Teixell, Antonio, Eliseo Teson, Juan-Camilo Ruiz, and Andres Mora, 2015, The structure of an inverted back-arc rift: Insights from a transect across the Eastern Cordillera of Colombia near Bogota, *in* C. Bartolini and P. Mann, eds., Petroleum geology and potential of the Colombian Caribbean Margin: AAPG Memoir 108, p. 499–516.

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# The Structure of an Inverted Back-arc Rift: Insights from a Transect across the Eastern Cordillera of Colombia near Bogota

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## ABSTRACT

Geologic maps, seismic profiles, and structural field data are used to constrain a structural cross section of the eastern Cordillera of Colombia, the Medina–Utica transect, from the Llanos to the middle Magdalena Valley forelands. The Medina–Utica transect illustrates the geometry and kinematic evolution of a continental back-arc region that evolved from rifting to compressional mountain building because of changes in the dynamics of the subduction zones nearby. As other orogens formed by rift inversion, the eastern Cordillera shows intense thrust deformation in the foothill margins, associated with the reactivation of the main former extensional margins, and an orogen interior with comparatively less deformation and relief (the Sabana de Bogota Plateau). While the orogen margins are dominated by basement-involved thick-skinned thrusting, the Sabana de Bogota is interpreted as a salt-detached fold belt with a basal decollement in lower Cretaceous evaporite at a depth of ca 4 km (2.4 mi). Anticlines in the Sabana de Bogota are interpreted to have formed as diapiric salt walls during the pre-orogenic rifting, later squeezed and welded during the Andean shortening, together with syntectonic sedimentation and halokinetic sequence development. A sequential restoration of the cross section to selected time steps based on a wealth of tectonics-sedimentation and thermochronological data enables to track the evolution of orogenic deformation. The total shortening in the Medina–Utica transect is calculated as 82 km (50.9 mi) (27% of the predeformed length). Compressional deformation in the area started probably near the Cretaceous-Tertiary boundary, manifested by localized folding and faulting in the Sabana de Bogota and foothills, much guided by the weak salt horizons. Evidence for gentle folding and thrusting persists through the Paleogene at low rates of <0.5 mm/a. By the Neogene the mountain belt was in full accretion, and rapid shortening at rates near 3 mm/a was accommodated by thrusting in the outer margins of the former rift system. The eastern Cordillera of Colombia exemplifies a pattern of tectonic evolution of inverted rifts in which deformation



DOI:10.1306/13531947M1083650

commences in the basin interiors in a distributed way, strongly controlled by weak stratigraphic units, and evolves to a point when intense shortening is shifted into the weak faults at the rift margins. This gives rise to prominent mountain topography, rapid erosion, and fast sedimentation in the forelands.

## INTRODUCTION

The back-arcs of subduction zones are complex regions subject to episodic changes in tectonic regime (i.e., regional extension or compression) because of variations in the geometry of the subducting plate (e.g., flat vs. steep slab), changes in plate kinematics, or the episodic collision of arcs and microcontinents throughout the subduction history. The northern Andes of Colombia and Venezuela consist of a complex system of deformational and magmatic mountain belts formed as a product of the interactions between the Nazca, Caribbean, and South American plates since Mesozoic times. Among these, the eastern Cordillera of Colombia illustrates the case of a former back-arc extensional basin within the continental South American plate, which was later submitted to shortening and constitutes an example of inversion orogenic belt (e.g., Nemcok et al., 2013, and papers therein).

The eastern Cordillera appears now as an NNE-trending, 110- to 200-km (68.3 to 124.2 mi)-wide thrust-fold belt that formed during the Cenozoic because of the transmission of stresses into the South American Continent by the accretion of arcs in the northwestern Andes, and was much controlled by the contractional reactivation of pre-existing faults of a Mesozoic back-arc rift (Colletta et al., 1990; Cooper et al., 1995; Mora et al., 2006, 2013). Progressive uplift of the doubly verging orogen of the Cordillera was associated with subsidence in the adjacent foreland basins of the Magdalena Valley and the Llanos (Figure 1). The large-scale structure of the eastern Cordillera of Colombia has been extensively reported by general cross sections that reflect diverse, often-conflicting conceptions of the dominant structural style (Campbell and Burgl, 1965; Julivert, 1970; Colletta et al., 1990; Dengo and Covey, 1993; Cooper et al., 1995; Roeder and Chamberlain, 1995; Restrepo-Pace et al., 2004; Toro et al., 2004; Cortes et al., 2006; Mora et al., 2008; Saylor et al., 2012; Teson et al., 2013). Conflicting views remain as to the nature of thrusting, whether dominantly thin- or thick-skinned, and to the magnitude of the associated thrust displacements.

This chapter describes a new structural transect through the central segment of the eastern Cordillera of Colombia, near the latitude of Bogota (the Medina–Utica transect; close to latitude 5° N, Figure 1), with the aim of providing a better understanding of the structural style by evaluating the role of low- and high-angle thrusting, folding, and salt tectonics across the profile. A moderate amount of compressional deformation and a very rich database including

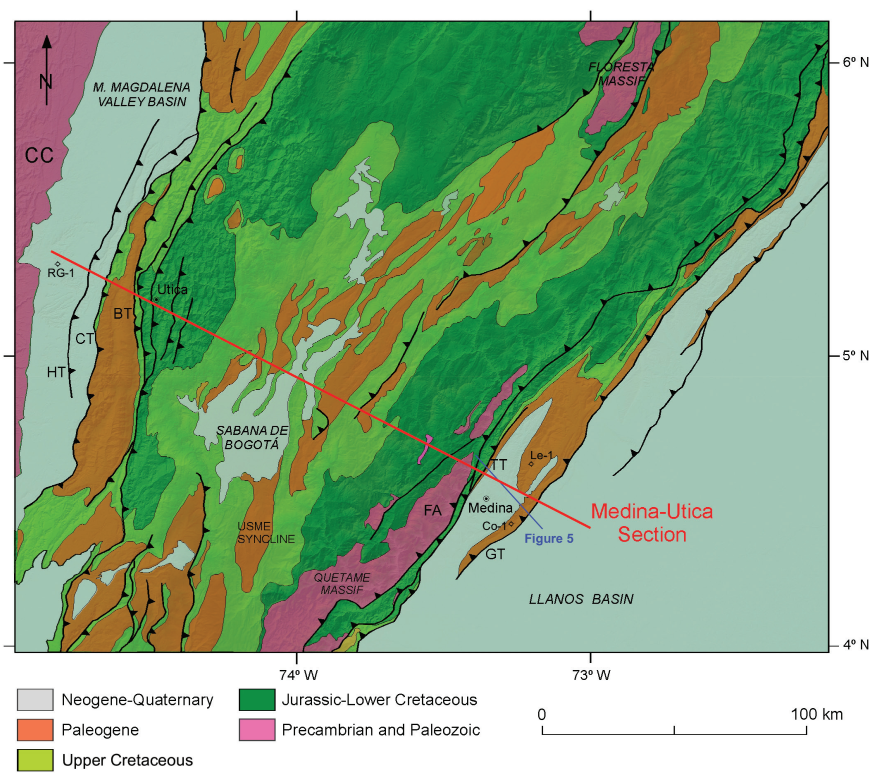


**Figure 1.** Geological sketch map of the central segment of the eastern Cordillera of Colombia indicating the transect line discussed in this chapter. This map is a synthesis of maps by Toro et al. (2004), Parra et al. (2009b), and unpublished maps by ICP-Ecopetrol. CC = central Cordillera, HT = Honda thrust, CT = Cambao thrust, BT = Bituima thrust, US = Usme syncline, TT = Tesalia thrust, FA = Farallones anticline, GT = Guaicaramo thrust, RG-1 = Rio Guarino well, Le-1 = Lengupa-1 well, Co-1 = Coporo-1 well. 50 km (31.1 mi)

stratigraphy, structural and seismic data, and low-temperature thermochronology make the eastern Cordillera an ideal type area for inverted rifts, of international reference. Lessons that can be gained from the study transect include the modalities of tectonic inversion at the basin scale, the contrast between the strongly reactivated rift margins and the rift interior, the role of anisotropy and weak formations (e.g., salt, to date insufficiently explored in the eastern Cordillera), and the recognition of a well-defined pattern of tectonic-morphologic evolution in time. The latter may be viewed as diagnostic of inversion orogens as they develop from initial stages of inversion to full mountain building (Babault et al., 2013). The eastern Cordillera of Colombia has been hydrocarbon productive for decades, especially in the foothill thrust belts, and to a lesser degree in the axial fold system.

