Thin-skinned and thick-skinned structural control on the evolution of a foreland basin petroleum system - Parrando and Guavio anticlines, Eastern Cordillera Llanos foothills, Colombia

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ABSTRACT

The Parrando anticline is located in the Llanos foothills on the eastern flank of the Eastern Cordillera of Colombia. To the northwest of the Parrando anticline area is the Guavio anticline, a large fault-bend fold, a structure that appears to be an unbreached trap with four-way closure and seal, but test wells show no commercial amounts of petroleum. Just 65 km to the northeast along strike is the giant Cusiana oil field. This study presents new 3D horizon maps, seismic and stratigraphic interpretations, and 1D basin models based on a 3D seismic volume (246 km2 5000 msec), 70 2D seismic lines (176 km), 18 wells with well log data and final well reports. A small fault-bend fold in the footwall of the Parrando thrust appears to have 4-way closure for a Mirador Formation trap. 1D models suggest hydrocarbon generation from 8 to 5 Ma, similar to the Cusiana system, but high-angle normal and transpressive faults may have permitted hydrocarbon escape. Just to the northwest across the Guaicaramo fault, the Guavio structure was formed by overlapping fault-bend folds (total relief 3.5 km) during late Miocene-Pliocene age (6-3 Ma) shortening (minimum 20 km) and inversion of the Guaicaramo normal fault. Unlike previous models, we interpret the basement fold as formed by a ramp from pre-Cretaceous basement to a double wedge fault, folding the Guaicaramo thrust footwall rocks. A thin-skinned bedding plane thrust fault ramping to the surface along the Guaicaramo fault may have preceded the formation of the Guavio anticline. Our 1D basin model for the Medina-1 well predicts that the Gacheta Formation source rocks began to expel oil at 18 Ma, at least 10 Myr before trap formation. The timing of thick-skinned and thin-skinned deformation, and trap formation were critical factors in the evolution of the Guavio, Parrando, and Cusiana petroleum systems. Most of the Guavio deformation results from repeated inversion of the Mesozoic Guaicaramo basin-bounding normal fault.

1. Introduction

The Guavio anticline (Fig. 1) is a large fault-bend fold located 11 km northwest of the Guaicaramo fault, a structure that appears to be an unbreached trap with four-way closure and seal, but test wells show no commercial amounts of petroleum. But only 65 km east across the Guaicaramo fault is the giant Cusiana oil field. Is the different petroleum potential related to timing and structural control on the evolution of the petroleum systems? The petroleum system at Cusiana has been well described (e.g., Cooper et al., 1995; Cazier et al., 1995), but the lack of economic hydrocarbons at Guavio has not been explained. In this paper we examine the timing and structural evolution of the Guavio anticline northwest of the Guaicaramo fault and the Parrando anticline southeast of the fault.

The Eastern Cordillera was formed by the inversion and shortening of Jurassic-Early Cretaceous back arc basins. The timing of the initial uplift of the Eastern Cordillera remains poorly constrained, with estimates ranging from 60 to 25 Ma (e.g., Horton et al., 2010a; Mora et al., 2010a). Maximum tectonic inversion and shortening in the Eastern Cordillera occurred in the middle Miocene to Pliocene (Van der Hammen, 1958; Dengo and Covey, 1993; Cooper et al., 1995) and has been attributed to the collision of the Baudó-Panama arc with the western active margin of South America (Duque-Caro, 1990; Kellogg et al., 2019). Estimates of shortening range from 70 km (Cooper et al., 1995; Tesón et al., 2013; Mora et al., 2013) to 150 km or more (Dengo and Covey, 1993; Roeder and Chamberlain, 1995). Conflicting views remain as to the nature of thrusting, whether dominantly thin- or thick-skinned, and to the magnitude of the associated thrust displacements.
Dengo and Covey (1993) proposed that the Eastern Cordillera is essentially an east-verging structure formed during two main tectonic phases. The first tectonic phase induced a thin-skinned basement detached style that created large, east-verging thrust faults with the greatest shortening in the middle Miocene to Pliocene (Cortés et al., 2006). During the Pliocene, deformation changed to basement involved as Jurassic and Early Cretaceous normal faults were inverted (Dengo and Covey, 1993). Other reconstructions of the Eastern Cordillera attribute most of the deformation to inversion of mid-crustal normal faults or thick-skinned deformation with minimal thin-skinned thrusting (e.g., Cooper et al., 1995; Mora et al., 2015).

