Timing of hydrocarbon entrapment in the eastern foothills of the Eastern Cordillera of Colombia

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ABSTRACT

The eastern foothills in the Colombian Eastern Cordillera have been an important oil-producing region since the discovery of the Cupiagua and Cusiana fields. Three organic-rich units are considered to be the main source rocks. The Aptian Fómeque and the Cenomanian-Coniacian Chipaque Formations comprise a siliciclastic to locally carbonate shallow marine shelf succession with type-II kerogen, whereas the Paleocene Los Cuervos Formation consists of marginal marine to nonmarine siliciclastic rocks with type-III kerogen. We modeled the petroleum systems of these three source units to characterize the hydrocarbon generation-accumulation processes within the basin. The structural record of the Eastern Cordillera shows that the most important tectonic event began in early Oligocene with contractional deformation along the Soapaga through Guaicaramo faults during early Miocene, culminating during the Pliocene with the Cusiana and Yopal faults. These variable rates of burial and exhumation resulted in contrasting time-temperature histories for each of the source rocks. The Fómeque Formation reached the oil window during the Paleocene in the south and the Eocene to the north. In contrast, the Chipaque Formation generation started during Early Oligocene in the south and by Late Oligocene to the north. Conversely, maturation for the Los Cuervos Formation was uniform along the foothills, reaching the oil window during Late Oligocene. Charge history modeling suggested that the Albian sandstones reservoirs were filled between Oligocene to Miocene. In contrast, the proven reservoirs in the area (the Upper Cretaceous, Paleocene, and Eocene sandstones) were filled by late Miocene, with a second episode of recent charge in the Eocene reservoirs, and perhaps active, from the Los Cuervos Formation. The results of this work proved that petroleum system modeling is useful not only to characterize generation-migration processes but it also can be used as a prediction tool in structurally complex areas such as the Colombian foothills.

Introduction

The eastern foothills in the Eastern Cordillera of Colombia have been an area of interest for oil exploration for decades. The first well (Guavio-1) drilled in the 1960s was abandoned. However, the well generated expectations that led to the drilling of other unsuccessful wells. In 1992, the discovery of gas and condensates in the Cusiana field propelled further discoveries such as the Cupiagua, Volcanera, and Dele fields (Figure 1).

The foothills province along the transition between the Eastern Cordillera and the Llanos Basin remains of great interest. However, the structural complexity of the area has become a technological and operational challenge. The difficulties range from accurately imaging subsurface structures for hydrocarbon exploration (due to complicated near-surface conditions, high topographic relief, and complex geologic structures) to reaching subsurface units of interest with precision and at reasonable cost during drilling (Estrada and Jaramillo, 2003).

The successful wells in the area showed great potential for light crude oil and gas, mainly in Cenozoic reservoirs. The well depths range from 4000 m (13,123 ft) to 5500 m (18,044 ft) with API gravities up to 45° (Rangel et al., 2017). Several studies have recognized and described the structural style of the area, including the thin-skinned domain with shallow thrust faults that only involve sedimentary rocks and increase the structural complexity toward the north (e.g., Cazier et al., 1995; Estrada and Jaramillo, 2003; Martinez, 2006; Jimenez et al., 2013). Although structural studies have facilitated the definition of the structural traps in this province, the charging mechanisms are not well-documented or well-understood.

Few studies related to understanding of the petroleum systems in the Eastern Cordillera and adjacent foothills have been published. Authors such as Cortés et al. (2009), Sanchez et al. (2015), and Mora et al. (2019) propose and document the timing for the processes of gen-

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eration, migration, and filling of the traps. Most authors agree that hydrocarbon generation at the basin scale started in the Eocene, with variations in reservoir charge that span millions of years depending on the analyzed structure. However, there are limited insights around the thermal evolution of the source rock in the area and the charging mechanism at reservoir scale. To answer these questions, petroleum system models become an essential tool to integrate structural, stratigraphy data along with organic geochemistry to reconstruct the timing and type of hydrocarbons involved in the charging of reservoir units within various traps.

A key objective of this paper is to test potential scenarios of petroleum generation, migration, and charge within the context of a high-resolution kinematic restoration.

Regional geology

The Eastern Cordillera is a divergent inversion orogen in the northern Andes limited to the east by the Guaicáramo fault system and to the west by the Bituima and La Salina fault systems. The province is divided into three sections (Figure 1): (1) the axial zone, between the central high plains east of the Arcabuco anticline and the synclines exposing Cenozoic rocks in the footwall of the Soapaga fault, (2) the eastern flank, including the Sopaga fault and the foothills, and the hanging walls of the Guaicaramo and Cusiana faults, and (3) the Llanos Basin, the low-relief foreland area located in the east of the Cusiana fault.

The evolution of the northern Andes is marked by the breakup of Pangea (Pindell and Dewey, 1982; Jaillard et al., 1990; Pindell and Erikson, 1993) accompanied by a marine transgression from Triassic to Cretaceous (Cooper et al., 1995; Sarmiento-Rojas et al., 2006). Others also relate the development of the Eastern Cordillera to a younger arc located behind a subduction-related magmatic arc (Maze, 1984; McCourt et al., 1984; Pindell and Erikson, 1993; Toussaint, 1995a, 1995b). The evidence of this magmatic arc includes a series of intrusive bodies of early Triassic-early Jurassic granodiorite (Spikings et al., 2015) such as the Ibagué and Segovia batholiths in the Central Cordillera.