## STRATIGRAPHIC SETTING

The eastern Cordillera in the Medina–Utica transect is dominated in outcrop by Cretaceous and Tertiary sedimentary rocks. Older rocks are restricted to upper Paleozoic slate and quartzite of the northern corner of the Quetame massif, in the eastern flank of the Cordillera (Figure 1). The post-Paleozoic rifting history of the eastern Cordillera dates back to the Triassic–Jurassic for a first, poorly constrained phase and then to the early Cretaceous for main phase, when a graben system roughly coincident with the present Cordillera was developed (Etayo et al., 1969; Cooper et al., 1995; Sarmiento-Rojas, 2001). Post-rift deposits accumulated through the late Cretaceous.

North of the study area, Jurassic rocks are constituted by fluvial–alluvial redbeds, controlled by syn-sedimentary extensional faults (Kammer and Sanchez, 2006). Although not exposed in the vicinity of the Medina-Udina transect, their existence in the subsurface under the western Sabana de Bogota is traditionally inferred (Campbell and Burgl, 1965; Cortes et al., 2006; Teson et al., 2013). Cretaceous rocks make up the bulk of the eastern Cordillera, consisting of marine sandstones and mudstones reaching up to 7500 m (24,606.3 ft). Figure 2 is a chronostratigraphic chart showing a number of lithostratigraphic units, which have received a variety of names according to different authors in different areas. A major challenge lies in the equivalence of the distinct stratigraphic successions in the eastern and western flanks of the Cordillera, at both sides of the axial plateau of the Sabana de Bogota. The eastern flank and foothills are constituted by alternating sandstone (Juntas, Une, Guadalupe) and mudstone (Macanal, Fomeque, Chipaque) formations, whereas the western flank is dominated by thick pelitic formations (Trincheras, Capotes, Pacho, Frontera, Conejo), with subordinate sandstone or siliceous rock (Murca–Utica, Socota, Hilo, Umir–Cimarrona) (Figure 2). This difference is often viewed as attesting for two originally different grabens or subbasins in the Cretaceous

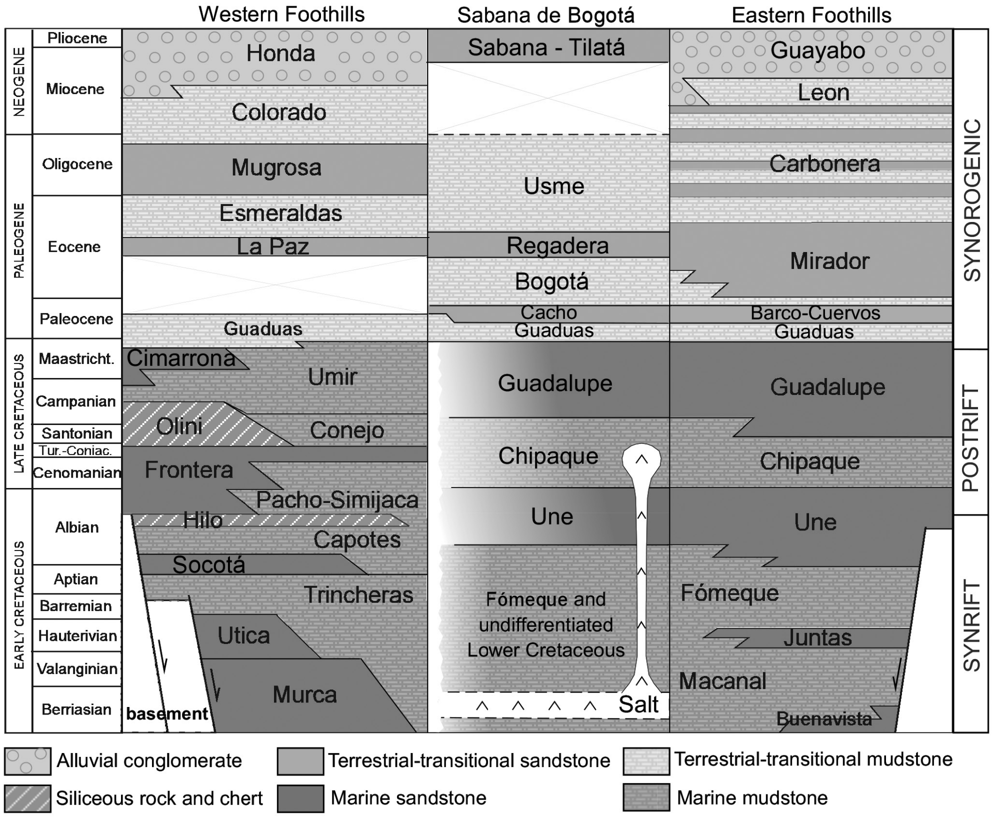


**Figure 2.** Stratigraphic units of the Cretaceous and the Cenozoic of the eastern Cordillera along the study transect (synthesized from Acosta and Ulloa, 2001; Sarmiento-Rojas, 2001; Restrepo-Pace et al., 2004; Parra et al., 2009a; Moreno et al., 2013, and own observations). The deep stratigraphy of the Sabana de Bogota is interpretative, as the lower unit that has been reached by wells is the Une Formation (see text for discussion).

rift, separated by an intervening high (Cocuy and Tablazo-Magdalena Subbasins; Cooper et al., 1995; Teson et al., 2013). The oldest rocks exposed in the Sabana de Bogota are of latest Cretaceous age, which together with limited well information hampers the detailed correlation between the subbasins and their stratigraphic units. Further discussion on the restored basin geometry is presented in the following sections.

Cenozoic rocks occur in the Sabana de Bogota and in the foothills (Figure 1). Cenozoic sedimentation started before the full growth of the eastern Cordillera of Colombia in a context of retro-arc foreland basin of the western and central Cordilleras. The first terrestrial deposits indicative of an overfilled basin appear in the late Maastrichtian–Paleocene (Guaduas Formation), for some authors witnessing the initial stages of tectonic inversion in the eastern Cordillera (Sarmiento-Rojas, 2001; Bayona et al., 2008). Synclines of the Sabana de Bogota preserve Paleocene to lower Oligocene sandstone and shale formations of terrestrial to transitional origin, covered unconformably by fluvio-lacustrine complexes of latest Miocene to Quaternary age (Julivert, 1963; Andriessen et al., 1993; Torres et al., 2005) (Figure 2). On the other hand, the foothills and the adjacent foreland basins contain a rather continuous Paleogene to Neogene succession, up to 6000 m (19,685 ft) thick, including thick molasse units derived from the eastern Cordillera margins (e.g., Carbonera, Guayabo, and Honda Formations, Figure 2) (Gomez et al., 2003; Restrepo-Pace et al., 2004; Parra et al., 2009a).

## DATA AND METHODS

This study is based on the integration of field, seismic, and well data along a traverse of the eastern Cordillera. The transect was selected on the lack of a recent, comprehensive, and detailed section in the Bogota segment of the chain (which do exist elsewhere, e.g., Teson et al., 2013) and spurred by the questions posed by singular geologic features as the axial plateau of the Sabana de Bogota. In addition, the analysis of the Medina–Utica transect benefited from a good synorogenic record in the foothills and Sabana, which enabled a reconstruction of the tectonic history.

Cross-section construction took into account field information including published geologic maps (McLaughlin and Arce, 1975; Ulloa et al., 1975; Ulloa and Acosta, 1988), internal report maps by the ICP-ECOPETROL, and own structural data (fault and bedding attitudes). Surface data were complemented with the interpretation of seismic profiles of the campaigns ME-1992, ME-1994, MVI-1997, J-1978, BSBP-1988, H-1978, HCBO-1997, and RG-1990, which covered the transect. In general the coverage is good in the foothills, being poorer in the Sabana de Bogota. Wells used for reference include the Lengupa, Coporo, Palomas, Suba, Suesca, Chitasuga, Zusne, and Rio Guarino.

The cross-section line is perpendicular to the general trend of the eastern Cordillera and to the main local structures. Evidence for significant out-of-the-plane movements was not detected. Section construction and restoration was performed with *Move* software. The main algorithm used was *fault-parallel flow* combined with *flexural slip unfolding* for the abundant cases where folds did not conform to simple fault-related folding relationships. Locally, deep reaches of the section that were presumably deformed by a component of ductile thickening were checked by area restoration. The same concept was used for weak evaporite rocks and mudstones. The deep geometry of the principal thrust faults, beyond their imaging in seismics, was achieved by trial-and-error iterations with the fault-parallel flow algorithm. Although this algorithm may not fully represent the deformation mechanisms operating in nature, the restrictions it imposed are comparable to other fault-related fold models, and it gives a reasonable first-order approximation to the fault geometry at depth.

A sequential restoration in selected steps was based on the analysis of tectonics-sedimentation relationships and on a wealth of thermochronological data (apatite and zircon fission tracks) from the foothills published in the works by Gomez et al. (2003), Mora et al. (2008), Parra et al. (2009a, 2010), and Moreno et al. (2013). While the geometry and deformation kinematics of the foothills is well constrained by surface and subsurface interpretation, the deep structure of the Sabana de Bogota remains less constrained. Nevertheless, a series of stratigraphic and structural arguments involving concepts of salt tectonics give clues to understand the Sabana de Bogota folding.