This study was based on a rich dataset provided by Frontera Energy Colombia, including a 3D seismic volume (246 km²), inlines: 631, crosslines: 630), 77 2D seismic lines (176 km), 18 wells with caliper, gamma-ray, sonic, density logs, check-shot surveys, and reports. We produced new 3D horizon maps, seismic and stratigraphic

Fig. 1. A. Tectonic map of the north Andes, showing block and plate boundaries after Cediel et al. (2003), Taboada et al. (2000), Symithe et al. (2015), and Kellogg et al. (2019). Abbreviations: CB, Choco block; CC, Central Cordillera; COR, EC, Eastern Cordillera; GM, Garzón Massif; MA, Merida (Venezuelan) Andes; NAB, North Andean block; P: Sierra de Perija; PB, Panama block; SM, Santander Massif; SN, Sierra Nevada de Santa Marta; WC, Western Cordillera. B. Eastern Cordillera regional map. C. Geologic location map of the study area- Parrando anticline and Guavio anticline after Alcârce et al. (2017). Blue dots: apatite fission track age sample locations (Mora et al., 2010b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
interpretations, and 1D basin models. We interpreted the Guavio and Parrando anticlines from 2D and 3D seismic reflection profiles using volume balancing methods (Suppe, 1983). We then retrodeformed the Guavio anticline to relate the timing of hydrocarbon expulsion (Medina-1 1D model) to the timing of Guavio trap formation, offering a possible explanation for the lack of commercial hydrocarbons in the Medina-1 well. We show that the Guacaramo thrust fault involved “thin-skinned” and “thick-skinned” deformation, fault-bend folding, and for the first time wedge faulting. We present the first structural interpretation of the Parrando anticline, a gentle fault-bend fold and breakthrough fault. Finally, we create schematic maps to illustrate the evolution of the eastern foothills petroleum system.

2. Geologic setting

2.1. Regional tectonics

Precambrian-early Paleozoic metamorphic rocks underlie the Central and Eastern Cordilleras (Cooper et al., 1995). During the Jurassic and Early Cretaceous, two rift basins developed in the Eastern Cordillera, either related to the separation of North America and South America (Jaillard et al., 1990) or extension in a backarc setting (Maze, 1984). Tectonic subsidence from extension and crustal thinning was followed by Cretaceous thermal subsidence as the lithosphere thermally equilibrated (Ojeda and Thesis, 1996). The thickness of Cretaceous basin fill is estimated to be from 5 km (Restrepo-Pace, 1989) to 8 km (Cardozo Puentes, 1988). At ~75 Ma, the Caribbean Large Igneous Province (CLIP) collided with South America, resulting in the accretion of the oceanic terrane of the Western Cordillera (Spikings et al., 2015). Subsequently buoyant Caribbean crust began agastically subducting under the North Andes, resulting in flat slab subduction and basement block uplifts in the overriding plate (Kellogg et al., 2019). 50 million years ago, the Caribbean plate ran into the Bahamas Bank on the North American plate and its motion relative to the American plates changed dramatically (Boschman et al., 2014). Included at length. Branquet et al. (2009) interpreted the Guavio anticline as a broad fault-bend fold with lateral variation in ramp height, ramp dip, and intermediate fold length. Branquet et al. (2002) interpreted the Guavio anticline as a basement pop-up related to dextral strike-slip faulting. Mora et al. (2006) and Parra et al. (2009a) interpreted the Guavio anticline as a broad fault-bend fold related to the Guacaramo thrust that splays at depth from the Tesalia fault. The Guavio anticline appears to be a fault-bend fold with 4-way closure and seal, but there is little or no commercial hydrocarbon. To present the first revised interpretation of the Guavio anticline structure and the first geologic model for the Parrando anticline.

2.3. Structural geology previous work

The geologic structure of the Medina Basin and eastern foothills of the Eastern Cordillera has been the subject of numerous regional studies (e.g., Rowan and Linares, 2000; Branquet et al., 2002; Mora et al., 2006, 2010a; Parra et al., 2009a, 2010; Jimenez et al., 2013). In this paper we present a revised interpretation of the Guavio anticline structure and the first geologic model for the Parrando anticline.

2.3.1. Guavio anticline

Structurally the Medina Basin contains the broad Guavio-Nazareth anticline–syncline pair between the Tesalia thrust to the west and the Guacaramo fault to the east (Fig. 1). Rowan and Linares (2000) used 2D seismic profiles, axial surface analysis, and fold-evolution matrices to produce a 3-dimensional model for the Guavio anticline. They interpreted the Guavio anticline as a fault-bend fold with lateral variations in ramp height, ramp dip, and intermediate flat length. Branquet et al. (2002) interpreted the Guavio anticline as a basement pop-up related to dextral strike-slip faulting. Mora et al. (2006) and Parra et al. (2009a) interpreted the Guavio anticline as a broad fault-bend fold related to the Guacaramo thrust that splays at depth from the Tesalia fault. The Guavio anticline appears to be a fault-bend fold with 4-way closure and seal, but there is little or no commercial hydrocarbon. To the west of the Guavio anticline, the Nazareth syncline is a highly asymmetric, east-verging fold that formed as a result of fault-propagation folding along the Servita/Tesalia fault system according to Parra et al. (2009a).

2.3.2. Parrando anticline

In this paper we present the first seismic images and structural interpretation for the Parrando anticline (Fig. 1). According to Parra et al. (2009a), deformation in the area is minor and results from the southward propagation of the Cusiana fault and the associated hanging-wall
La Florida anticline within en-echelon segments of the fold-thrust belt. Mora (2007) and Parra et al. (2010) interpreted folding in the footwall of the Guaicaramo thrust near Chaparral 1 well (Fig. 1) as fault-propagation folding related to movement on the Guaicaramo thrust. Based on the absence of growth strata in seismic lines of Miocene-Pliocene sediments in the footwall of the Guaicaramo thrust fault, Mora (2007) and Parra et al. (2010) predicted a maximum age of 5 Ma for initial thrusting along the Guaicaramo fault.