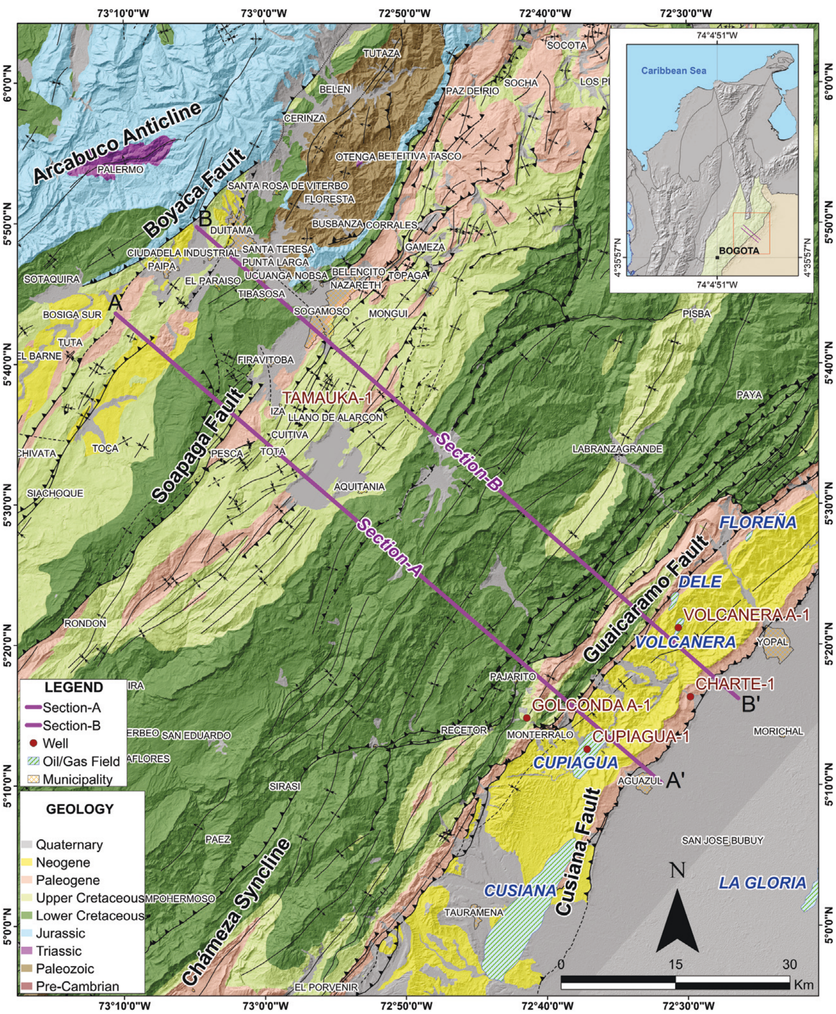

Figure 1. Location of the area of interest in the eastern foothills of the Eastern Cordillera showing the main structural features. Notice the location of the two cross sections modeled in this study (sections A and B), some wells and oil/gas fields. These sections are approximately 95 km (59 mi) of length each.

During the Late Jurassic to the Early Cretaceous (Aptian), synrift sedimentation was characterized by the transition from fluvial to marine sedimentation recorded by thick intervals of fine-grained sedimentary units (e.g., Mora et al., 2019). This early deposition was accompanied by Jurassic volcanism (e.g., Bocas Formation), and it was tectonically controlled by the Bituima-La Salina, Bucaramanga, and Boyacá extensional faults (Kammer and Sánchez, 2006; Clavijo et al., 2008; Mora et al., 2009; Tesón et al., 2013).

Following the synrift phase, postrift thermal subsidence started by the Albian and finished during the Campanian (Caballero et al., 2013a) or Maastrichtian (Sarmiento-Rojas et al., 2006) with initial uplift of the Central Cordillera (Parra et al., 2012; Bayona et al., 2013). During the Cretaceous, sedimentation in the Eastern Cordillera was mainly marine, providing conditions for the deposition of the most important source rocks in eastern Cordillera, the Chipaque Formation (Cazier et al., 1995; Cortés et al., 2009; García et al., 2015; Mora et al., 2015b; Sanchez et al., 2015), and one of the most important reservoirs in the foothills, the Guadalupe Group (Figure 2).

After the synrift and postrift phases, regional contraction led to inversion of the basin. Inversion began with the earliest documented exhumation of the Central Cordillera in the Late Cretaceous (approximately 78 Ma) (Parra et al., 2012; Caballero et al., 2013a, 2013b) and advanced eastward, with thrust-induced denudation documented along the La Salina and Soapaga faults during the Eocene (approximately 40–30 Ma) (Mora et al., 2013a, 2013b; Reyes-Harker et al., 2015).

Farther east, sediment provenance and thermochronological data indicate the first important inversion event occurred during the Oligocene (approximately 33–23 Ma) (Parra et al., 2009; Horton et al., 2010; Bande et al., 2012), including reactivation of the Soapaga fault (Saylor et al., 2012). Low-amplitude detachment folding, thrusting, and associated unconformities have been well-documented and became more evident in the foothills by late Oligocene to early Miocene time (Martinez, 2006; Mora et al., 2010, 2014; Jimenez et al., 2013; Tamara et al., 2015).

Several authors have documented deformation geometries of late Oligocene-early Miocene structures

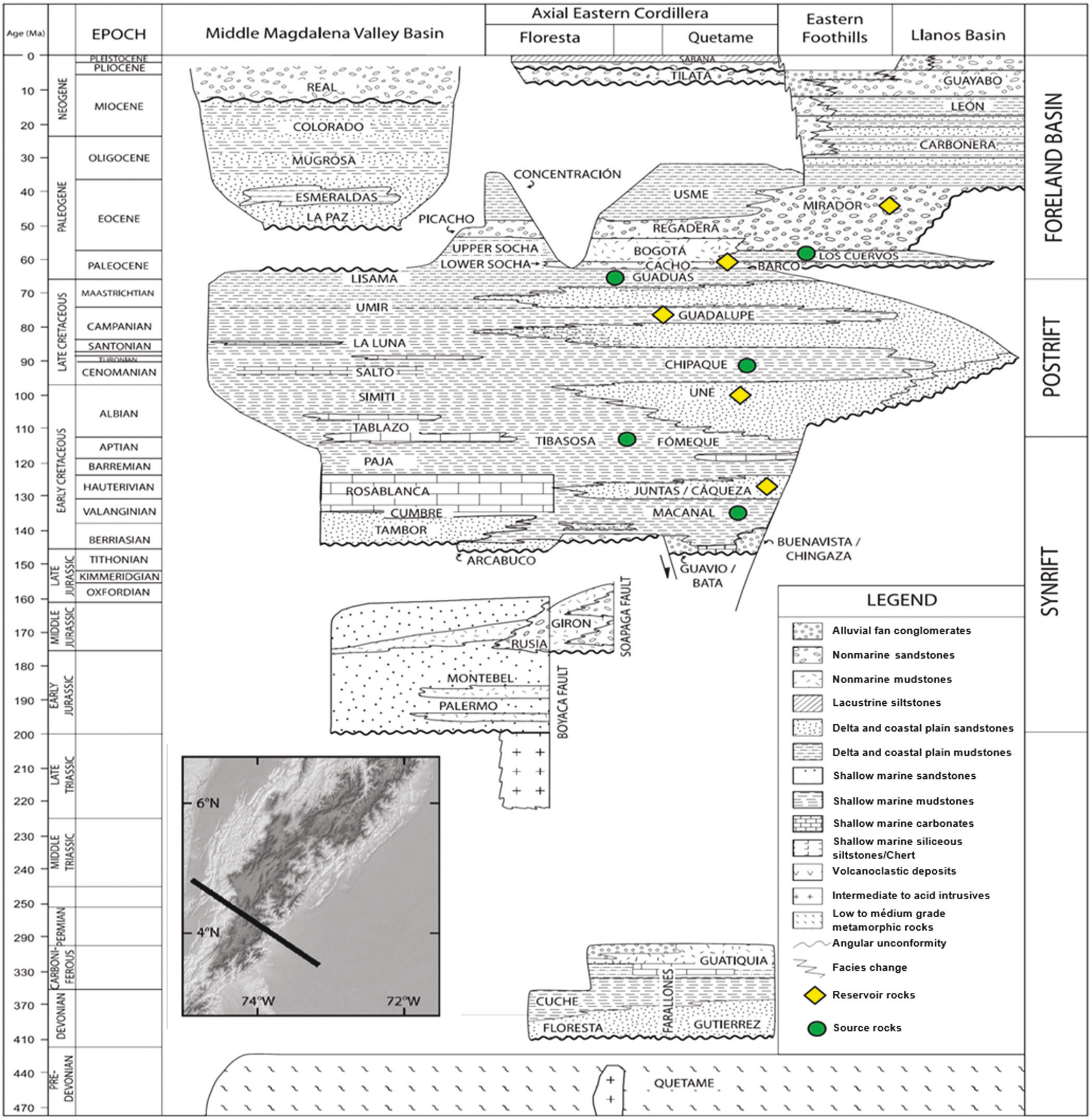

Figure 2. Chronostratigraphic framework for the axial zone of the Eastern Cordillera and its foothills (modified from Parra et al., 2009; Mora et al., 2015b).

in the axial zone of the Eastern Cordillera (Mora et al., 2013b; De la Parra et al., 2015; Kammer et al., 2020). The deformation was focused farther east, with reverse motion along of the Pajarito, Guaicaramo, and Yopal faults during Miocene-Pliocene time, between 23 and 5 Ma (Horton et al., 2010, 2020; Mora et al., 2010, 2015b; Bande et al., 2012; Ramírez et al., 2012).