## A BALANCED SECTION ALONG THE MEDINA–UTICA TRANSECT

The large-scale cross-sectional structure of the eastern Cordillera of Colombia in the Medina–Utica transect is presented in Figure 3. The Cordillera shows a clear structural and geomorphic zonation, which consists of steep orogen flanks and foothills with high topographic and tectonic relief and dominated by outward-verging thrust systems and an axial plateau (the Sabana de Bogota), characterized by relatively symmetric folds with minor thrust displacements (Julivert, 1970; Mora et al., 2008). The intense thrust deformation observed in the foothills is localized in the former rift margins, whereas the rift interior suffered comparatively much less deformation. This is a feature that occurs in other intra-continental inversion orogens as

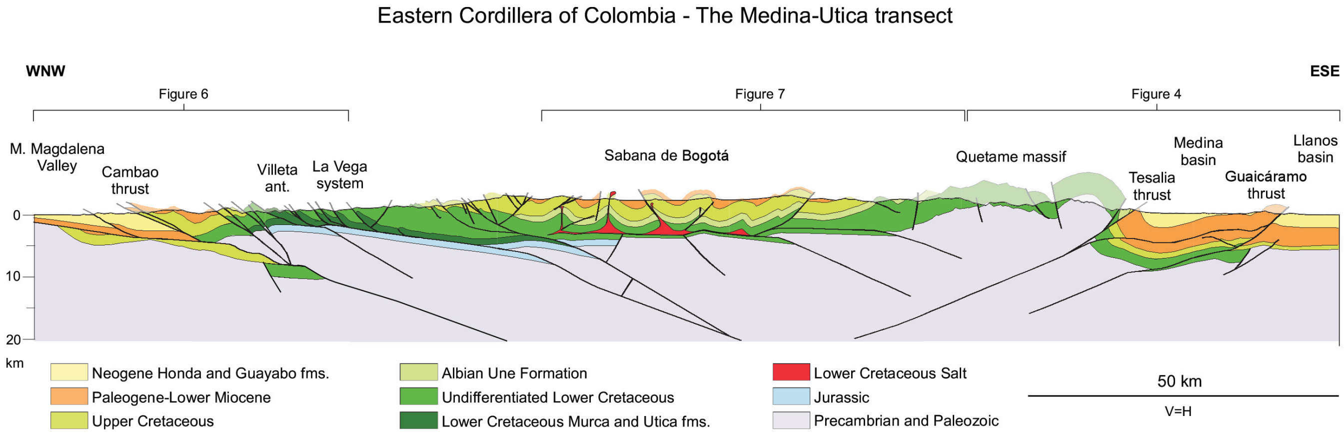


**Figure 3.** Geologic cross section of the eastern Cordillera of Colombia near the latitude of Bogota from the middle Magdalena Valley to the Llanos Basin (Medina–Utica transect). See Figure 1 for location. The ends of the cross-section line are at 5° 19′ 56″ N, 74° 47′ 27″ W and 4° 27′ 45″ N, 73° 06′ 10″ W. 10 km (6.2 mi)

in the Atlas Mountains of Morocco, to which the eastern Cordillera of Colombia shows remarkable similarities (Teixell et al., 2003; Babault et al., 2013).

The thrust belts at the Cordillera flanks are asymmetric with regard to deformation intensity and structural relief. In the eastern side, evidence of thick-skinned deformation is provided by the Quetame basement massif (Figures 1 and 3), the highest structural culmination of the Cordillera, which was uplifted by a major, west-dipping thrust. The synorogenic basins of Medina and Llanos contain the thickest accumulations of Cenozoic synorogenic sediments (up to 6000 m [19,685 ft]). The western flank shows less structural relief. The basement is not exposed, and even though the existence of a major basement-involved thrust can be inferred in the subsurface (Figure 3), thin-skinned thrust segments detached at different stratigraphic levels do occur. Synorogenic deposits are thinner (ca 4000 m [13,123.4 ft]), and, as in the east, they are deformed by shallow thrust systems at the mountain front.

## The Eastern Foothills Belt

The section crosses the eastern foothills through the Medina Basin, a detached Tertiary thrust-top basin that forms the frontal imbricate sheet of the eastern Cordillera (Figures 1, 3, and 4). This area has been intensely investigated from structural and basin analysis perspectives in the past years (Rowan and Linares, 2000; Branquet et al., 2002; Mora et al., 2006, 2010a; Parra et al., 2009a, 2010; Jimenez et al., 2013) and has been imaged by numerous seismic profiles. Figure 5 shows a sample seismic profile across the Medina Basin that runs close to the study transect and was the basis for the subsurface interpretation.

The frontal thrust of the Cordillera is the Guaicaramo fault, which brings Oligocene rocks of the Medina Basin on the Neogene of the Llanos Basin (Figure 4). Near the surface, the Guaicaramo thrust fault appears as a hanging wall flat or low-angle ramp in the Carbonera Formation, whereas the same formation is cut in the footwall with a high-angle ramp geometry (Figures 4 and 5). We interpret this discrepancy as resulting from a bedding-parallel detachment in the Carbonera Formation under the Medina Basin (the Aguaclara thrust; Branquet et al., 2002), which formed first and was later reactivated by the upper segment of the Guaicaramo fault. Interpretation of seismic profiles suggests a hidden lower Cretaceous graben under the Guaicaramo fault (Jimenez et al., 2013), which was mildly uplifted by a short-cut thrust (Figure 5).

The Medina Basin shows a broad anticline–syncline pair between the Guaicaramo fault and the Tesalia thrust to the rear, which carries the Quetame basement massif and its cover on top of Oligocene and Miocene rocks. Seismic profiles show the existence of minor folds and thrusts in the core of the gentle Guavio anticline at the level of the Mirador and older formations (Figure 5). These structures do not affect the middle and upper part of the Carbonera Formation, being truncated at the level of the lower Carbonera Formation. The position of the truncation coincides with the interpreted position of the Aguaclara thrust. A possible alternative interpretation is that these structures formed contemporaneously with the Aguaclara thrust, which acted as a roof thrust, the lower Carbonera Formation flowing disharmonically between anticlines and synclines. However, in the light of comparable structures at the same stratigraphic level imaged in the northeastern foothills (Mora et al., 2013), we contend that the fold-to-thrust structures in the core of the Guavio anticline are early features that were erosionally truncated by the Carbonera Formation and that the unconformity was later reactivated by the Aguaclara thrust.

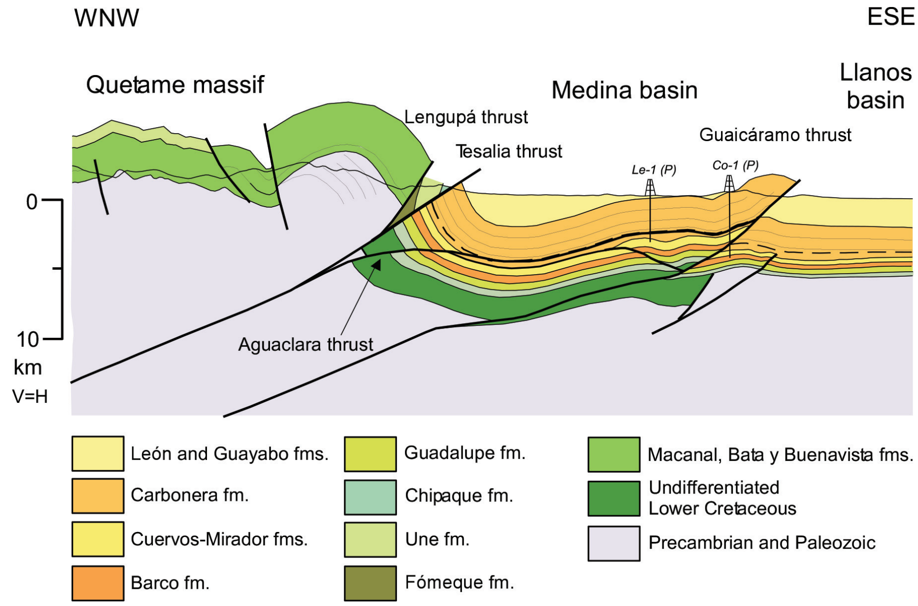


**Figure 4.** Close-up of the section of the eastern foothills along the Medina–Utica transect, showing the main structural elements from the Quetame massif to the Llanos foreland basin (see ages of stratigraphic formations in Figure 2). The dashed line within the Carbonera Formation indicates an intraformational unconformity (and its correlative paraconformity), partially reactivated as a thrust fault (see text for discussion). Le-1 (P): Lengupa-1 well (projected), Co-1 (P): Coporo-1 well (projected). 10 km (6.2 mi)