2.4. Petroleum geology previous work

2.4.1. Guavio

Sánchez et al. (2015) used 1-D simulations to predict that oil generation from the Chipaque Formation (Gacheta equivalent) began at the end of the Paleocene (ca. 58 Ma) southeast of the present Eastern Cordillera (west of the Tesalia fault in Fig. 1) and progressed northward. The Sánchez et al. (2015) 1D model assumed exponentially decreasing heat flow ranging from ~63 to 33 mW/m² associated with postrift lithospheric thermal contraction, with an increase in the basal heat flux up to nearly 80 mW/m² during and after the Oligocene when intense mountain building (Parra et al., 2009b; Mora et al., 2010a, 2010b) presumably caused isotherm advection and higher basal heat flux (Mora et al., 2015). At a regional level, oil generation west of the Tesalia fault ceased abruptly between approximately 25 and 20 Ma as a result of the onset of exhumation of the Eastern Cordillera (Parra et al., 2009b; Mora et al., 2010a). According to Sánchez et al. (2015) locations east of the main inversion faults (Servitá, Tesalia, Pajarito), generated very little to no oil. Between 50 and 25 Ma the generation area expanded to encompass its largest geographical extent, excluding only the easternmost locations in the present-day eastern foothills and active foredeep depozone. During this period, the greatest volume of oil was generated as most of the organic facies in the Chipaque Formation reached peak generation and expulsion (Sánchez et al., 2015).

1D analysis of sediment accumulation in the Medina Basin (Parra et al., 2010) reflects a three-stage history characterised by an Eocene-early Oligocene episode of slow sediment accumulation with rates of 30–70 m/Myr that separates two periods of faster accumulation during Late Cretaceous-Paleocene (100 m/Myr) and late Oligocene-Pliocene time (220 m/Myr), respectively. By the early Miocene (20 Ma) in Guavio, the Chipaque organic facies was 49%–100% converted (Sánchez et al., 2015).

2.4.2. Parrando

According to the Sánchez et al. (2015) 1D models, at present there is only one local kitchen in the eastern foothills east of the Guaicaramo fault near the Cusiana oil field (near Rio Chitamena E—1 well in Fig. 1). A 1D model by Cazier et al. (1995) showed rapid burial of the Cusiana area under Guayabo Formation sediments. Near Cusiana, the Gachetá Formation began to expel oil, before thrusting began, at 120 °C at 8 Ma (Cazier et al., 1995). Gas with some oil began to be expelled at 150 °C at 6 Ma, immediately before thrusting began, and continues to present day. The presence of hydrocarbons in Parrando-1 (Fig. 1) confirms the presence of an active petroleum system near Parrando.
3. Data and methodology

3.1. Seismic interpretation

Data for this study included a 3D seismic volume, (246 km² 5000 msec), 70 2D seismic lines (176 km), 18 wells with caliper, gamma-ray, sonic, density logs, and checkshot surveys. The 2D survey parameters (such as Automatic Gain Control - AGC) and datum were adjusted to merge with the 3D survey. The surface geology maps (Fig. 1) were obtained from the Colombian Geological Survey for Block 229 (Montoya et al., 2013) and the geologic map of Colombia (Alcárce et al., 2017). This study is based on integration of geophysical and geological interpretation. Seismic reflection profiles provided the main structural control for the subsurface geological interpretation constrained with available exploration wells. The research included seismic interpretation, structural modelling, 1D basin modeling, and data analyses. Seismic interpretation was carried out using Petrel software, including regional seismic stratigraphy, structural maps, surface attributes and time-depth conversion. PetroMod software was used to generate 1D basin models, including burial history curves and source rock maturity.

The Medina-1 well log was used to identify seismic units in the Guavio anticline (Fig. 1). The velocity model for Medina-1 well (Fig. 3a) was from a check shot survey after Parra (2008). A synthetic seismogram (Fig. 3b) was generated from the well density log using 25 Hz Ricker wavelets.

Identification of horizons in the 3D seismic volume southeast of the Guicaramo fault was based on a well tie to the Parrando-1 well (Fig. 1). A time depth chart for Parrando-1 was based on a well check shot survey (Fig. 4a, after Petrobras, 2008). The sonic log was then edited and used to produce a synthetic seismogram (Fig. 4b). Fig. 4b shows the Parrando-1 Gamma ray log with formation tops after Petrobras (2008) and the good fit between the synthetic and the 3D seismic in the lower part of the section.

3.2. Structural profiles and restoration

Structural models were created with Move software and were constrained by seismic and well data and surface geology. Digital elevation models (DEMs) were uploaded with the geologic maps to construct cross sections using volume-balancing techniques (Suppe, 1983). Surface geology, topography, and well data were displayed on the seismic sections as close to 1:1 vertical exaggeration as possible. Regions of homogeneous dip (dip domains) and major discontinuities were identified. Spectral analysis was used to identify fundamental step-up angles (Suppe, 1983). Stratigraphic thicknesses were determined from surface geology, seismic, and well data, and depths to basal detachments were estimated from the seismic profiles. The Guavio profile was then retrodeformed to test the interpretation and predict the timing of potential migration pathways and trap formation. Eight 2D seismic profiles and the Medina-1 well were used to constrain the geologic interpretation for the Guavio anticline. The interpretation of the Parrando anticline east of the Guicaramo fault presented in this paper was based on 3D seismic data and two drilled wells (Parrando and Chaparral). Petroleum systems analysis utilized PetroMod software to generate 1D basin models including burial history curves and source rock maturity.