Early Andean shortening coincided with a change from marine to nonmarine environments (Sarmiento-Rojas et al., 2006), leading to important Paleogene reservoir rocks of fluvial to marginal marine origins, including the Barco (Paleocene), Mirador (Eocene), and Carbonera (Oligocene) Formations. This phase also included deposition of one of the secondary source rocks, the Los Cuervos Formation (Paleocene) (Rangel et al., 2017).

Finally, Mora et al. (2010, 2014) and Ketcham et al. (2018) present apatite fission track results and thermokinematic models showing that the most important exhumation event along the eastern foothills began by approximately 10 Ma. This deformation involved displacement of the most important thrust sheets and the formation of the main antiformal and duplex structures in the eastern foothills, including the Monterralo and Rio Tocaría faults (Martinez, 2006; Mora et al., 2014; Ketcham et al., 2018). Late-Miocene deformation coincided with the main phase of uplift in the Eastern Cordillera (e.g., Mora and Parra, 2008; Anderson et al., 2015, 2016). Such topographic growth accelerated flexural deformation of the Llanos foreland plate and facilitated the creation of the large accommodation space in front of the Eastern Cordillera, where a thick succession of dominantly fluvial sediments was deposited (Cooper et al., 1995; Delgado et al., 2012).

The sequence of deformation in the eastern foothills, the object of many past studies (Kammer and Mora, 1999; Martinez et al., 2006; Jimenez et al., 2013), has been recently summarized by Mora et al. (2020).

The Cupiaga, Floreña, and Pauto structures

The Cupiagua structure is a large anticline (Figure 1) limited by reverse faults. Crude oils from this structure are mainly light oils with an API gravity of 32°–37°. The main reservoirs are the Mirador Formation and the Guadalupe Group, along with the Une Formation as a secondary reservoir (Ramon and Fajardo, 2006).

The Floreña and Pauto structures are limited by closed faults in a duplex structure (Figure 1); this duplex structure is not present in the Cupiagua area. Crude oils from the Floreña and Pauto structures are similar to Cupiagua, ranging from 30° to 38° in API gravity. Some crude oils show dissolved condensates, as in

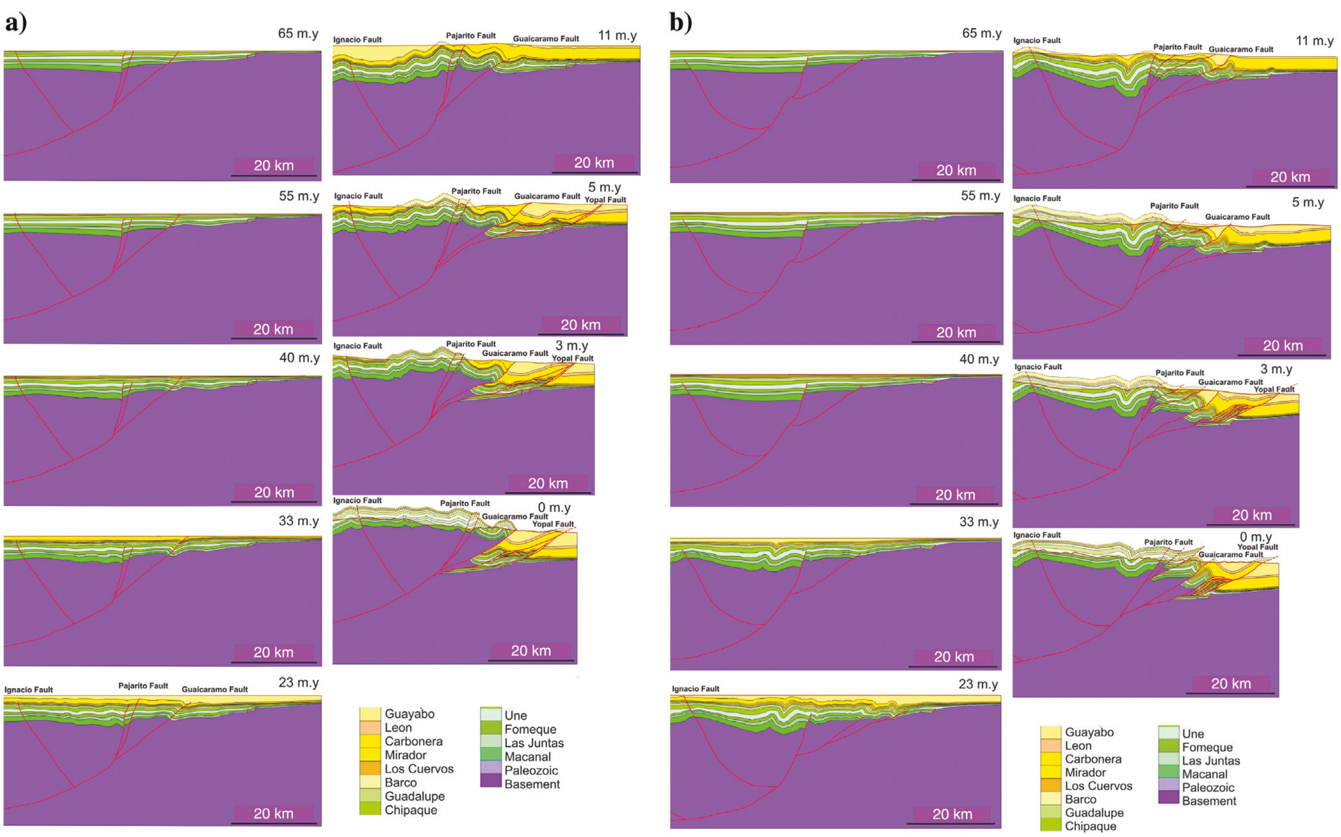

Figure 3. Kinematic restoration for (a) section A to the south and (b) section B to the north included in Figure 1. The vertical scale is twice the horizontal. (a) Cupiagua structure (south area, the A-A′ section). (b) Floreña-Pauto structures (north area, the B-B′ section).

the case of the Pauto Sur field (Rangel et al., 2017). The main reservoirs in these structures are from the Mirador Formation, followed in importance by reservoirs of the Guadalupe Group and the Barco Formation (Mejia Hernandez, 2015).