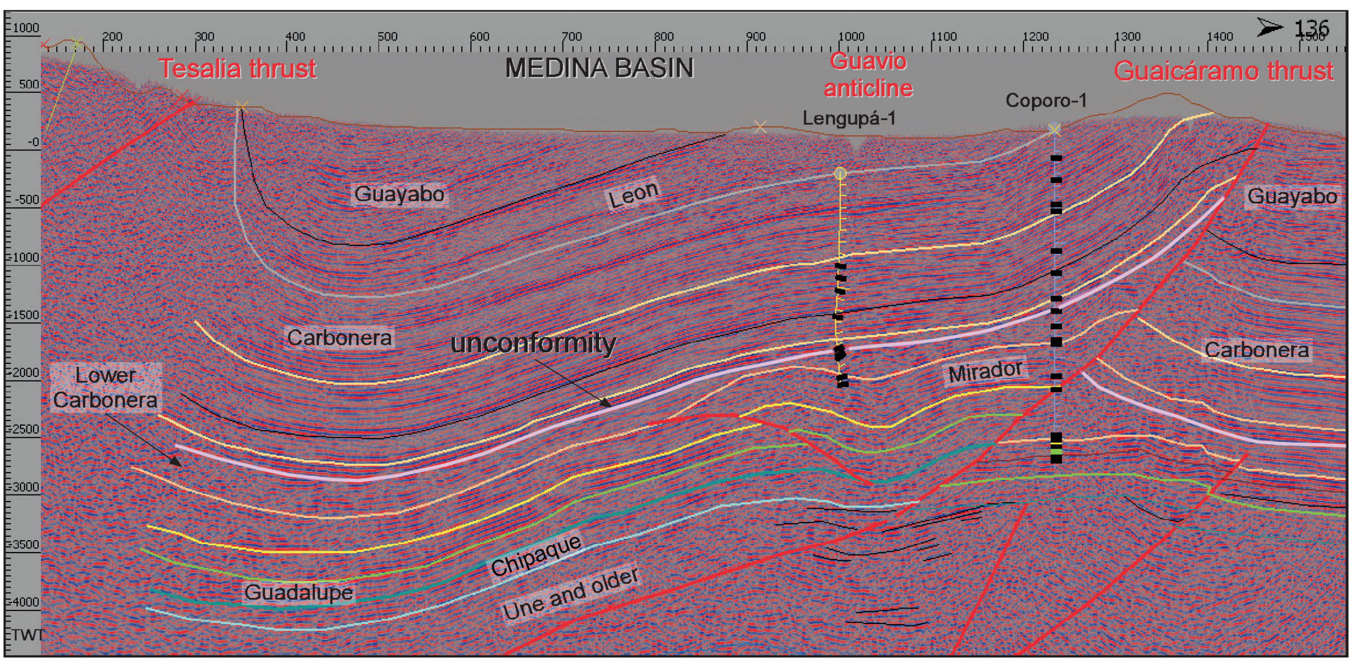


**Figure 5.** Two-way traveltime-interpreted seismic reflection profile ME-1992-1440 across the Medina thrust-top basin in the western foothills. Note the unconformity in the lower Carbonera Formation truncating deep thrust-related folds in the core of the Guavio anticline. We interpret that the unconformity has been used as a slip surface under the Medina Basin (named the Aguaclara thrust; see Figure 4 and text for discussion), explaining the mismatch of the fault cut-off angles of the Carbonera Formation in the hanging wall and footwall of the Guaicaramo thrust. The location of the profile is given in Figure 1.

The western limb of the Medina Basin syncline is very steep at the level of the Carbonera and lower Guayabo Formations. Neogene conglomerates of the Guayabo Formation exhibit growth strata indicative of syn-sedimentary folding and bed rotation. Limb tilting is due to the combined action of the rear ramps of the Aguaclara and Guaicaramo thrusts (Figure 4). The strongly emergent Tesalia thrust was interpreted as an out-of-sequence thrust by Mora et al. (2010a).

The thickness of the Cretaceous cover of the Quetame massif is much increased with respect to the Medina Basin, indicating that the Tesalia thrust derives from the reactivation of a former normal fault.

Other minor extensional faults, reactivated or not, are common around the massif (Mora et al., 2006), which must correspond to the edge of a former major graben. Basement and Cretaceous rocks in the hanging wall of the Tesalia thrust are folded into a major overturned anticline (the Farallones anticline), the forelimb of which is cut by the Lengupa fault, which separates normal from strongly overturned beds (Figure 4). The fault-fold geometry does not obey to simple models of fault-related folding, and a significant component of buckling and ductile deformation must have operated. Comparable geometries in the southern foothills in the Guatiquia area were interpreted by Parravano (2013) as favored by the existence of salt in the lower part of the Cretaceous succession. This interpretation could not be confirmed in the Farallones area, but the occurrence of salt springs at Mambita, 20 km (12.4 mi) to the NE of the study section, and of the salt- and fault-related emerald deposits at Chivor (Cheilletz and Giuliani, 1996) suggests it cannot be discarded. The backlimb of the Farallones anticline consists of a gently dipping, monoclinal succession of Cretaceous beds that overlie the Paleozoic of the Quetame massif and plunge under the Sabana de Bogota (Figure 3). We suppose the existence of deep east-dipping thrust faults underlying this succession (Figure 3), to account for the folding of the Sabana de Bogota described later.

## The Western Flank and Foothills

The western foothills, adjacent to the middle Magdalena Valley foreland basin, are characterized by west-verging thrust sheets involving again Cretaceous and Tertiary rocks in the surface (Figure 6). The amount of shortening and structural relief is less than in the eastern foothills; basement is not exposed at the surface, but its involvement in thrusting at depth is unequivocally inferred from cross-section construction on account of the varying structural elevation of the Cretaceous units (Figures 3 and 6). On the basis of stratigraphic changes, previous studies reported reactivated extensional faults defining major thrust units (Salina, Bituima, Cambao thrusts; Gomez et al., 2003; Restrepo-Pace et al., 2004; Cortes et al., 2006; Moretti et al., 2010; Moreno et al., 2013).

The largest displacement is observed in the Cambao thrust, which carries an interpreted basement wedge in its rear (Figure 6). A hanging wall syncline in the Cambao thrust sheet (the Guaduas syncline) contains a Paleogene succession displaying growth strata indicative of early folding (Gomez et al., 2003). An important architectural element of the middle Magdalena Valley and foothills is an angular unconformity at the base of the middle Eocene La Paz Formation (Gomez et al., 2003) (Figure 2). In front of the Cambao thrust

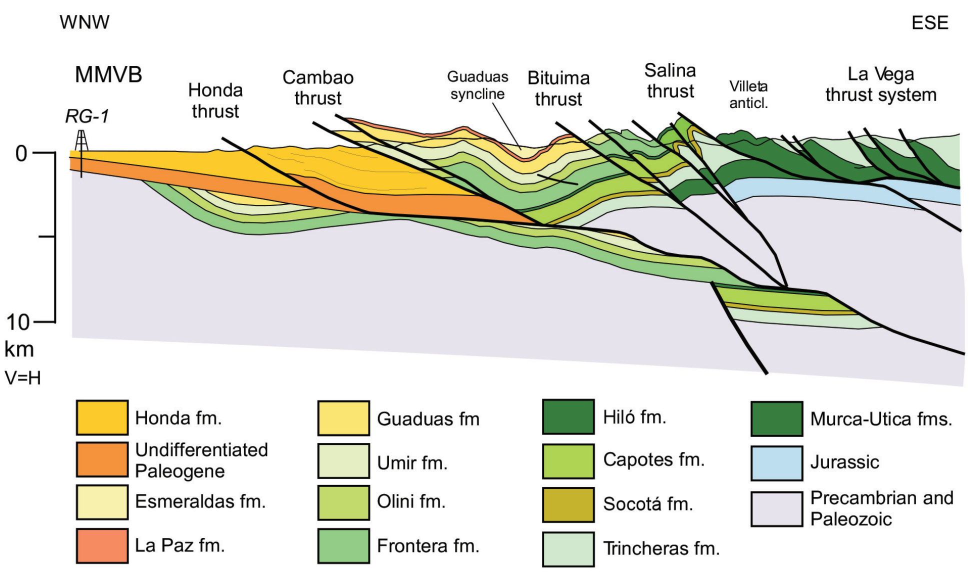


**Figure 6.** Close-up of the cross section of the western foothills along the Medina–Utica transect, showing the principal structural units from the Villeta anticlinorium to the middle Magdalena Valley Basin (see ages of stratigraphic formations in Figure 2). Thickening of the Trincheras Formation in the footwall of the Salina thrust is attributed to ductile flattening. The deep structure represented under the basal thrust fault in the eastern part of the section has been interpreted on the basis of ramp-flat template constraints. Comparable interpretations involving hidden graben systems were presented by Moreno et al. (2013). Normal faults were not reactivated probably because of their steep dip and were bypassed by structures as the Cambao thrust. Folds under the MMVB that appear truncated by the mid-Eocene unconformity in the western part of the section are observed in seismic profiles and have been previously reported by Caballero et al. (2013). MMVB = Middle Magdalena Valley Basin, RG-1 = Rio Guarino well. 10 km (6.2 mi)

sheet, the frontal Honda thrust sheet is detached in that unconformity and carries a Tertiary succession that culminates with thick Neogene conglomerates of the Honda Formation (Figure 6).