4. Results

4.1. Guavio

Fig. 5 shows an uninterpreted and interpreted seismic profile through the Guavio anticline. The NW side of the profile is 2D line ME-1981-09-MII. This line was chosen because the seismic quality was better than the 2D dip line seismic profile passing through Medina-1 well. The SE end of the profile is from the 3D seismic volume. The hanging wall horizon picks are constrained by the Medina-1 well (Fig. 3, projected 4.2 km along a profile parallel to structural strike, Fig. 6). Previous formation top picks in the lower part of the well are consistent from the Gacheta Formation to the top of Carbonera Formation. We note however, that picks for the top of the Leon Formation vary considerably. The footwall formation top picks are tied to the Parrando-1 well (Fig. 4) through the 3D seismic volume. Apparent surface dips are from Branquet et al. (2002) and Montoya et al. (2013). Displacement on the Cusiana fault (Fig. 1) dies out before intersecting this profile (Fig. 5). Displacement on the Parrando fault (Fig. 1) also decreases to the south and is negligible on this profile (Fig. 5).

Fig. 7 extends the structural interpretation to the northwest to the Tesalia fault showing the interpretation of Parra et al. (2009a) and the location of the Nazareth pseudo well (this paper). The surface geology (Montoya et al., 2013) and seismic profile clearly show that locally the Guicaramo thrust is a bedding plane thrust at the base of the Guadalupe Formation. Seismic reflectors dip unbroken to the northwest on the flank of the Guavio anticline showing no basement pop-up fault as proposed by Branquet et al. (2002). Instead, we interpret the Guavio anticline as formed by overtopping ramp anticlines. The upper fold was formed by a ramp thrust from a base Uplift Formation detachment near the Lower-Cretaceous, Upper-Cretaceous unconformity to a base Guadalupe Formation bedding plane thrust. The fault location was determined from dip domain boundaries visible in the seismic profile. Beneath the upper Guavio fault-bend fold is a basement ramp anticline leading to a bedding plane flat at the Upper Cretaceous basement unconformity east of the Guicaramo thrust. We interpret the basement fault as a blind thrust or wedge fault because a minimum 5 km of shortening was required to form the basement ramp anticline with a foreland dipping limb in the footwall of the Guicaramo thrust. This amount of shortening is not observed in the foreland southeast of the Guicaramo thrust along the profile trend. Total shortening in the nearby Parrando anticline east of the Guicaramo thrust was only about 1 km. We interpret the southeast-dipping reflectors observed in the footwall of the Guicaramo thrust as the southeast flank of the basement fault-bend fold. The basement ramp anticline produced 2 km of relief with 5 km of shortening. The upper ramp anticline produced 1.5 km of relief with 14 km of shortening. Our overlapping ramp anticline interpretation for the Guavio anticline is similar to that of Parra et al. (2009a) and Mora et al. (2010b) for a profile 14 km to the south. However, unlike the Parra et al. (2009a) and Mora et al. (2010b) profiles, we interpret the basement fault-bend fold as formed by a ramp in pre-Cretaceous basement to a double wedge fault that forms the southeast-dipping forelimb in the Guicaramo thrust footwall. The Guicaramo footwall structure was termed the Cabuyarito anticline by Mora et al. (2010b) and interpreted as a fault-propagation fold.

4.1.1. Retrodeformed Guavio cross section

The Guavio profile was retrodeformed to late Miocene (9 Ma) by flattening on the top of the Leon Formation (Fig. 8A). There are no major unconformities or growth structures in the Leon Formation or in the lower Guayabo Formation, suggesting that the first order present structures were formed after deposition of the Leon and lower Guayabo formations (late Miocene-Pliocene or younger than 7 Ma). The only possible exception is thin-skinned thrusting on the Guicaramo thrust (Fig. 8D) where earlier ramp erosion would have been subsequently removed by later uplift (see discussion of thin-skinned vs thick-skinned deformation in section 5.1). In fact, a seismic reflection based volume-balanced cross section for the northern termination of the Guavio anticline, just 11 km northeast of Medina-1 well, clearly shows that thin-skinned thrusting preceded thick-skinned basement involved deformation (Albesher et al., 2019). To the northwest, fault-propagation folding probably began to occur by the middle Miocene (Parra et al., 2009a) on the Lengupa and Tesalia faults (Fig. 7). Apatite and zircon fission track ages by Mora et al. (2008); Parra et al. (2009b); Mora et al. (2010a); Mora et al. (2010b); Ramirez-Arias et al. (2012); and Mora et al. (2013)
suggest that uplift on the Tesalia fault system may have begun by early Miocene. Conformable tight folding of Leon Formation sediments in the Nazareth syncline forelimb of the Tesalia basement fault propagation fold (Fig. 7) demonstrates a maximum late Miocene age (< 9Ma) for the greatest Tesalia basement folding and uplift. The Early and Late Cretaceous stratigraphic section thickens abruptly northwest of the Guaicaramo fault (Fig. 8A) filling accommodation space produced by Early Cretaceous normal fault extension and Late Cretaceous thermal subsidence on the Guaicaramo fault.