Methodology

We constructed two 2D petroleum systems models using PetroMod^{M} from two cross sections (Figure 1), constructed and restored following methodologies established for the Colombian Andes (Almendral et al., 2015; Mora et al., 2015a; Carrillo et al., 2016). The lithologic, petrophysical, organic, and thermal properties used as input data were obtained from the collection and integration of stratigraphic, sedimentologic, and geochemical information from well and outcrop samples in and near the study area.

Although the procedures to restore the two sections are provided by Carrillo et al. (2016), this study represents the first high-resolution restoration that integrates all of the previous data sets into a single petroleum systems model.

The hydrocarbon generation and migration process was modeled in the two cross sections to evaluate the impact of Eastern Cordillera uplift on the charge history of the study area. The southern section A and the northern section B are related to the Cupiagua and Floreña-Pauto structures, respectively (Figure 1).

Kinematic restoration

For each cross section, 15 stratigraphic horizons and the main faults were interpreted as the geometric input for the petroleum system models. Eight stages of Cenozoic deformation were sequentially restored for discrete time slices corresponding to 3, 5, 11, 23, 33, 40, 55, and 65 Ma (Figure 3). In general, the local kinematic histories follow the timing scenario described by McClay et al. (2018) for the Andean foothills, where basement faults provide a backstop during the progressive foreland-ward (eastward) activation and synchronous motion of frontal thin-skinned structures.

The precise timing of the deformation was defined on the basis of cross-cutting relationships (Martinez, 2006; Mora et al., 2010) and a wealth of sediment provenance and thermochronological data (e.g., Horton et al., 2010, 2020; Mora et al., 2010, 2014; Bande et al., 2012; Ramírez et al., 2012; Jimenez et al., 2013). The preexisting data sets provide a robust framework for modeling the restored cross sections.

Source rocks' bulk geochemical features

This study includes two Mesozoic source rocks and one Cenozoic source rock. The Mesozoic source rocks are composed of the Fómeque (Aptian) and Chipaque (Cenomanian-Coniacian) Formations, represented by an interval of organic shale, limestone, and siltstone, along with interbedded sandstone deposited in a shallow marine platform with type II organic matter (with total organic carbon [TOC] values of approximately 4% and HI value of 350–400 mgHC/g rock).

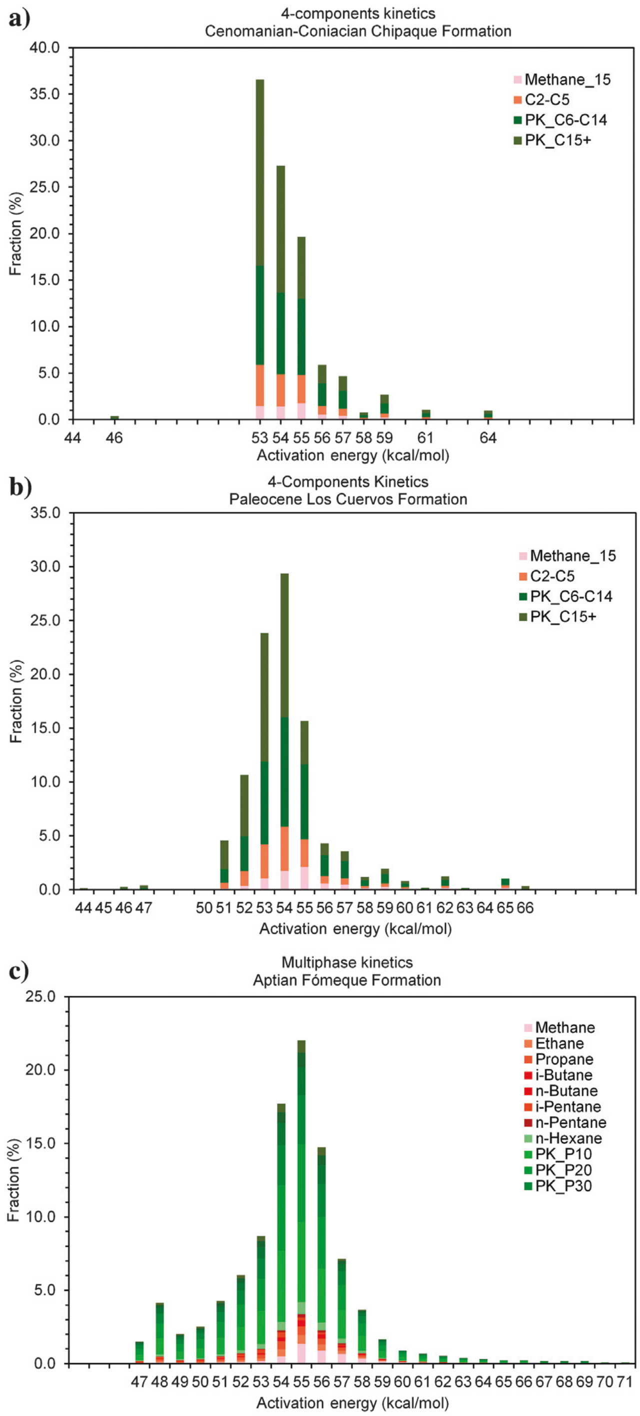

Figure 4. Kinetic distribution used in this study. (a) Kinetic distribution of the Chipaque Formation and (b) kinetic distribution of the Los Cuervos Formation. Kinetic models were built for immature outcrop samples of these formations using the PhaseKinetic approach through MSSV pyrolysis (Horsfield and Di Primio, 2006). (c) Kinetic distribution of the Fómeque Formation. The kinetic model for this source rock was obtained from the PetroMod library using a type II/III kinetics proposed by Vandenbroucke et al. (1999).

The Cenozoic source rock from the Paleocene Los Cuervos Formation is constituted by siliciclastic rocks with organic-rich intervals related to transitional environments with type III organic matter (with a TOC of 4.6% and an HI value of 323 mgHC/g rock). The geochemical parameters are summarized in Table 1.

Kinetic distributions

We considered different kinetic distributions in this study, taking into account the different types of organic matter in the source rocks selected. Kinetic models were built for outcrop samples of the immature Chipaque and Los Cuervos source rocks using the PhaseKinetic approach through microscale sealed vessel (MSSV) pyrolysis (as described by Horsfield and Di Primio, 2006). These source rock samples were analyzed by nonisothermal open system pyrolysis at four different laboratory heating rates (0.7, 2.0, 5.0, and 15 K/min) using a Source Rock Analyzer. The generated bulk petroleum formation curves serve as the input for the bulk kinetic models consisting of an activation energy distribution and a single frequency factor. MSSV pyrolysis was used to populate the bulk kinetic models with compositional information (Figure 4a and 4b). In contrast, due to the lack of an immature sample for the Fómeque Formation, the kinetic model for this source rock was obtained from the PetroMod library using a type II/III kinetics proposed by Vandenbroucke et al. (1999) (Figure 4c).

Heat flow trends

We define different heat flow trends in this study for the axial and foothills zones of the Eastern Cordillera (Figure 5). Three tectonic stages were taken into account for each heat flow trend: the synrift, postrift, and inversion stages. The heat flow values for the synrift and postrift stages were calculated based on mantle stretch factors calculated by Sarmiento-Rojas et al.

