Kammer et al. (2020). Alternative interpretations suggest the influence of salt tectonics in the structural style of this area (e.g., Parravano et al., 2015). Parravano et al. (2015) interpreted an overturned panel of Cretaceous rocks encountered during drilling of the Anaconda well as having been formed under the influence of salt tectonics on the basis of the salt occurrences of the Upin salt mine. However, the occurrence of lower Cretaceous salt is not ubiquitous and cannot be generalized for the Eastern Foothills. Moreover, other areas along strike with similar structural styles have documented the absence of salt layers (e.g., Kammer et al., 2020). Therefore, salt could be locally intensifying the degree of folding in overturned panels deforming lower Cretaceous rocks (Parravano et al., 2015); however, the available evidence shows that it is not the most decisive or ubiquitous factor influencing structural styles for the folded Paleozoic rocks in this segment.

An additional consideration is the fact that there is no documented precursor rift system along most of the Caguán Foothills, whereas inverted master faults have been well documented in the Llanos Foothills. We hypothesize that the presence of these faults would act as a buttress or as a strain riser as documented in the same region by Mora et al. (2006) or in the Alps (Coward et al., 1991; de Graciansky et al., 1989; Gillcrist et al., 1987; Huyghe & Mugnier, 1995).

North of the Ariari–Guatiquía region, there is another major change in structural style, with thin–skinned deformation becoming very important. However, we draw important distinctions between the two situations, in which a broad thin–skinned anticline such as the Guavio Anticline (Figure 8) contrasts with the narrow antiform containing at least three main thrust stacks in the piedemonte region (Figure 10). It has been suggested that the Guavio Anticline overlies a major basement high, which could be related to a Neocomian normal fault (Figure 12; e.g., Mora et al., 2006; Velasquez, 2002). If this is the case, the Guavio Anticline may reflect a thin–skinned fault–bend fold on top of a basement step (Casero et al., 1997; Jimenez et al., 2013; Mora et al., 2006, 2010b; Rowan & Linares, 2000; Teixell et al., 2015). In contrast, the piedemonte antiform has been attributed to closely spaced faulted detachment folds (e.g., Jimenez et al., 2013; Martinez, 2006). We synthesize these observations as follows. Both the Ariari–Guatiquía and Guavio segments have well–documented Paleozoic rocks below Mesozoic – Cenozoic cover units, which contrasts sharply with the Caguán Foothills. However, the thick–skin structural style in the Ariari–Guatiquía segment is more similar to that documented here for the Caguán Foothills. Therefore, we hypothesize that the spatial onset of thin–skinned deformation in the Guavio segment is closely related to the presence of a thicker Mesozoic – Cenozoic stratigraphic succession in comparison to the southern Ariari–Guatiquía segment.

One critical geometric contradiction—that the Guavio segment has broader thin–skin structures while the piedemonte segment has anticlines stacked atop each other—could be influenced by the spacing of pre–Andean syn–rift features (normal faults) in a foreland position east of the main master syn–rift boundary faults. Such features could be absent, have less displacement, or be closer together in the piedemonte segment, since gravity data reveal no such basement high beneath the piedemonte antiform (see Figures 8, 11 where the frontal thrust sheets are interpreted as being controlled by underlying Cretaceous normal faults, which are more broadly spaced and have more throw in the Guavio segment [Figure 8] than in the piedemonte antiform [Figure 11]).

Mora et al. (2014) suggested several possible reasons for thrust stacking in the piedemonte segment of the Colombian foothills: The presence of minor–displacement syn–rift normal faults; stratigraphic pinch–out or changing properties (becoming thinner or coarser) of the basal Chipaque detachment; and thickness of sedimentary Cenozoic units which act as a backstop for a forelandward propagation of thin–skinned deformation. In areas like the Bolivian Andes, even climate has been suggested as a potential controlling factor for thin–skinned foothill–style deformation (Horton, 1999; Montgomery et al., 2001). However, in both the Bolivian and Colombian cases, the coincidence between the presence and thickness of detachment horizons and the overall width of the thin–skinned deformation front is well expressed. Further, as Mora et al. (2015b) documented, the potential role of climate in the evolution of the Colombian foothills could also be suggested as a mechanism in regions of enhanced tectonism such as along contractional horsetails (syntaxes) close to the termination of major basement faults like the Algeciras Fault (e.g., Rosello et al., 2004). This scenario, however, is not applicable to the context of multiple thrust stacks in the piedemonte segment. Instead, in the partially analogous Magdalena Valley Foothills belt, Moreno et al. (2013) document so–called bypass structures, which are fold–thrust structures above ancient normal faults. This and the Guavio case could be templates for the piedemonte foothills, where stacking and structural styles are also partially controlled by underlying normal faults (see Figures 8 and 11 where the frontal thrust sheets are interpreted to be controlled by underlying Cretaceous normal faults). Finally, the spatial coincidence between stacked anticlines and the thickest Cenozoic sedimentary record (Mora et al., 2014), suggests a potential causal relationship, as has been shown experimentally (Banks & Warburton, 1986; Bonini, 2001, 2007).