We identify at least three deformation events in the Neogene/Quaternary evolution of the Guavio structure. The first was the compressive inversion of the Guaicaramo normal fault with 800 m reverse slip (Fig. 8B). The second event was formation of a basement ramp anticline with 2 km of relief (Fig. 8C). The southeast limb of this fold is observed in the footwall block of the Guaiacaramo thrust. This fold was formed by a blind double wedge fault with over 5 km of slip. We interpret this as a wedge fault, because minimal slip is observed to the southeast of the wedge tip. The upper bedding plane ramp crops out as a thin-skinned thrust at the surface. Additional bedding plane thrusting on the base Guadalupe Formation detachment may have accommodated more than the minimum 5 km observed (Fig. 8D), since angular unconformities evidencing earlier thrusting would have been eroded during subsequent basement uplift. We estimate the thickness of Early Cretaceous units involved in the hanging wall of this basement fold as 1–3 km based on the 3 km thick overturned section cropping out west of the Tesalia fault (Fig. 7, Parra et al., 2009a). The final event was the formation of the Guavio fault-bend fold with 1.5 km of relief produced by 14 km of slip on the Guaiacaramo ramp thrust (Fig. 8D).
estimate at least 20 km of total Neogene/Quaternary shortening on the Guavio fold thrust system. Since lower and middle Guayabo Formation horizons are conformably folded on both flanks of the Guavio anticline, we conclude that the basement fault-bend fold and the Guavio fault-bend fold occurred in the last 6 million years, probably 6-3 Ma during the late Miocene-Pliocene uplift phase (e.g., Anderson et al., 2016).

4.2. Parrando

Fig. 9 shows an uninterpreted and interpreted seismic profile of the Parrando anticline. The profile is merged 2D line 43BR-VN05-06 and 3D seismic inline 136. The profile is depth corrected based on a check shot survey for Parrando-1 well (Fig. 4a) and horizons were identified from the well tie at Parrando-1 (Fig. 4b). For location see Fig. 1. The geometry of the Parrando ramp anticline requires a deeper hanging wall flat and a shallower footwall flat to form the forelimb of the fold. The listric breakthrough reverse fault alone cannot produce the anticline. A flat-ramp-flat geometry is required. In this case, the breakthrough reverse fault has only 200 m of slip. The ramp anticline was formed by an earlier 1 km of slip. The position of the hanging wall flat near the base of the Carbonera is determined by the footwall cutoffs against the fault ramp observed in the seismic profile. In this image (Fig. 9) forelimb cutoffs for the ramp anticline are not clearly observed in the footwall, but the position of the footwall flat in the middle Carbonera Formation is indicated by the intersection of the fault ramp and the hinge axis for the gentle forelimb dip domain observed in the hanging wall. We interpret the apparent discrepancy between the hangingwall versus the footwall thickness of the Carbonera Formation

Fig. 4. a. Time (TWT)-depth graph for Parrando-1 from a well check shot survey (Petrobras, 2008). b. Parrando-1 well tie with 3D seismic (inline 139) showing the good fit in the lower part of the section. Gamma ray log with formation tops is shown on the left (after Petrobras, 2008). Amplitude, power spectrum, and phase spectrum are shown for the zero wave wavelet used to create the synthetic seismogram. Gamma ray log (for color explanation see Fig. 2). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
as stratigraphic, predating the Parrando anticline, and perhaps serving to initiate the ramp location. The Parrando anticline is a gentle fault-bend fold (200 m relief) with a small break through fault in the forelimb. The structure was produced by 1.2 km of total shortening.

Conformable folding of the Guayabo Formation above the Leon Formation indicates that the Parrando anticline is very young, and probably formed in the last 3 Myr. A separate smaller fault-bend fold also deformed the Mirador reservoir rocks in the footwall. Several vertical

Fig. 5. Uninterpreted and interpreted seismic profiles of the Guavio anticline and Guaicamo thrust. Horizontal and vertical scales are approximately equal. See Fig. 1 for profile location.

Fig. 6. Uninterpreted and interpreted seismic profile parallel to structural strike of the Guavio anticline. Horizontal and vertical scales are approximately equal. See Fig. 1 for profile location.
faults in the footwall show normal offsets that may be produced by lithospheric loading or minor out-of-plane dextral shear.

Spectral decomposition (Continuous Wavelet Transformation) and seismic multi-attribute analysis were used to detect fluvial systems in the Parrando footwall (Saeid et al., 2018). The results suggest new potential stratigraphic plays in meandering channels and overbank deposits. In addition, a distinct change in river drainage directions during the deposition of Carbonera (C5) may reflect early Miocene (~20 Ma) uplift of the nearby mountain front possibly related to thinned strata in the Nazareth petrulc (Saeid et al., 2018).