Table 1. Geochemical properties of source rocks used in the modeling of the petroleum systems.

Formation name	Age of deposition	Lithology	TOC (wt%)	HI (mgHC/g rock)	Kerogen type	Kinetics
Los Cuervos	Paleocene	Shale, siltstone, and coal	4.6	323	II/III	Horsfield and Diprimio (2006)
Chipaque	Cenomanian	Shale and siltstone	4	350	II/III	Horsfield and Diprimio (2006)
Fómeque	Aptian	Shale and carbonates	4	400	II/III	Vandenbroucke et al. (1999)

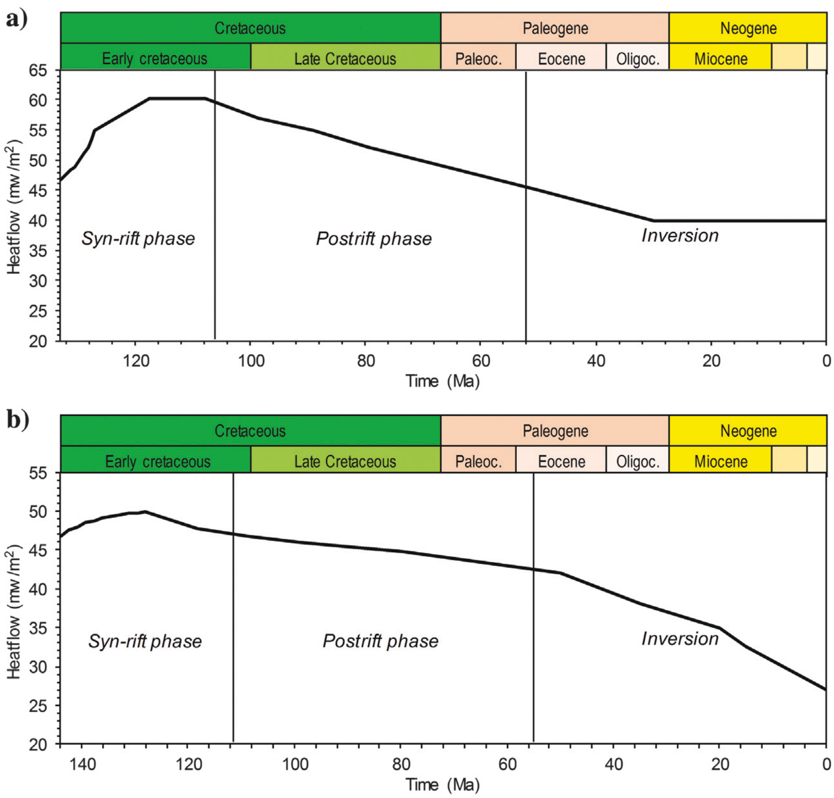

Figure 5. Heat flow trends calculated based on the crustal stretching factors measured by Sarmiento-Rojas et al. (2006). (a) Heat flow trend for the axial zone of the Eastern Cordillera and (b) heat flow trend for the eastern foothills of the Eastern Cordillera. The heat flow was considered equal or constant from the last value of the postrift stage computed by Sarmiento-Rojas (2001). (a) The heat flow for the axial zone is considered to be approximately 50 mW/m^2 in the axial zone of the Eastern Cordillera (Bachu et al., 1995), and (b) the heat flow is approximately 35 mW/m^2 in the foothills zone.

(2006) following crustal stretching models constructed by McKenzie (1978) and integrated into PetroMod 2D. This integration led to the observed heat flow trends (Figure 5a and 5b). Concerning the inversion stage related to Andean orogenesis, the heat flow was considered equal or constant compared to the final value of the preceding postrift stage computed by Sarmiento-Rojas (2001). These heat flow values vary from 35 mW/m^2 in the foothills to 50 mW/m^2 in the axial zone of the Eastern Cordillera (Bachu et al., 1995).

Thermal calibration

To constrain and calibrate the thermal evolution obtained in this study for the axial and foothills regions, we used vitrinite reflectance (%Ro) and downhole temperature data from two wells close to the modeled cross sections (Figure 6).

Thermal maturity and charge modeling results

We show the main results from the thermal maturity and charge modeling done in the Cupiagua and Floreña-Pauto structures located, respectively, at the south and north of the studied area (sections A and B, respectively, Figures 7, 8, 9, and 10).

We conclude that two main mechanisms have guided the thermal evolution of the source rocks. The first is associated with higher heat flow during Cretaceous extensional and thermal subsidence (Figure 5). The second is related to tectonic loading and the accumulation of thick Neogene rocks. Although the extension-related and thermal subsidence phases are regional in extent, the younger sedimentary and tectonic loads have local variations that depend on the structure considered.

Section A (south) Cupiagua structure

In the south (the Cupiagua structure), different source rocks reached the oil window along the western flank of the Eastern Cordillera (Figure 7). The Aptian Fómeque Formation reached the oil window during the Paleocene and Early Eocene (Figure 8). On the other hand, the tectonic load and the highest thickness of Neogene rocks triggered the thermal evolution of the Chipaque and Los Cuervos Formations. These source rocks reached the oil window during the Oligocene and Miocene, respectively (Figure 8). Thermal modeling suggests that the transformation ratio of the Fómeque, Chipaque, and Los Cuervos Formations is close to 100% at present (Figure 9).

At the Cupiagua structure modeled in section A, several charge events from different source rocks can be observed (Figure 10). A first event occurred during the Late Cretaceous involved Fómeque source rock charging Une Formation reservoirs. In contrast, reservoirs from the Guadalupe, Barco, and Mirador units were charged from Chipaque and Fómeque source rocks during Paleocene to Oligocene episodes. Finally, the Los Cuervos source rock expelled hydrocarbons during the Miocene, charging reservoirs mainly in the Mirador Formation. Source rocks from the Los Cuervos Formation are currently located in the final part of the oil window, whereas those from the Fómeque and Chipaque Formations are located in the dry gas zone (Figure 8).

Section B (north) Floreña-Pauto structure

The thermal history of the Floreña-Pauto structure in the north contrasts with that observed in the Cupiagua structure in the south (Figure 7). These differences are related to substantial variations in the sedimentary and