To summarize the evolution of this region, we suggest two situations with similar starting points that later diverged because of the sedimentary sequence thickness (Figure 13a, 13b). Both of them show a prestrained region with a master normal fault to the left (west) and more frontal normal faults with less displacement. For example, this could be the situation during the Early Cretaceous for the Eastern Llanos Foothills in the Ariari–Guatiquía segment and also in the piedemonte segment. The onset of inversion with significant exhumation could have occurred by the Oligocene along the master normal faults, with additional minor inversion in the more frontal normal faults with less displacement. However, deposition from the Oligocene to Neogene is much thicker in areas like the piedemonte segment, leading to more buttressing and intense folding than has occurred in the Ariari–Guatiquía

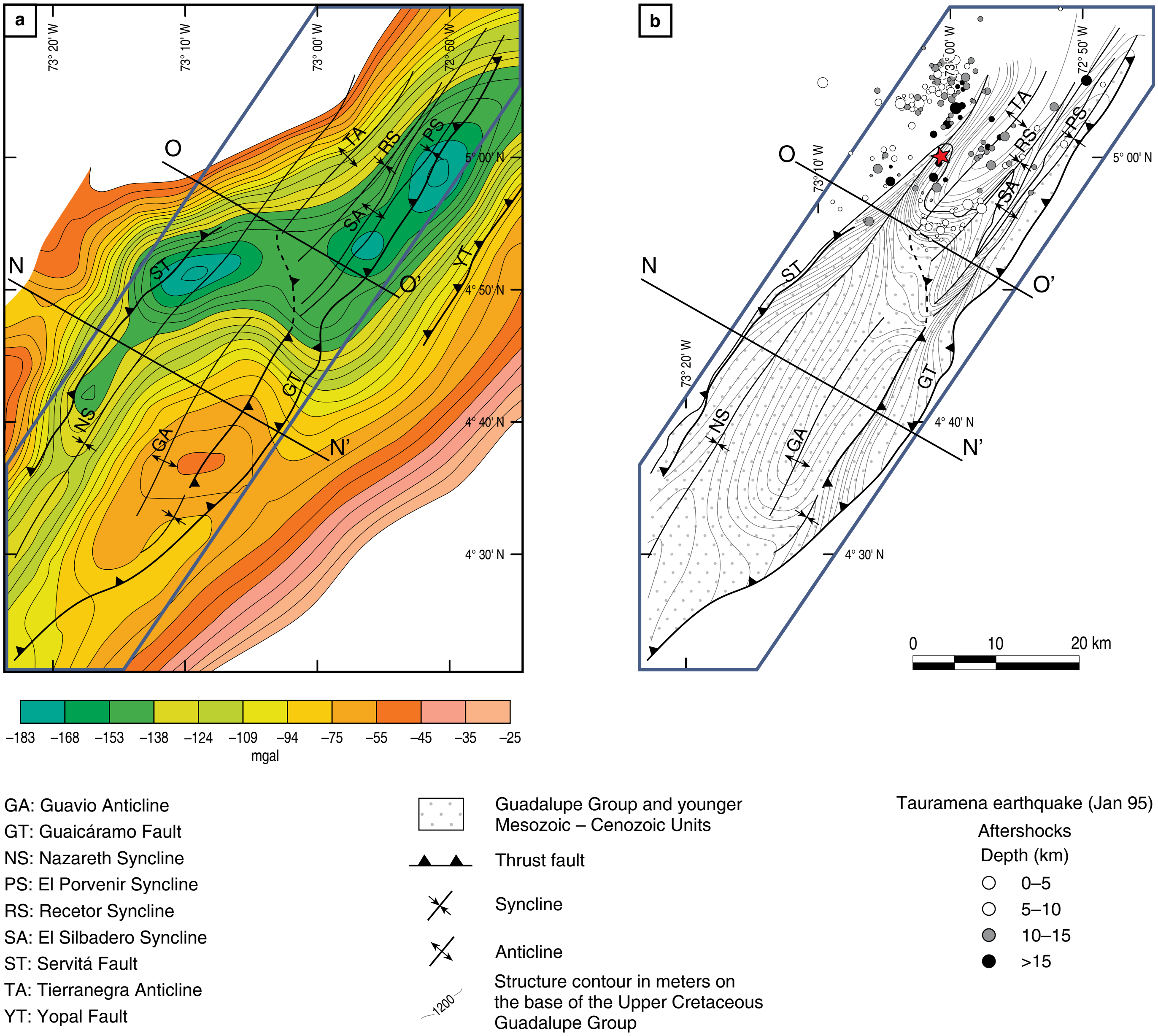

Figure 12. (a) Compilation of the main structural features and gravimetry showing the segmentation of the Eastern Foothills front and the location of the inferred inherited anisotropies. The map depicts variations in Bouguer anomaly in mGal (after Velasquez, 2002). Gravimetric lows are in green colors; orange and red colors show gravimetrical highs. **(b)** Structure contour map to the top of the Cretaceous and aftershocks of the Tauramena earthquake (the star shows the location of the main shock) showing the different structural styles in two different segments of the Guaicáramo thrust. Note the tight folding and periclinal terminations in the northern segment and the presence of seismicity just north of these periclinal terminations (see text for further discussion). Cross–section N–N' shows the location of Figure 8. Cross–section O–O' shows the location of Figure 9. Notice that Figures 8 and 9 are located in Figure 1, therefore with that spatial reference Figure 12 can also be located in Figure 1. Figure after Mora et al. (2006).

segment, which underwent a more classical inversion. In the piedemonte segment, apart from the minor inversion of the smaller Neocomian faults they may prompt the typical case of possible effects of pre–existing basement topography on thrust fault ramping described by Schedl & Wiltschko (1987). The overall differences in styles between the Ariari–Guatiquía segment and the piedemonte segment would therefore have been caused by the thicker sedimentites.

Recent studies (Mora et al., 2019a, 2019b) suggest that the Upper Cretaceous source rocks in the foothills would have been mature and in the oil window by the late Miocene to recent period. Given that this is also the timing of the most important shortening and antiformal stacking in these structures (Ketcham et al., 2016), we suggest, as initially proposed by Mora et al. (2010b) for the thin–skinned sub–Andean basins of South America in general, that the presence of source rocks in the oil