Seismic profiles and cross-section template constraints suggest an important substructure under the Cambao thrust and the Eocene unconformity, which include bypass structures in the far footwall of the thrust and buckle folds truncated by the unconformity (Figure 6). Comparable structures have been recently reported for other segments of the western foothills belt by Caballero et al. (2013) and Moreno et al. (2013). The Rio Guarino well in the middle Magdalena Valley, at the end of the cross section, drilled crystalline rocks directly under the middle Eocene, consistent with the folded structure (Figure 6). Bedding dips of the Eocene units of the middle Magdalena Valley are about 8°–9°, which are probably too high to be explained solely by thrust-related foreland flexure; a component of large-scale buckle folding in the adjacent central Cordillera may account for part of the observed tilting.

Between the foothills and the Sabana de Bogota, in the hanging wall of the Salina thrust (Figures 3 and 6), lower Cretaceous mudstones dominate in outcrop and are deformed into a system of closely spaced thrusts accompanied by minor-scale folding and slaty cleavage (the La Vega thrust system; Cortes et al., 2006). A frontal culmination of the system is called the Villeta anticlinorium (Ulloa and Acosta, 1998), which also coincides spatially with the deep basement culmination of the Cambao thrust (so its structural elevation results from the combined effect of the two thrust systems; Figures 3 and 6). The basal Cretaceous Murca and Utica turbiditic sandstones are the older units observed in the thrust system, occasionally displaying hanging wall flat geometry at the thrusts, which suggests that the system is detached at the base of these sandstone units.

The nature of rocks under the detachment is unknown; by inference of analogy to the stratigraphy exposed in the Cordillera to the north of the transect (Arcabuco–Floresta massif areas; Kammer and Sanchez, 2006), a panel of Jurassic rocks is tentatively represented, as mentioned earlier (Figure 3). The continuation of the La Vega floor thrust to the east in the subsurface is uncertain as there is no evidence of major basement culminations that could totally root the west-directed slip of the La Vega thrust system. A component of homogeneous shortening will be used in the balancing of the deeper stratigraphic units.

## The Sabana de Bogota

The axial zone of the eastern Cordillera around Bogota constitutes a low-relief plateau at high elevation (ca 2600 m [8530.2]), at variance to other orogenic belts where the internal core is usually a high-relief mountain zone characterized by intensely deformed and exhumed rocks. The Sabana de Bogota has a relatively simple fold structure and is dominated in outcrop by young sedimentary units (upper Cretaceous and younger) (Figure 7). The structure of the Sabana has received comparatively less attention than the highly productive Cordilleran foothills, although this situation is changing as the exploration interest is renewed in recent times. The basic elements of the surface structure are described in works by Julivert (1963, 1970) and Cortes et al. (2006), but the deep subsurface structure is usually poorly imaged in available seismic reflection profiles and is drilled by a limited number of wells.

The Sabana de Bogota folds have wavelengths around 10 km (6.2 mi) and are relatively cylindrical, although they show notable bends in map view (Julivert, 1963). They consist of narrow anticlines and relatively wider synclines, typically with a poorly defined vergence. The Sabana region keeps a rather homogeneous structural elevation as defined by fold envelopes (Figures 3 and 7). The fold style and the low taper of the system suggest the existence of a low-friction detachment under the Sabana folds. Depth-to-detachment calculations based on the method by Chamberlin (1910) and using the top of the Guadalupe Formation as a reference level indicate that such detachment level might be 4 km (2.4 mi) below the surface of the Sabana. Anticlinal fold limbs commonly show overturned flaps (e.g., Julivert, 1963), and salt diapirs are occasionally present (e.g., Zipaquira, Nemocon; McLaughlin, 1972). The age of the source salt is uncertain, although enclaves within the salt bodies suggest it was deposited at the level of the earliest Cretaceous Macanal or Fomeque Formations (Lopez et al., 1988). This is approximately the position of our estimated detachment level in the subsurface, and accordingly we interpret the Sabana as a salt-detached fold belt. Overturned flaps may represent salt-related deformation similar to that described in well-documented diapiric provinces (e.g., Rowan et al., 2003; Graham et al., 2012). We propose that many folds in the Sabana de Bogota were originally cored by salt and were later squeezed during continuous shortening, so the salt formation was removed from most of them and the fold limbs became welded (although its existence at depth is suggested by the abundant brine springs reported in Campbell and Burgl, 1965, and McLaughlin, 1972). Stacked unconformity-bounded units and growth strata in the upper Cretaceous and Paleogene of the Usme syncline near Bogota (Julivert, 1963; Gomez et al., 2005) are very similar to halokinetic sequences reported in other compressional salt provinces (Giles and Lawton, 2002; Rowan et al., 2003) (Figure 8).

After a sedimentary hiatus that comprises most of the Oligocene and Miocene (Figure 2), the

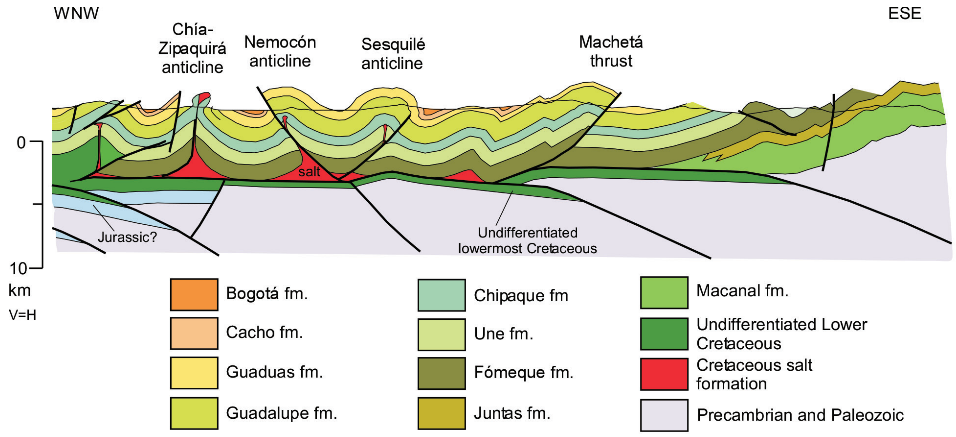


**Figure 7.** Close-up of the cross section of the Sabana de Bogota. The interpretation of the deep structure of the fold system is based on structural arguments and depth-to-detachment calculations, as it is poorly imaged in seismic profiles (see text for discussion). Note the excess length shown by the Chipaque and Guadalupe Formations with respect to the Une and older Formations in the Chia anticline and the faulted anticline to the west. What is labeled as Fomeque Formation under the Sabana de Bogota (western part of the section) may include lateral time equivalents of the Macanal and Juntas Formations exposed in the western limb of the Quetame massif (eastern part of the section). 10 km (6.2 mi)