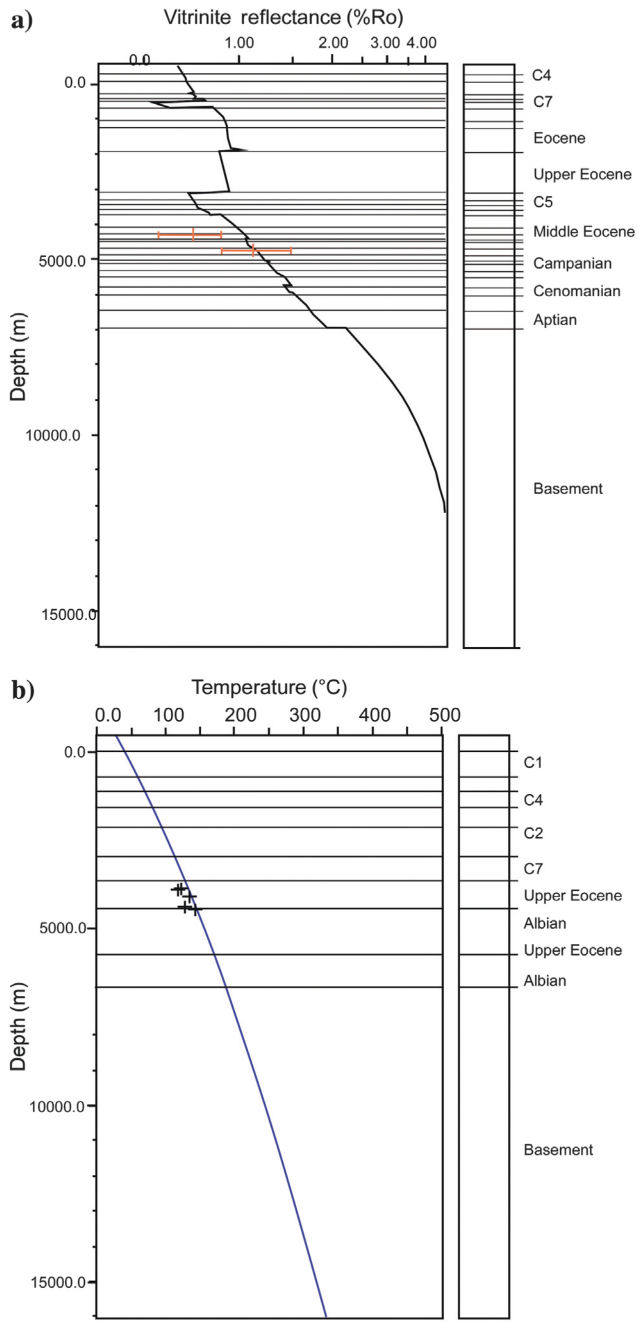

Figure 6. Example of thermal calibration for two wells near the modeled sections. (a) Vitrinite reflectance and (b) temperature.

tectonic overburden associated with the duplex structures formed in this area during Andean orogenesis.

Source rock intervals from the Aptian Fómeque Formation reached the oil window during the Oligocene. Meanwhile, source rocks from the Cenomanian-Coniacian Chipaque Formation and the Paleocene Los Cuervos Formation reached the oil window in the early and middle Miocene, respectively (Figure 8). To date, the transformation ratios of the Fómeque and Chipaque Formations are close to 100%, whereas the Los Cuervos Formation reached only 50% (Figure 9).

Discussion

The results of petroleum system modeling in this study represent a precise simulation of the hydrocarbon charge history in a structurally complex folded belt such as the foothills of the Colombian Andes along the transition from the Eastern Cordillera to the Llanos Basin. They show the importance of integrating petroleum system modeling with a robust sequential kinematic restoration when working on complex structural provinces. The tectonic evolution of the foothills is based on a large amount of recently published data (Mora et al., 2010, 2014; Bande et al., 2012; Ramírez et al., 2012; Jimenez et al., 2013).

Three types of overburden scenarios are identified. First, a tectonic overburden is related to thick-skinned deformation along the Guaicaramo fault that puts the Proterozoic basement on the Cretaceous and Paleocene source rocks. A second type of overburden is associated with thin-skinned deformation east of the Guaicaramo fault that produced several complex structures and duplexes that caused differential thermal maturation of the deepest levels. Finally, a third type of overburden involves the deposition of Miocene-Pliocene synorogenic sediments over the past 5 Myr.

The duplex structures gave rise to a complex thermal and charge process involving a variety of source rocks that charged reservoirs located at different depths and different stratigraphic levels (Figures 10 and 11). The overburden differences due to the formation of duplex structures have generated high thermal maturity in the Floreña and Pauto structures (section B to the north) relative to the Cupiagua structure (section A to the south) where no duplex structures are present (Figure 8a and 8b). However, variations in tectonic overburden have also induced temporal differences in the entrance to the oil window. For instance, the Chipaque Formation entered the oil window in the middle Eocene in section A but, by the end of the Eocene in section B, meaning a difference of approximately 10 Myr between

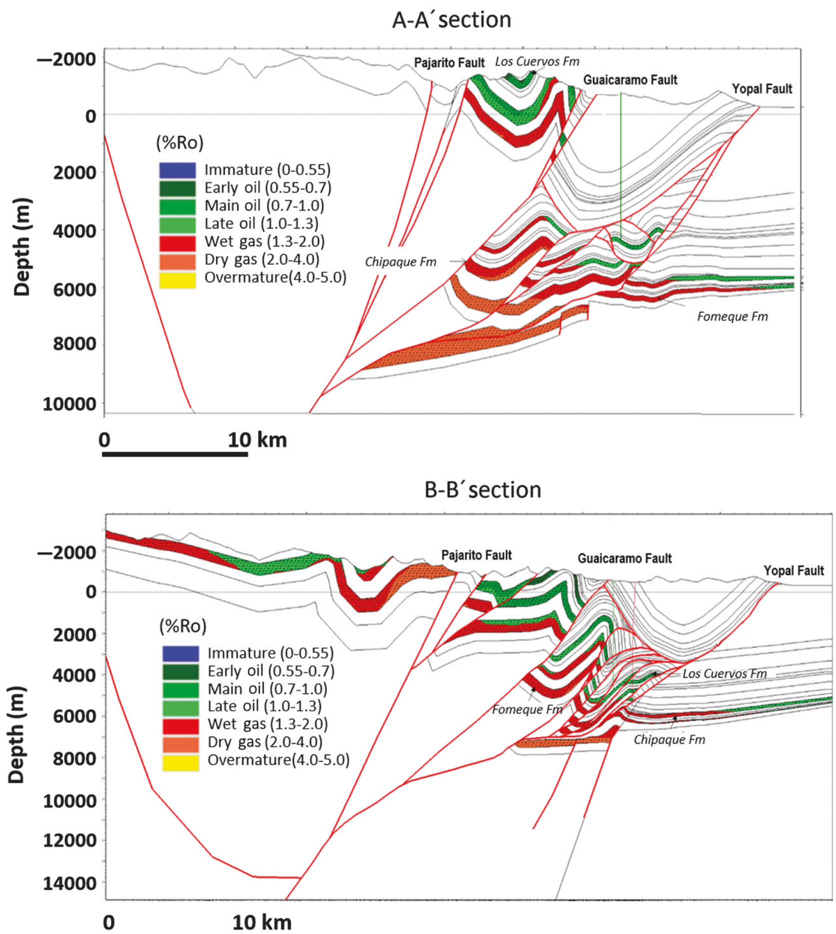

Figure 7. The rank of thermal maturity according to Sweeney and Burnham (1990). (a) The Cupiagua structure (section A) to the south. (b) The Floreña-Pauto structure (section B) to the north. It is noticeable that the same source rock can be at different thermal maturity levels, depending upon the thrust sheet position in the thin-skinned system.

the onset of generation from south to north. At present, the Chipaque Formation is located in the shallowest levels of the section A, at the peak of the oil generation window; in contrast, in the deepest levels, this formation is within the dry gas window (Figure 8).