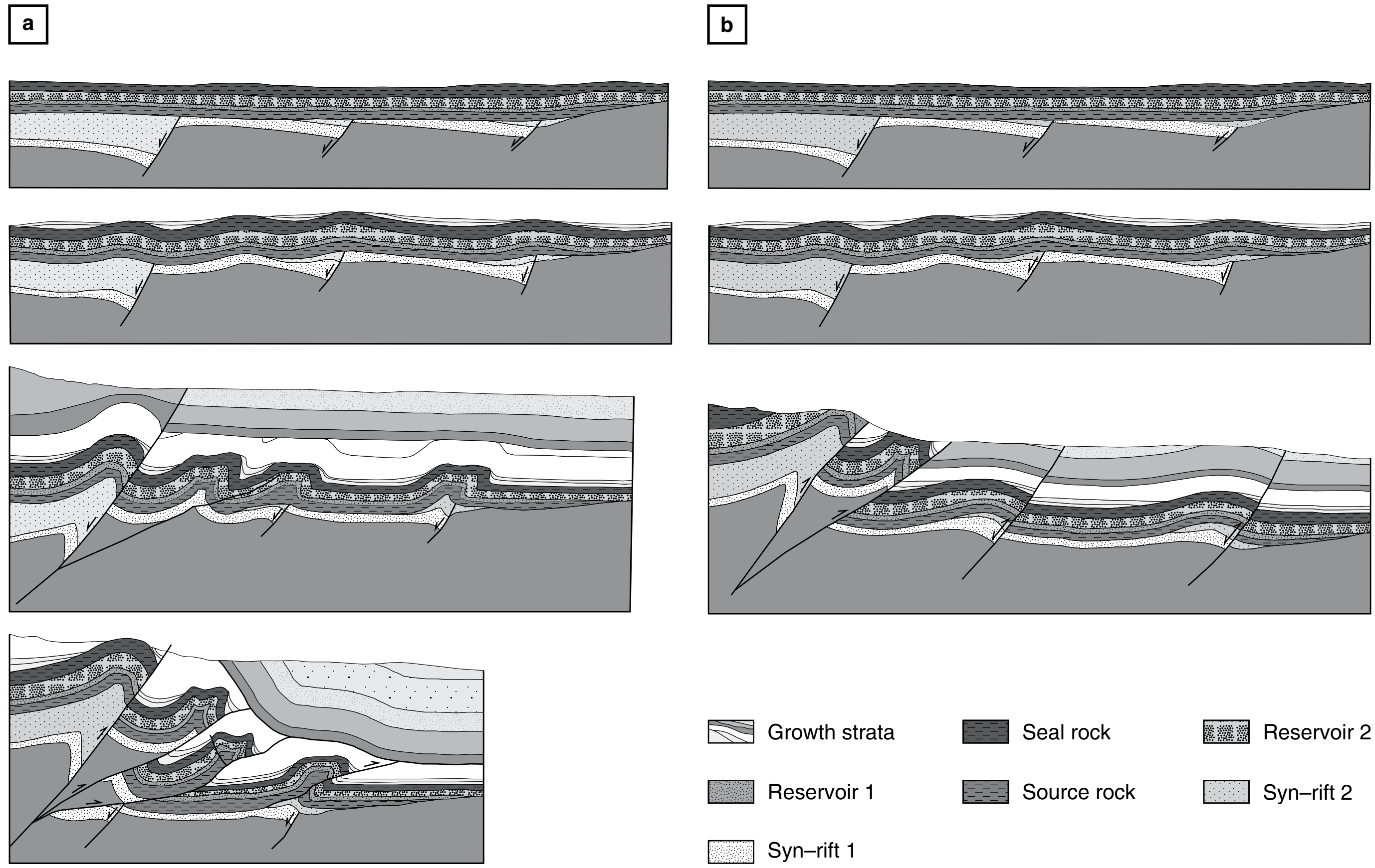

Figure 13. Summary evolutionary sketch of two end members of the Eastern Foothills. **(a)** Thin–skinned end member with thick sedimentary cover. **(b)** Thick–skinned end member with thin sedimentary cover.

window favored the role of those horizons as efficient detachments during the Pliocene – Pleistocene. One important line of evidence to reinforce that idea is the fact that other shaley horizons in the Eastern Foothills, like the Miocene C2 Member of the Carbonera Formation (Gomez et al., 2009), has never been documented as a detachment horizon for shallow foothill structures. Moreover, to the south in the Ariari–Guatiquía segment, poor and immature source rocks and less burial would not favor thin–skinned deformation.

We suggest that this sequence of evolutionary events and deformation geometries potentially can be found in other areas, such as the Sierras Pampeanas (Jordan & Allmendinger, 1986; Ramos et al., 2002) for the thick–skinned end members or the Peruvian sub–Andean ranges for thin–skinned behavior (e.g., Mora et al., 2014).

There is a final aspect that has not been mentioned in this review. This is the role of oblique stresses reactivating pre–existing normal faults in transpressional or contractional terrains. Without this factor, reactivation of normal faults in contraction would be extremely difficult. Our review is based on 2D cross–sections and makes minor mention of this factor. Previous studies (e.g., Branquet et al., 2002; Rosello et al., 2004) have considered that oblique stresses and wrench tectonics are instrumental for the origin and structural styles in the Eastern Cordillera and associated foothills. We agree that stresses impinging obliquely on the pre–existing anisotropies are