4.3. Hydrocarbon maturation and migration

Burial and thermal histories were constructed for Medina-1, Parrando, and a Nazareth pseudo-well using PetroMod thermal modeling software. The present-day heat flow was estimated from borehole-corrected downhole temperatures and from regional paleo heat-flow estimates (INGEOMINAS-ANH, 2008). The heat flow used for the foreland burial history was 35–46 mW/m², typical for foreland basins worldwide. From these histories, timing of hydrocarbon charge may be inferred.

4.3.1. Nazareth pseudo-well and Medina-1

We located a Nazareth pseudo-well in the deepest Gachetá/Chipaque formation source rock in the Nazareth syncline 17 km southwest of Medina-1 well (Figs. 1 and 7) in order to estimate the maximum local potential source rock maturity in the Medina basin to the present. Burial rates increased about 35 Ma with the deposition of the Carbonera Formation accumulating 3.6 km of sediment in 20 Myr at an average rate of 0.18 mm/yr. At 23 Ma the deposition rate increased to 0.38 mm/yr (Parra et al., 2009a). 1-D modelling based solely on the Medina-1 well underestimates the source rock burial depths by 1 km. From these histories, timing of hydrocarbon charge may be inferred.

4.3.2. Parrando 1D model

Southeast of the Guaviacaramo fault at Parrando-1 well, we estimated the burial history with a 1-D model (Fig. 10c), assuming a total maximum pre-erosion thickness of Guayabo and Leon formations of 3600 m. The heat flow assumed for the Parrando 1-D burial history was 35 mW/m², a typical value for a foreland basin, and within the range of values used by Cazier et al. (1995) for their Cusiana 1-D model. In Parrando, the model predicts that the Gachetá Formation began to expel oil at 120 °C at 7 Ma (Fig. 10c), just prior to Andean trap formation. Near Cusiana, Cazier et al. (1995) obtained very similar results predicting that the Gachetá Formation began to expel oil at 8 Ma and 120 °C, which was just before folding and thrusting began. Our burial model predictions are also similar to 1-D models by Albesher et al. (2019) for Bromelia-1 and Rio Chitamena E−1 wells to the northeast along the La Florida anticline structural strike (Fig. 1).

The presence of hydrocarbons in C5 in Parrando-1 confirms the presence of an active hydrocarbon migration system and suggests the potential for Carbonera oil accumulations (Petrominerales, 2009). Four sandstone intervals at the base of C5 encountered oil shows. In general, the porosity and permeability are relatively low, the maximum porosity is about 10–12% and the permeability ranges from 15 to 60 md.

4.3.3. Petroleum system evolution, source pods, expulsion, and trap formation

The three schematic maps in Fig. 11 show the evolution of the petroleum systems in the Medina basin and Parrando foreland basin over the last 18 Myr. We use published isopachs (Silva et al., 2013), our new 1-D burial models, and new backstripped isopachs from the Parrando 3-D seismic volume to predict source pod locations, migration pathways, and trap locations. Depths to Gachetá Formation source rocks are estimated from 1-D models for the Nazareth pseudo-well, Medina-1, and Parrando-1 wells (this paper), and for Bromelia-1 and Rio Chitamena E−1 wells (Albesher et al., 2019). Parrando area maps show contour trends for depth to Gachetá Formation after stripping off sediment layers at 18 Ma (Fig. 11a), 7 Ma (Fig. 10b), and Present (Fig. 10c).

At 18 Ma (Fig. 11a) the Nazareth source pod began expulsion southeastward toward the Llanos. However, the Guaviac anticline trap
Fig. 8. Retro-deformed cross section for Guavio anticline (Fig. 5). For location, see Fig. 1. No vertical exaggeration. A: late Miocene (before 9 Ma), B: inversion of Guaicaramo normal fault, C: Pliocene (post 6 Ma) blind fault-bend-fold double wedge fault, D: 2nd fault-bend fold, present day, E: alternative model with bedding plane thrusting preceding formation of the basement ramp anticline.

had not formed, so hydrocarbons continued updip toward the Llanos. The timing of initial compressive inversion of the Guaicaramo Lower Cretaceous age normal fault is uncertain. Saeid et al. (2018) interpret an abrupt change in stream flow directions in C-5 to indicate the rise of incipient foothills in the area of the Guaicaramo thrust at about 22 Ma. In a seismic reflection profile from the Medina basin 27 km southwest of Medina-1, Teixell et al. (2015) noted an angular unconformity in the lower Carbonera Formation truncating deep thrust-related folds in the core of the Guavio anticline. A compilation of radiometric age data for the Medina foothills area (Albesher et al., 2019) suggests initial uplift on the Tesalia fault at 25 Ma, and uplift on the Guaicaramo at 12-8 Ma and 4 Ma to present. Based on the absence of growth strata in Miocene-Pliocene sediments in the footwall of the Guaicaramo thrust fault, Mora (2007) and Parra et al. (2010) predicted a maximum age of 5 Ma for initial thrusting along the Guaicaramo fault. In any case, at 18 Ma hydrocarbons either migrated updip to the Llanos or escaped to the surface on an early thin-skinned Guaicaramo thrust ramp.

At 7 Ma (Fig. 11b) the Guavio structural trap began to form, but most of the Nazareth-Medina hydrocarbon was already expelled. Hydrocarbon generation began in the eastern foothills southeast of the Guaicaramo fault at about 8–7 Ma as source rocks were rapidly buried by Guayabo Formation sediments.