Similar thermal maturity variations can be observed in the source rock of the Paleocene Los Cuervos Formation in the same section (Figure 7). In particular, the thermal evolution of the Los Cuervos Formation was tectonically controlled by the Yopal fault. Hydrocarbon generation ended in late Miocene-Pliocene time in the hanging wall of the Yopal fault, whereas generation is still ongoing in the front and in the deeper thrust sheets. At present, the Los Cuervos Formation is in the dry gas generation window.

In the northern and southern sections, the charge process took place in different pulses involving different source rocks (Figures 10 and 11). The first pulse, derived from Fómeque Formation source rock, charged Une Formation reservoirs during Eocene-Oligocene time. Subsequently, a second pulse from Cenomanian-Coniacian Chipaque source rock charged Miocene reservoirs in the Guadalupe Group and the Barco Formation. Finally, a third pulse, from the Paleocene Los Cuervos source rock charged sandstones reservoir from the Mirador Formation during late Oligocene to late Miocene time, through lateral and short-distance migration routes likely facilitated by faults (Figure 11).

In this way, we can propose several petroleum systems in the foothills regions: Chipaque-Guadalupe (.), Chipaque-Barco (.), and Los Cuervos-Mirador (.). and the speculative oil systems Fómeque-Une (?) and Chipaque-Une (?). However, we suggest the presence of mixed oils in the reservoirs of the region, produced by multiple source rocks and multiple expulsion stages. Detailed geochemical studies including specific age biomarkers can be used to test this hypothesis.

Reservoirs from the Mirador Formation represent more than 50% of the entrapped volume, followed by the reservoirs in the Barco Formation and the Guadalupe Group (Figures 10 and 11). In contrast, proposed reservoirs related to the Une Formation have not been confirmed because they have not yet been tested through drilling.

Finally, taking into account the simulated depth of hydrocarbon generation, the modeling results suggest that light oils of 30°–38° API gravity have charged the modeled structures.

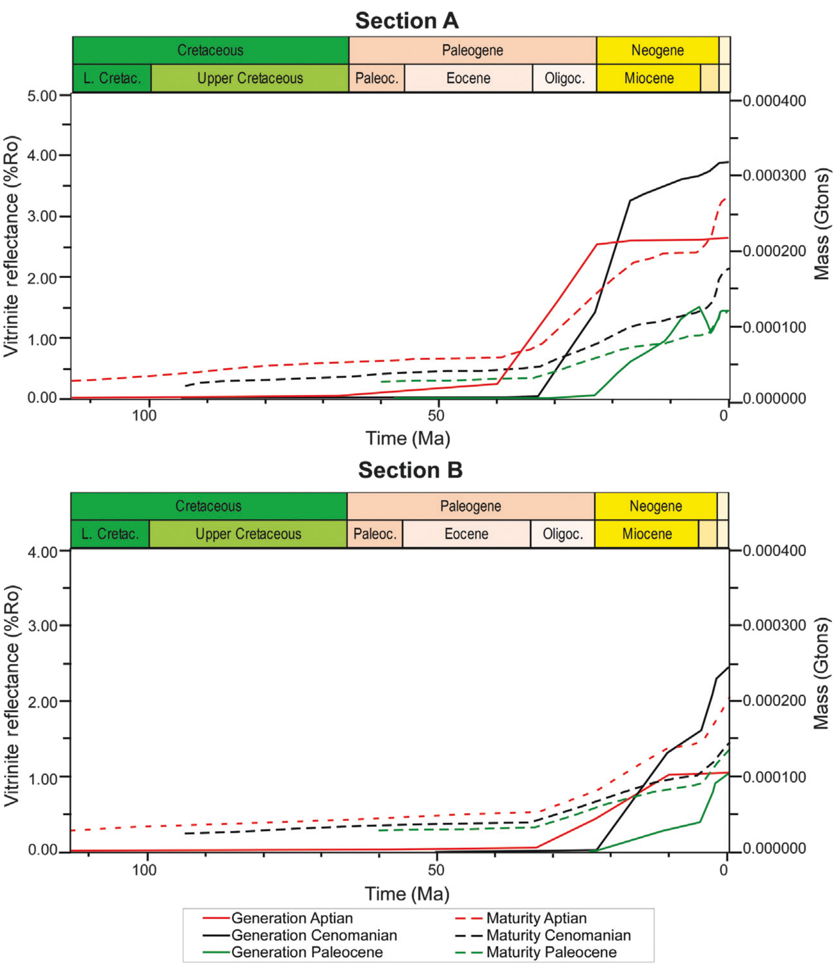

Figure 8. Generation and maturity in sections A and B. We can observe that Aptian source rock from the Fómeque Formation reached the oil window in the Oligocene. In contrast, Cenomanian-Coniacian from the Chipaque Formation and Paleocene source rock from the Los Cuervos Formation reached the oil window in the early and middle Miocene, respectively.

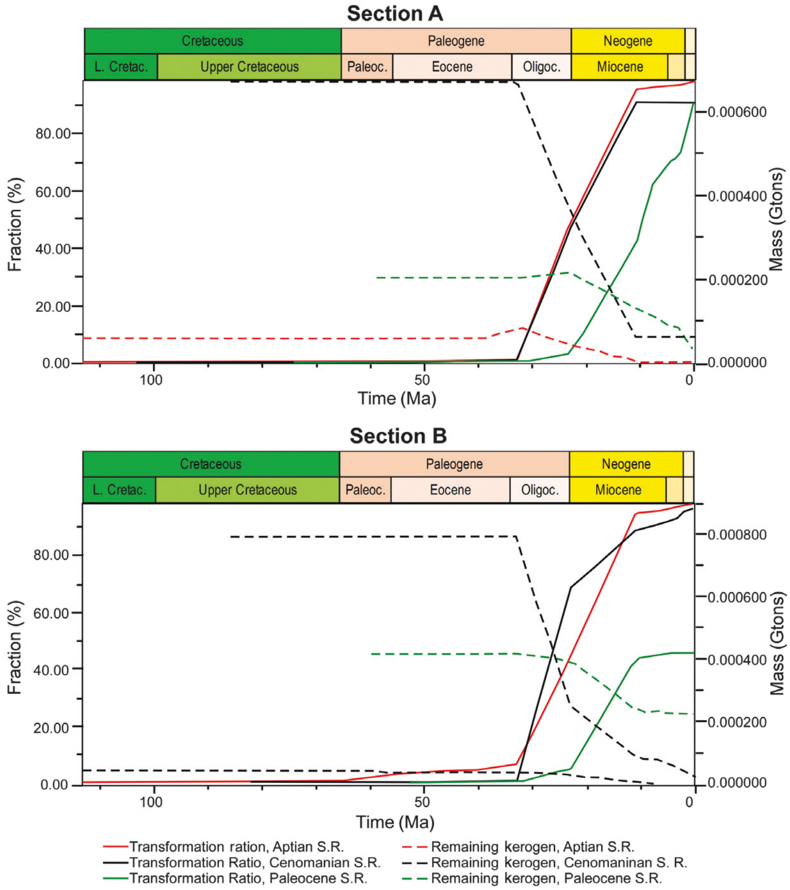

Figure 9. Transformation ratio and remaining potential in sections A and B. Differences in this ratio can be observed in the two sections. At the present time, the transformation rate of the Fómeque and Chipaque Formations is close to 100%, whereas the Los Cuervos Formation reached only 50%.