instrumental for their reactivation in the foothills (e.g., Mora et al., 2006, 2010a). However, it is significant that well documented strike–slip faults like the Algeciras Fault, display minor strike–slip movements and are localized structures, with narrow deformation zones, mainly south of 4° N latitude. Therefore, we believe that stresses are not purely orthogonal to the structures but also strike–slip tectonics are not dominant in the Eastern Foothills of Colombia. Previous studies support this (e.g., Tesón et al., 2013).

6. Conclusions

In this chapter we propose that the main differences between the Caguán–Putumayo and Llanos Foothills belts of Colombia are related to the type of basement involved in the deformation front, the thickness of the sedimentary units, the presence or absence of detachments, and the spacing and throw inferred in buried inherited Mesozoic normal faults. The presence of a crystalline basement and thin sedimentary cover in Caguán promotes the development of broad basement uplifts with little folding, while thick sedimentary cover and a more metasedimentary basement facilitates the development of thin–skinned structures and duplexes in the Llanos Foothills. Moreover, buried normal faults are more easily reactivated wherever the applied stresses are oblique with respect to the inherited anisotropies. The initial evolution of both foothill belts was similar and progressive, but since the mid–Miocene, their structural styles showed significant departures due to the above–mentioned features. The time (ca. 30 Ma) required to progressively develop the Eastern Foothills of Colombia and the factors involved in such development represent important templates for other folded belts worldwide.

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