At present (Fig. 11c) eastward and southeastward hydrocarbon generation continues from the Cusiana source pod southeast of the Guaicaramo fault. The Guaicaramo fault effectively seals the Medina basin from the active hydrocarbon sources in the eastern foothills.

5. Discussion

5.1. Thin-skinned versus thick-skinned deformation

While this study does not confirm that thin-skinned thrusting preceded thick-skinned basement deformation, it does not rule it out as stratigraphic evidence for an unconformity related to thin-skinned ramp thrusting on the Guaicaramo thrust would have been removed by erosion during Pliocene basement uplift (Fig. 8c and e).

Dengo and Covey (1993) proposed that the Eastern Cordillera is essentially an east-verging structure formed during two main tectonic
Fig. 10. Burial histories for source rocks (Gacheta/Chipaque Formation) assuming constant heat flow of 35 mW/m², (A) Medina-1, (B) Nazareth PW (C) Parrando-1.
Fig. 11. Petroleum system evolution in Medina basin and adjacent Parrando anticline showing estimated depths for source rocks (Gacheta/Chipaque formations) and migration pathways. 1D models for Medina, Parrando, and Nazareth pseudo well (this study). 1D models for Bromelia and Río Chitamena wells (Albesher et al., 2019). A: 18 Ma – Nazareth source pod begins expulsion southeast toward Llanos. B: 7 Ma – Guavio trap begins to form, but much of HC has already been expelled. C: Present – expulsion continues southeast of the Guaiacarao fault.

phases. The first tectonic phase induced a thin-skinned style that created large, east-verging thrust faults, detached into Lower and Upper Cretaceous and Paleogene sequences, with the greatest shortening in the middle-Miocene to Pliocene. During the Pliocene, deformation changed from basement-detached to basement involved as Jurassic and Early Cretaceous normal faults were inverted (Dengo and Covey, 1993).

There are various estimated ages for the initiation of thin-skinned thrusting in the Eastern Cordillera. Corredor (2003) estimated over 50 km of Oligocene ENE-WSW shortening in the northern Eastern Cordillera. The Oligocene age deformation is defined in the present eastern foothills area by the base of Carbonera (C6) unconformity, marking an important stage of Cenozoic crustal shortening in the pre-Early Cordillera foreland basin (Corredor, 2003; Martinez, 2006; Egbue and Kellogg, 2012). In a seismic reflection profile from the Medina basin 27 km southwest of Medina-1, Teixell et al. (2015) also noted an angular unconformity in the lower Carbonera Formation truncating deep thrust-related folds in the core of the Guavio anticline. The Lower Carbonera Formation angular unconformity is also visible in our seismic profile parallel to strike of the Guavio anticline (Fig. 6).

Saeid et al. (2018) interpret an abrupt change in stream flow directions in Carbonera (C 5) to indicate the rise of incipient foothills in the area of the Guaiacarao thrust at about 22 Ma. Structural reconstructions by Jimenez et al. (2013) and Mora et al. (2010a, 2010b) show short wavelength late Oligocene to middle Miocene folding that suggests thin-skinned deformation. Sediment provenance data also show a late Oligocene early-Miocene timing of exhumation of these structures (Horton et al., 2010b; Bande et al., 2012). A compilation of radiometric age data for the Guavio foothills area (Albesher et al., 2019) suggests initial uplift on the Tesalia fault at 25 Ma, and uplift on the Guaiacarao at 12–8 Ma and 4 Ma to present.

To the south in the Garzón Massif, early to middle Miocene thin-skinned imbricate thrusting over basement rocks resulted in approximately 43 km of shortening (Saeid et al., 2017; Wolaver et al., 2015) contemporaneous with the uplift of the southern Central Cordillera (~16–9 Ma) (Villagómez and Spikings, 2013). The thin-skinned thrusting was followed by an out-of-sequence late Miocene (6 Ma to present) Laramide-style thick-skinned basement uplift of the range which produced much of the structural relief of the Eastern Cordillera (Dengo and Covey, 1993; Garcia, 2008; Mora et al., 2010a; Egbue and Kellogg, 2012) and the Garzón Massif (Saeid et al., 2017). The authors note that there are geometric and kinematic linkages between some ramp-flat structures and basement-involved structures in the Eastern Cordillera that show that they may have a shared or hybrid heritage.

Prior to the basement Laramide orogeny in the U.S. Rocky Mountains, the region was the site of a Cordilleran foreland basin associated with thin-skinned deformation and flexural loading of a fold-thrust belt. Subsequent thin-skinned deformation (Laramide orogeny) partitioned the regional foreland basin and caused more than 4 km of localized exhumation of crystalline basement blocks, accompanied by localized subsidence of intermontane basins. It is generally accepted that the switch of deformation style from thin-skinned to thick-skinned was caused by the change from normal high-angle subduction to low-angle subduction of buoyant Farallon oceanic lithosphere beneath western North America (e.g., Saleeby, 2003; DeCelles, 2004; Liu et al., 2008; Fan and Carrapa, 2014).