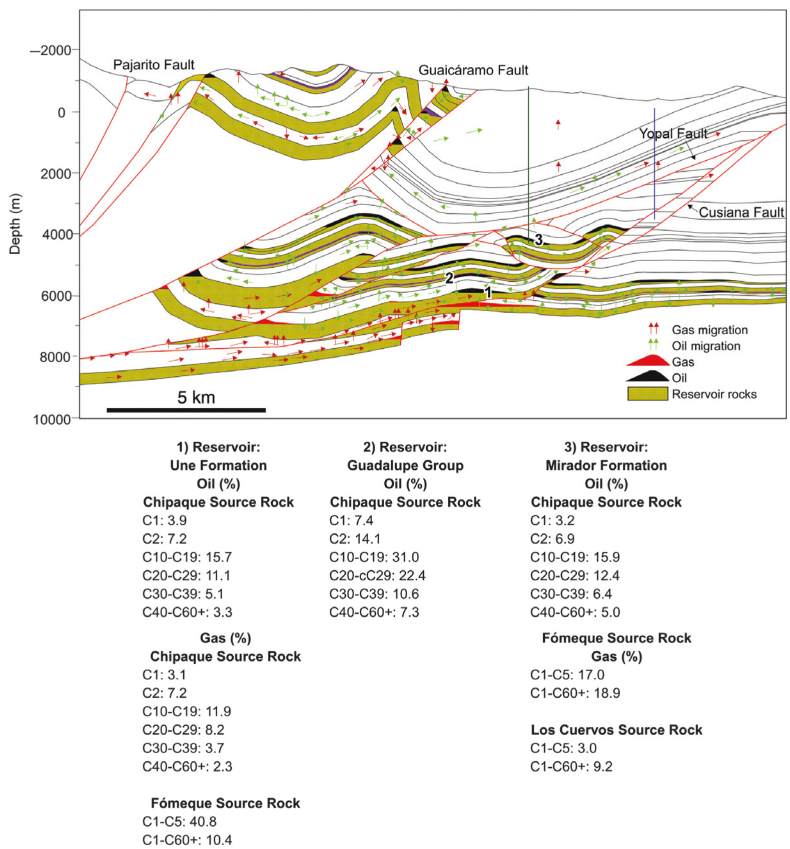

Figure 10. Detailed view of the charge into main oil and gas fields and reservoirs in the Cupiagua structure (section A). Differences in the structural framework in both sections are observable. The main oil and gas reservoirs are shown. These are Albian, Campanian-Maastrichtian, Paleocene, and Eocene sandstones. The different migration paths and sources that charged the reservoirs are shown.

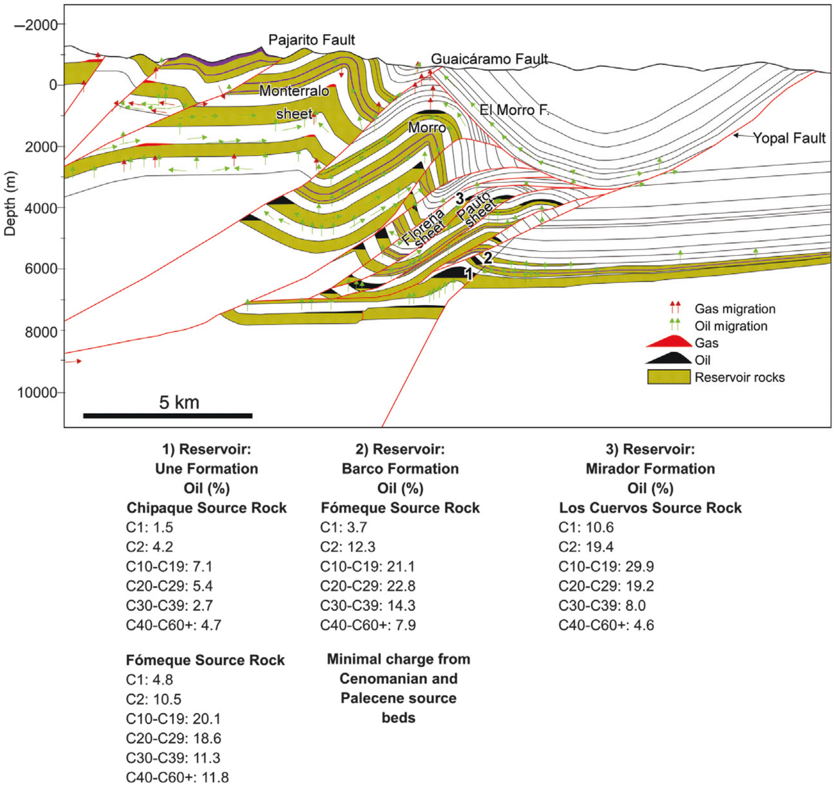

Figure 11. Detailed view of the charge into the main oil and gas fields and reservoirs in the Floreña-Pauto structure (section B). Differences in the structural framework in both sections are observable. The main oil and gas reservoirs are shown. These are Albian, Campanian-Maastrichtian, Paleocene, and Eocene sandstones. The different migration paths and sources that charged the reservoirs are shown.

Conclusion

The results of this study demonstrate the importance of including a robust sequential kinematic restoration in petroleum system modeling of structurally complex areas such as the foothills of the Eastern Cordillera of Colombia.

Two main mechanisms have controlled the thermal maturity evolution in the area: variations in heat flow during the different tectonic phases of the region and variations in the overburden associated with differential tectonic loading and basin infilling.

At the scale of individual prospects, differences in overburden related to contrasting structural regimes have to be considered to understand the charge processes. In the study area, the formation of duplex structures helped to generate a high thermal maturity in the Floreña and Pauto structures, in contrast to the Cupiagua structure where no duplex structures are present.

Furthermore, variations in the tectonic overburden, as related to the structural emplacement of different fault blocks, induced timing differences in the entrance to the oil window for the source rocks considered in this study:

- The Fómeque Formation (Aptian) reached the generation window during the Paleocene to the south (section A), but at the end of the Eocene to the north (section B).
- The Chipaque Formation (Coniacian-Cenomanian) entered the oil window in the early Oligocene in the southern sectors of the study area (section A), but it was in the late Oligocene in the northern sectors (section B).
- The Los Cuervos Formation (Paleocene) reached the oil window during the Miocene in both areas.

Finally, this study suggests the presence of mixed oils in the reservoirs of the region, as produced by multiple source rocks and multiple expulsion stages. Detailed geochemical studies with specific age biomarkers can help test this hypothesis.

The Cenomanian-Coniacian source rocks reached the oil window in the southern area by the early Oligocene and the northern area by the late Oligocene. However, Paleocene source rock reached the oil window by the early Miocene in both areas; depending on the structural position, it can be in the generation window today.

The hydrocarbons that charged the modeled structures are light oils (30°–38° API) with a mixture of condensates and gases, with a clear correlation between the amount of gas and the depth of the reservoir.

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Data and materials availability

Data associated with this research are confidential and cannot be released.

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Biographies and photographs of the authors are not available.