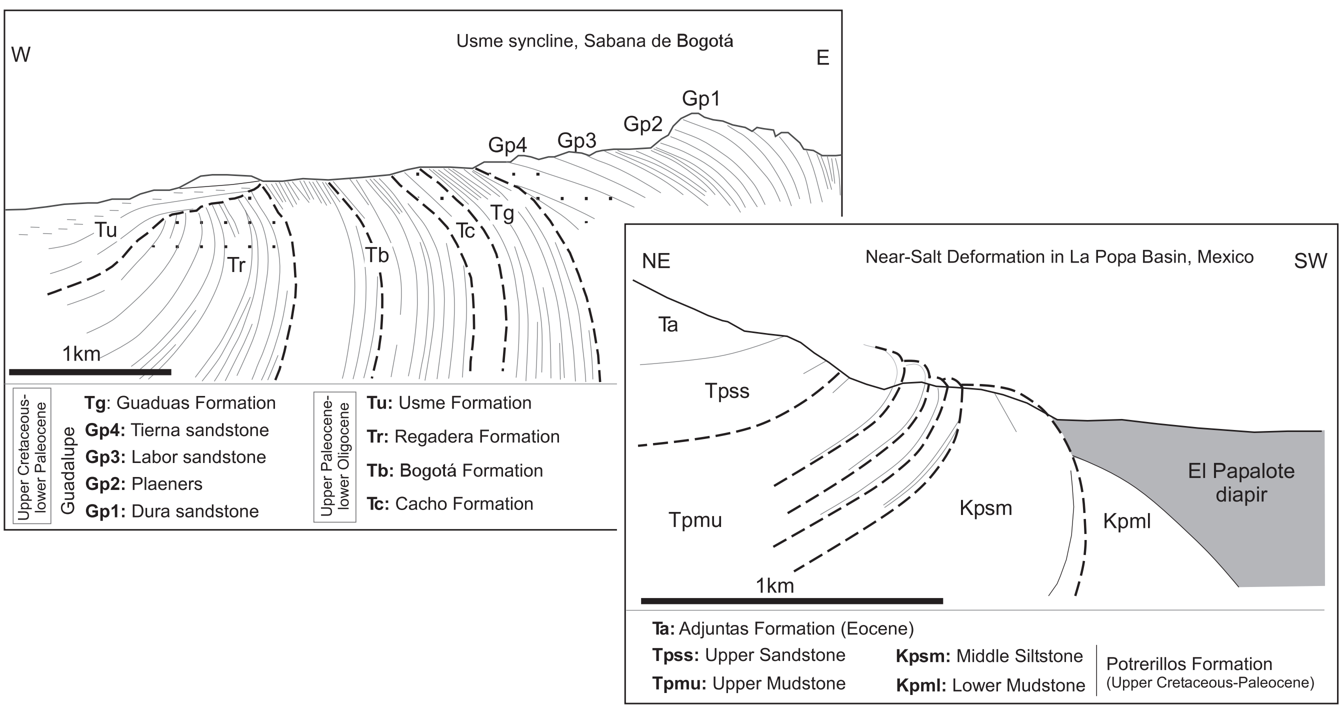


**Figure 8.** Comparison between the stacked growth-strata wedges of the Usme syncline in the Sabana de Bogota (see the location of Usme syncline in Figure 1) (redrawn from Gomez et al., 2005, after Julivert, 1963) and halokinetic sequences adjacent to the El Papalote diapir of the La Popa Basin, Mexico (after Rowan et al., 2003). We interpret that the salt wall that was originally adjacent to the Usme syncline has been squeezed and completely welded by subsequent shortening. 1 km (0.6 mi)

unconformable Tilata and Sabana fluvio-lacustrine formations partially filled synclinal depressions in the Sabana de Bogota and contributed to smooth the relief of the plateau as we see it today. These units are relatively thin and could not be appropriately represented at the scale of the cross section.

## TIMING OF DEFORMATION AND SEQUENTIAL RESTORATION

Many previous authors consider a main Andean phase starting in the Miocene and continuing into recent times as the principal episode of mountain building in the eastern Cordillera of Colombia, which was a retroarc foreland basin of the central Cordillera before that time (e.g., Dengo and Covey 1993; Cooper et al., 1995; Hoorn et al., 1995; Toro et al., 2004; Bayona et al., 2008; Horton et al., 2010; Mora et al., 2010b). Nevertheless, abundant evidence for Paleogene deformation indicates that this foreland basin was far from being stable and was the locus of progressive disruption and compartmentalization.

Compelling evidence for Paleogene compressional deformation in the vicinity of the Medina–Utica transect includes (1) the regional mid-Eocene unconformity in the western foothills and in the middle Magdalena Valley (Gomez et al., 2003; Restrepo-Pace et al., 2004; Parra et al., 2012; Caballero et al., 2013), (2) the growth strata reported (Figure 8) and the flexural modeling tasks performed in the Paleogene units of the Sabana de Bogota (Julivert, 1963; Sarmiento-Rojas, 2001; Gomez et al., 2005; Bayona et al., 2008), (3) the geochronology of the emerald deposits of the eastern foothills district, which were interpreted as formed by thrust-related salt brine migration at 65 Ma (Cheilletz and Giuliani, 1996), (4) the early Oligocene unconformity locally imaged by seismics in the eastern foothills (Figure 5), and (5) an increase in subsidence rate recorded in the Medina Basin at ca 31 Ma (Parra et al., 2009a). These deformations in the former rift basin created local topographic barriers that did not totally prevent connection between the central Cordillera and the Llanos, and they significantly controlled the sedimentary thicknesses, the paleo-geography, and the sediment dispersal, which flowed NNE parallel to the growing folds (Gomez et al., 2005; Mora et al., 2013; Silva et al., 2013). Compressional deformation may have started in the latest Cretaceous with the initial shortening of salt walls in the Sabana de Bogota, as indicated by the age of the earliest growth strata reported (Figure 8). The successive unconformity-bounded units that we suggest to be halokinetic sequences formed in compression persist in time at least until the early Oligocene, contemporaneously with fault-related folding in the Guaduas growth syncline (Moreno et al., 2013) and in the Medina Basin (Figure 5).

The main emergence of the major thrust faults that record strong inversion of the former rift margins commenced in the late Oligocene to early Miocene, as recently indicated by subsidence, exhumation, and sediment provenance analysis (Parra et al., 2009a,b; Mora et al., 2010b; Horton et al., 2010). Detrital zircon geochronology reveals a recycling of the Paleogene Sabana de Bogota sediments into the Carbonera Formation of the eastern foothills during this time. An important milestone in the uplift history of the Cordillera is in mid- to late Miocene times, when paleo-currents in the middle Magdalena Valley molasse shifted completely to the west (Guerrero, 1993), and detrital zircons of Meso-Cenozoic age (which indicate a central Cordillera provenance) disappeared in the eastern foothills (Horton et al., 2010), indicating that the eastern Cordillera had already become an effective topographic barrier that separated the central Cordillera from the Llanos Basin.

As for specific structures, apatite fission track data indicated to Gomez et al. (2003) an initial cooling of the Villeta anticlinorium and the leading edge of the Cambao thrust sheet sometime between 15 Ma and 10 Ma. Recent zircon (U–Th)/He and apatite fission track cooling ages obtained in the same areas range in the mid-Miocene to early Pliocene interval (Moreno et al., 2013), reinforcing ongoing uplift since at least the mid-Miocene (and probably before, according to thermal modeling; Parra et al., 2009b; Moreno et al., 2013), consistently with the conglomeratic fluxes of the Honda Formation appearing ca 10–13 Ma (Guerrero, 1993; Hoorn et al., 1995; Gomez et al., 2003).

Samples in the Sabana de Bogota are not reset for thermochronology aiming to orogenic growth, and in the Quetame massif, zircon fission tracks yielded mid-Miocene cooling ages (comparable to those in the western foothills, and consistently with the contemporaneous conglomeratic influx of the Guayabo Formation), whereas thermal modeling suggested that uplift had commenced by early Miocene times (Parra et al., 2009b). Exhumation rates in the eastern foothills increased dramatically some 4–5 Ma ago, recorded by very young fission track ages in the Quetame massif (<3 Ma), which probably reflect tectonic-climate feedbacks in the strongly emergent eastern margin of the Cordillera in the latest Neogene and Quaternary (Mora et al., 2008; this volume). On the other side, the western foothills do not show such hints for intense recent active deformation.

## Sequential Restoration of the Medina–Utica Section

According to the timing of deformation described earlier, the Medina–Utica section has been kinematically restored to sequential steps that inform about the geometry of the early graben system and on the evolution of shortening with time. The stages selected represent important milestones in the orogenic evolution of the eastern Cordillera, for which there was sufficient constraints from tectonics-sedimentation data. Thermochronological data used to constrain the restoration included central cooling ages as reported earlier and thermal models (e.g., Parra et al., 2009b; Moreno et al., 2013, for the area around the transect).

The restored section to the pre-orogenic stage has been placed at 70 Ma (Figure 9A), previous to the inferred salt-related early compressional folding in the Sabana de Bogota. This section illustrates the eastern Cordillera rift system, with the two early Cretaceous subbasins of the Cocuy and Magdalena–Tablazo Grabens, similarly to restored sections performed elsewhere in the northern eastern Cordillera (Mora et al., 2013; Teson et al., 2013), but comparatively less marked. We interpret that salt diapirs or walls had been formed in the intervening gentle high between the two subbasins. Their existence in the pre-compression stage is suggested by section restoration, as the lower Cretaceous formations have a length deficit with respect to the upper Cretaceous in the Sabana de Bogota anticlines (Figure 7).

The Cocuy and Magdalena–Tablazo Subbasins become less defined by the late early Cretaceous, when extensional fault activity was already waning. Laterally expansive deposits indicative of thermal subsidence begin around the Cenomanian in both the eastern (upper Une or Chipaque Formations) and western basin margins (Frontera Formation).

The first intermediate stage aims to illustrate the Paleogene contraction at 40 Ma (Figure 9B) and is based essentially on tectonics-sedimentation relationships (angular and progressive unconformities) in the Sabana de Bogota and foothills. Folding at this stage is spatially restricted, occurring within an aggradational foreland basin where the bulk of the sediment derives from the central Cordillera and the Guyana craton (not represented in the figure). Growing folds recorded by the Paleogene deposits require displacement be transferred from initial basement thrusting in both sides of the Quetame massif and the Cambao thrust. The next stage corresponds to late Miocene times (10 Ma; Figure 9C), aiming to the main Andean episode of mountain building recorded by the conglomerate formations in the forelands and by abundant thermochronological data, which give clues to the depths of burial at that time. This stage represents the full accretion of the Cordillera, by strong tectonic inversion of the rift basin margins, and leaving the rift interior comparatively quiescent. The passage from this stage to the present-day state (Figure 9D) illustrates well the continued deformation and very strong exhumation of the eastern Cordillera, concentrated mainly in the eastern side and attested by the very recent cooling ages in the Quetame basement massif and eastern foothills.