Early-to-middle Miocene thin-skinned imbricate thrusting over the Garzón Massif basement rocks (Saeid et al., 2017; Wolaver et al., 2015) as well as in the Eastern Cordillera was roughly contemporaneous with the uplift of the southern Central Cordillera (~16–9 Ma) (Villagómez and Spikings, 2013) as well as the northward advance of arc volcanism and “normal” high angle Nazca subduction (Kellogg et al., 2019). A spike in volcanic arc activity in the Choco terrane and just east of the terrane from 15 to 5 Ma (Gómez-Tapias et al., 2013) brackets the initial Panama-Choco-North Andes (PB and CB and NAB in Fig. 1A) collision. Five million years ago, volcanic activity abruptly ended again north of 5.5°N as the subducting Nazca lithosphere underthrust the shallow-dipping retreating Caribbean slab (Taboada et al., 2009).

Across the northern Andes, basement blocks were rapidly uplifted 7–12 km in the last 10 Myr, including the Venezuelan Andes, Sierra de Perija, Santander Massif, Eastern Cordillera, Garzon Massif, and the Santa Marta Massif (Fig. 1A; see Kellogg et al., 2019 for references). The spatial distribution of these numerous Laramide-style basement block uplifts correlates with buoyant Caribbean low-angle to flat slab subduction and resultant low heat flow. The timing (last 10 Myr), spatial distribution and orientation, and high rates of shortening (5–15 mm/yr) and uplift (0.5–1.0 mm/yr) also suggest that the uplifts were accelerated by the Panama-Choco—North Andes arc-contingent collision and accretion, especially the Eastern Cordillera of Colombia (e.g., Egbue et al., 2014).

6. Conclusions

To the northwest of Medina basin, fault-propagation folding probably began to occur by the middle Miocene on the Lengupa and Tesalia faults. Radiometric age data for the Guavio foothills area by Mora et al. (2008); Parra et al. (2009b); Mora et al. (2010a); Mora et al. (2010b); Ramírez-Arias et al. (2012); and Mora et al. (2013) suggest initial uplift on the Tesalia fault at 25 Ma, and uplift on the Guaiacarao at 12–8 Ma and 4 Ma to present.

Most of the Guavio deformation results from repeated inversion of the Mesozoic Guaiacarao basin-bounding normal fault. The Guavio structure was formed by overlapping fault-bend folds during late Miocene-Pliocene age (6–3 Ma) shortening. A thin-skinned bedding plane thrust fault may have preceded the Guavio anticline ramping to the surface along the Guaiacarao fault. A seismically constrained volume-balanced cross section for the northern termination of the Guavio anticline, northeast of Medina-1 well, shows that thin-skinned thrusting preceded thick-skinned basin involved deformation (Albesher et al., 2019). Unlike previous interpretations, we interpret the basement fault-bend fold as formed by a ramp in pre-Cretaceous basement that transfers slip to the Guaiacarao thrust by a wedge fault forming a southeast-dipping forelimb in the footwall. We interpret the basement fault as a blind thrust or wedge fault because of minimal shortening observed southeast of the Guaiacarao fault. We estimate at least 20 km of total Neogene/Quaternary shortening and 2.5 km of structural relief on the Guavio fold thrust system.

Our 1D basin model for the Medina-1 well suggests that the Gacheta Formation source rocks began to expel oil at 18 Ma, at least 11 Myr before trap formation at 7 Ma. Thus, hydrocarbons either migrated updpip to the Llanos or escaped to the surface along the thin-skinned Guaiacarao thrust ramp prior to Guavio trap formation.

The Parrando anticline is a gentle fault-bend fold southeast of the Guaiacarao fault with a small break through fault in the forelimb. The fold began as a ramp anticline within the Carbonera Formation with about 1 km of slip. Subsequently, the ramp broke through the forelimb to the surface with 200 m of displacement. Conformable folding of the Guayabo Formation above the Leon Formation indicates that the Parrando anticline is very young, and probably formed in the last 3 Myr. A separate smaller fault-bend fold also deformed the Mirador
reservoir rocks in the footwall. Several vertical faults in the footwall show normal offsets that may be produced by lithospheric loading or minor out-of-plane dextral shear.

The small fault-bend fold in the footwall of the Parrando thrust appears to have 4-way closure forming a Mirador Formation trap, and 1D models suggest hydrocarbon generation in a source pod southeast of the Guacaruro fault from 8 to 5 Ma, similar to the Cusiana system. However, high-angle normal and transpressal faults may have permitted hydrocarbon escape. At present, the Guacaruro fault effectively seals the Medina basin from the active hydrocarbon sources in the eastern foothills.

The timing of thick-skinned and thin-skinned deformation, and trap formation were thus critical factors in the evolution of the Medina and Cusiana petroleum systems. Hydrocarbon expulsion preceded formation of the Guavio anticlinal trap by 11–15 Myr, while the critical moment and trap formation were synchronous for the Cusiana system. Generation and trap timing were favorable for the small Parrando footwall structure, but abundant fractures formed escape pathways. The presence of hydrocarbons in C5 in Parrando-1 confirms the presence of an active hydrocarbon system and suggests the potential for Carbonera Formation oil accumulations.

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Appendix A. Supplementary data

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References