The comparison between the present-day and completely restored section of Figure 9A indicates ca 82 km (50.9 mi) of total orogenic shortening along the Medina–Utica transect of the eastern Cordillera. The evolution of shortening in time will be discussed in the following section.

## DISCUSSION

The cross section presented in this work puts forward a combination of thick- and thin-skinned thrusting to account for the compressional structure of the eastern Cordillera of Colombia. Basement-involved, thick-skinned thrusting dominates in the Cordilleran flanks (Figure 3), in the line of previous interpretations by Colletta et al. (1990), Cooper et al. (1995), Cortes et al. (2006), Mora et al. (2008), and Teson et al. (2013). On the basis of kinematic modeling with *Move* software, we estimated the dip of the main basement ramps to be 18°–20° (Figure 3). Second-order detachments can exist locally at certain stratigraphic intervals (e.g., the Oligocene unconformity in the Aguaclara thrust of the eastern foothills or the mid-Eocene unconformity in the Honda thrust of the western foothills).

A shallow decollement within the Cretaceous sedimentary cover is deduced for the axial zone of the Cordillera, flooring a thin-skinned fold system in the Sabana de Bogota. The depth of ca 4 km (2.4 mi) calculated for this detachment leads us to conclude that basement is not involved in the individual folds of the Sabana that we observe at the surface. The fold style together with the occurrence of occasional salt diapirs and numerous salt springs suggests the detachment is at a salt formation. Systematic overturned flaps in the fold limbs (sometimes occurring in both limbs of the same anticline) are best explained by squeezing of a very weak formation as salt; the latest Cretaceous to Eocene age of the angular unconformities and growth strata recording the process of limb overturning (Figure 8) indicates that this process occurred in a setting of regional compression. It follows that the important role of salt has probably been obliterated by welding and dissolution, as happens in many sub-aerial fold belts. Punctual, columnar salt diapirs are nowadays preserved in localities as Zipaquira where cross-faults interfere with anticlinal structures and may have enabled further salt rise. As for the timing of the initial salt movement, the lack of exposure of units older than the upper Cretaceous Chipaque Formation and the poor resolution of seismic data do not allow us to be conclusive. However, clues may come from cross-section balancing, because when we attempt to complete the sections at depth, the sectional length of the upper Cretaceous formations in the Sabana anticlines is larger than that of the lower Cretaceous (e.g., western part of Figure 7). This may indicate that salt walls experienced a first stage of growth in the early Cretaceous, were subsequently overlapped by the upper Cretaceous, and then experienced a second phase of rising by squeezing during the early stages of shortening in the Paleogene.

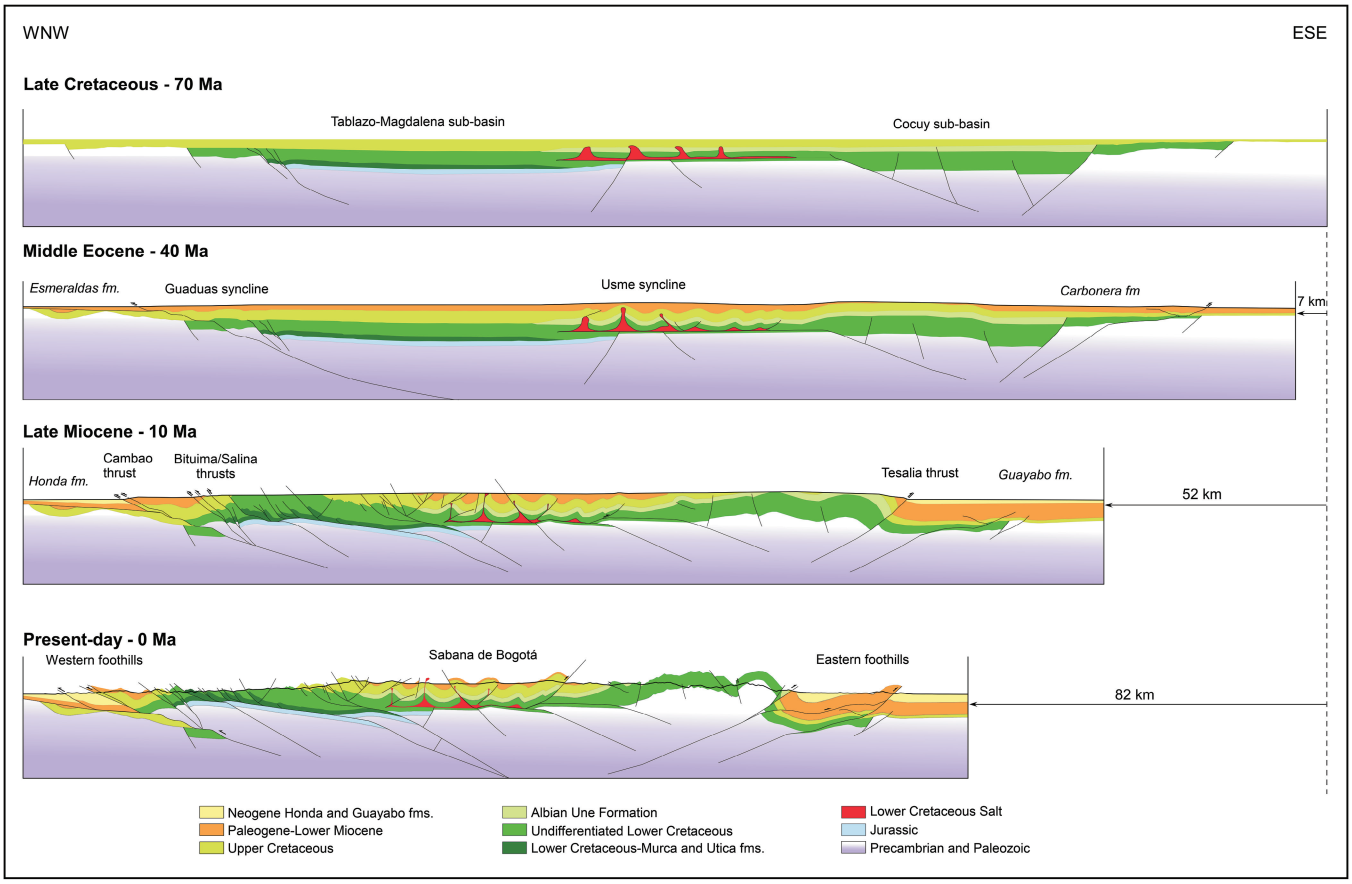


**Figure 9.** Restoration of the Medina–Utica section in sequential steps, based on structural geometries, tectonics–sedimentation relationships, and thermochronology (see text for discussion).

The original stratigraphic position of the source salt formation in the Sabana de Bogota is uncertain (e.g., McLaughlin, 1972; Lopez et al., 1988). If we project the stratigraphic units outcropping in the western side of the Quetame massif with constant thickness, the calculated depth places the detachment in the level of the Hauterivian Juntas or Fomeque Formations (Figure 2). However, exposed evaporitic layers and associated emerald deposits in the foothills area are hosted in the Berriasian (Cheilletz and Giuliani, 1996; Banks et al., 2000; Branquet et al., 2002). Since additional evidence for two distinct evaporite layers in the lower Cretaceous of the eastern Cordillera is missing, we assume that the salt formation underlying the Sabana de Bogota is also of Berriasian age, as reported for the foothills. In the process of cross-section construction, this requires a thinning of the lowermost Cretaceous units under the eastern Sabana, so the depth estimated for the salt detachment corresponds to a base-Cretaceous level. This might be the main geometrical clue for an ancient extensional fault system bordering the Cocuy Subbasin in the latitude of the Medina–Utica transect (Figure 9A).

The pre-salt structure under the Sabana de Bogota is largely conjectural and might be the target of further exploration. The existence of basement faults at depth can be inferred from the Floresta massif located 150 km (93.2 mi) northward along strike (Figure 1). Such pre-salt faults do also appear as a requirement to balance shortening across different levels. However, the homogeneous structural elevation of the Sabana de Bogota fold system indicates that basement culminations of high structural relief as the Floresta massif do not exist in the Bogota area, a problem that also exists in the axial zone of other inverted rifts as the central Moroccan Atlas Mountains.

Another remaining uncertainty lies on the significance of the distinct stratigraphic successions of the Cretaceous of both flanks of the Cordillera. As previously suggested, these may also reflect the individualization of the Cocuy and Tablazo–Magdalena Subbasins during the lower Cretaceous, but the Medina–Utica transect does not bring further light on the subject. The position of the western pinch-outs of the thick sand units that characterize the eastern flank of the Cordillera is unknown (e.g., Juntas, Une, Guadalupe Formations), and they have been represented in the restored sections of Figure 9 in a schematic way.

The sequential retrodeformation of the Medina–Utica cross section enables discussion of the magnitude of orogenic shortening in the central segment of the eastern Cordillera of Colombia and its distribution in time. The 82 km (50.9 mi) of total shortening calculated between the present day and the section restored to 70 Ma represents 27% of the original length. Errors in the amount shortening calculated could arise from an underestimation of the internal strain, from an incorrect location of fault cut-offs in the subsurface, or from an incorrect assessment of the dip of the main thrust faults. Strain studies have not been performed in the region, and even though a certain amount of layer-parallel shortening is common in thrust belts and can be expected for the Cordillera, it is noteworthy that tectonic cleavage is absent along the entire transect, with the local exception of fold hinges in the frontal units of the La Vega thrust system. The location of fault cut-offs wherever they are not exposed has followed the principle of minimizing shortening, but always taking into account fault-fold geometries (e.g., hanging wall cut-off angles, template constraints, and axial surfaces of presumed fault-bend folds). As discussed earlier, we have followed the restrictions imposed by kinematic restoration in the assessment of fault dips; despite the limitations arising from not reproducing the real, complex deformation mechanisms operating in nature, the ramp angles obtained (18°–20°) are close to those commonly observed in thrust belts (e.g., Suppe, 1983).

With regard to the shortening history, there is an uncertainty as for the initiation of orogenic compression in the eastern Cordillera. Taking a probable start at 70–65 Ma, just after the completely restored state at 70 Ma (as indicated by growth strata in the Sabana de Bogota and by the fault-related emerald mineralization in the foothills), our proposed section would yield an average shortening rate of ca 1.2 mm/a until the Quaternary. This value has a limited significance, because the tectonic history described earlier suggests that shortening was probably not acquired at a constant rate. With our sequential restoration (Figure 9), the shortening acquired at the selected steps is ca 7 km (4.3 mi) at 40 Ma and ca 52 km (32.3 mi) at 10 Ma, which provide deformation rates between the steps. A bias is imposed by the timing of the steps selected, which are based on data availability and may not accurately reflect the precise timing of potential changes in the deformation rate. If we assume an initiation of shortening at 65 Ma, the shortening rate in the first interval (65–40 Ma) is estimated in ca 0.3 mm/a, while it increases to 1.5 mm/a in the second interval (40–10 Ma) and to 3 mm/a from 10 Ma to 0 Ma. The two-step increase in the deformation rate may not be real, as there is little resolution in the interval between 40 Ma and 10 Ma, hampered by the difficulty to construct a reliable intermediate section. The strong increase in subsidence recorded by the Carbonera Formation in the early Miocene (ca 25 Ma; Parra et al., 2010) could indicate that the slow deformation rates recorded for the first interval persisted until that time, when they changed to the faster rates measured for the most recent interval. In the light of this uncertainty, the results that we can safely retain is that orogenic shortening in the eastern Cordillera began at a low rate in the early Tertiary (<0.5 mm/a) and proceeded at much faster rates (ca 3mm/a) from some time in the Neogene.

The Sabana de Bogota Plateau has been the target of studies that aimed to the uplift history, which were carried out independently of the estimates of the timing of deformation. The late Neogene fluvio-lacustrine deposits of the Sabana contain paleo-flora, which has been compared to the range of temperature tolerance for modern nearest living relatives, by which Van der Hammen et al. (1973) and Hooghiemstra et al. (2006) inferred low altitudes in the axial zone of the Cordillera until the latest Miocene and a rapid surface uplift of ca 1500 m ± 500 between 6 Ma and 3 Ma. Babault et al. (2013) (following Gregory-Wodzicki, 2000) discussed that the error margins of the method may be large (±1500 m [4921.3 ft]), implying that the proposed paleo-elevation change may not have been reliably resolved by the nearest living relatives method. Although it is likely that the eastern Cordillera did experience an important uplift during the late Neogene, as suggested by the evidence of contemporaneous deformation and by the young fission track ages of the Quetame massif (Mora et al., 2008), it is improbable that the axial zone of the Cordillera remained at low altitude until 6 Ma, as we can deduce from the tectonics-sedimentation and sediment provenance studies (e.g., Guerrero, 1993; Parra et al., 2009a; Horton et al., 2010). Our section restoration indicates that more than 50% of the total shortening of the eastern Cordillera (52 km [32.3 mi]) was already acquired by 10 Ma, with which it seems likely than more than half of the current elevation of the axial zone (ca 2600 m [8530.2 ft]) was already attained by that time.

Whatever the precise timing, the eastern Cordillera uplift is expressed in a specific pattern of landscape evolution that has been recently put forward by Babault et al. (2013). In contrast with the two-sided wedge profile characteristic of many collision mountain belts, the eastern Cordillera displays an axial plateau of low relief (Mora et al., 2008), dominated by rivers flowing parallel to the tectonic structures. The flanks of the Cordillera are, on the other hand, dominated by slope-controlled transverse rivers, with high relief. The rapidly incising transverse rivers are capturing the earlier longitudinal streams of the plateau, thus reducing its aerial extent (Struth et al., 2012; Babault et al., 2013), a process that has probably been persisting in the last Ma. Should it proceed with continuous mountain building in the eastern Cordillera, it may lead to the eventual disappearance of the Sabana de Bogota Plateau into a transverse-dominated drainage. Other inversion mountain belts as the Moroccan Atlas are experiencing a similar evolution (e.g., Babault et al., 2013), suggesting that it may represent a pattern of geomorphic evolution common in inversion orogens as they grow topographically.

## CONCLUSIONS

A balanced section across the eastern Cordillera of Colombia near the latitude of Bogota (the Medina–Utica transect) illustrates the structure of a back-arc rift system that was submitted to compression and tectonic inversion. The main extensional faults originally bordering the rift were reactivated as basement-involved thrust faults, defining a dominant thick-skinned tectonic style for the orogen margins. Feedbacks between section construction and restoration suggest ramp angles of 18°–20° for the main border thrusts.

The two lower Cretaceous subbasins of Cocuy and Tablazo–Magdalena defined in other segments of the chain can be tentatively identified in the process of section restoration. Extensional faulting was comparatively more important in their respective outer margins, which later concentrated the principal thrust displacements creating the Llanos and middle Magdalena foothill belts of the Cordillera. The inner margins of the subbasins experienced comparatively less reactivation.

The axial zone of the Cordillera is a high plateau with comparatively less deformation and structural relief (the Sabana de Bogota). We interpret that salt tectonics played an important role in the structural development of the Sabana, which is deformed into a thin-skinned fold system above a weak detachment that we attribute to lowermost Cretaceous salt. We propose that evaporite rocks formed diapiric salt walls during the Cretaceous extension, which were subsequently obscured by diapir squeezing and welding during the Cenozoic compression. Other detached cover systems exist in the western flank of the Cordillera (the imbricate fan at La Vega-Villeta), in that case without evidence of salt, which is consistent with a dominant unidirectional vergence indicative of a more frictional detachment.

The comparison between the present-day and a restored section to the pre-orogenic state at 70 Ma indicates a total shortening of ca 82 km (50.9 mi) (27% of the original length). Sparse evidence suggests that the compressional deformation history commenced near the Cretaceous–Tertiary boundary, in close association to salt, either in the Sabana de Bogota (as recorded by halokinetic sequences of growth strata), and in the eastern foothills (associated to fault-related emerald mineralization). Localized folding continued throughout the Paleogene and requires initial movement in the precursor of the large basement thrusts that experienced major emergence and caused major mountain building during the Neogene. In parallel, sequential section restoration constrained by tectonics-sedimentation relationships and published thermochronology indicates that shortening commenced at an average rate of <0.5 mm/a in the early Paleogene, accelerating to 3 mm/a in the Neogene, rates that continue to recent times. The eastern Cordillera of Colombia exemplifies a pattern of tectonic evolution that is common in inverted rifts (e.g., Babault et al., 2013), where rift interiors initially deform in a distributed way, much controlled by weak stratigraphic horizons, and possibly harden to a point when intense deformation is shifted into the weak faults at the rift margins and prominent mountain topography is acquired.

## ACKNOWLEDGMENTS

This research was made possible through the support of the ICP–ECOPETROL, Bucaramanga (Project: "Cronologia de la deformacion en las cuencas subandinas"). We thank the ICP for permission to publish the results. Additional support was provided by Spanish project CGL2010-15416. The software *move* used in cross-section construction and restoration was provided by Midland Valley through the ASI program. The work benefited from assistance and discussion in the lab or in the field with M. Julivert, M. Patiño, Y.H. Cortes, M.L. Arboleya, J. Babault, J. Castellanos, L. Jimenez, and L. Campiño.

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