Regional Study and Petroleum System Modeling of the Eastern Llanos Basin*

André Vayssaire[1], Hussein Abdallah[1], Wilber Hermoza[1], and Eduardo G. Figari Negri[1]

Search and Discovery Article #10564 (2014)
Posted January 13, 2014

*Adapted from extended abstract prepared for oral presentation at AAPG International Conference & Exhibition, Cartagena, Colombia, September 8-11, 2013 AAPG©2013

[1]Repsol, Madrid, Spain (avayssaire@repsol.com)

Abstract

The Llanos Basin is one of the most prolific and largest sedimentary basin in Colombia. Located along the western margin of the Guyana Shield it covers more than 200.000 km², bounded westward by the Andean Cordillera. During the last several years the Geological Studies Group of REPSOL conducted a regional study of the area. The main challenge was not only to understand the geologic evolution of the basin and its remaining potential but also to create a consistent G&G framework. The variable quality of the seismic coming from different surveys, processes and reference datums, the lack of edited wells, and the heterogeneity in the stratigraphic criteria were the main hurdles to generate a coherent database.

The principal milestones of the study were: seismic interpretation, well correlations, petrophysical analysis, reservoir facies mapping, structural restoration, and 3D petroleum system modeling . The studied area includes part of the foothills for a better timing estimation because a significant part of the hydrocarbon was expulsed below it in the earliest stage due to the important overburden of this area. The Upper Cretaceous Gacheta source rock shows a Plio-Pleistocene expulsion pick. It reached the gas window in the South where expulsion started in early Miocene. Hypothetical Lower Cretaceous source rock could have expulsed hydrocarbons since Late Cretaceous, but the migration may have been essentially westward, toward the Magdalena Valley.

Tertiary source rocks, like Los Cuervos and Carbonera, are also mature at present day along the Cordillera, but expelled quantities could be much lower in comparison with Gacheta. It appears that petroleum expulsed in the very North of the basin have migration routes that focus toward Caño Limon. The most favorable places for long distance lateral migration are in the central part of the foreland basin, where the Gacheta source is also the most prolific. The existence of a Paleozoic petroleum system remains unknown. Even though more than 150 wells have encountered Paleozoic rocks, most were suspended at the top of the Paleozoic section. The northern and southern parts of the basin show large compressive structures that require detailed studies and evaluation of their possible petroleum potential.

The Llanos Basin and Database

The Llanos Basin is one of the most prolific and largest sedimentary basin in Colombia. It is located between the Eastern Cordillera and the Guyana Shield and covers more than 200.000 km^2 (Figure 1). The basin has two main distinctive structural domains. The western area is characterized by a compressive and transpressive deformation belt, known as the Llanos Foothills. It hosts giant Colombian hydrocarbon fields (Cusiana, Cupiagua, Volcanera, Capachos, Gibraltar, etc.). The Llanos foreland basin, also called Eastern Llanos, is less deformed and is characterized by a Neogene basin-fill affected by normal faults and gravitational features. Caño Limón, Caño Yarumal and Rubiales are the principal discoveries in it. Cumulative discovered reserves are estimated to be about 4500 Mmboe in the Foothills and 3000 Mmboe in the Foreland.

The exploration activity started in the 1940's, but it was only in the 1970's and 1980's that the most important fields were discovered. Repsol started to explore the area in the 1980's. It discovered the Capachos field and has shares in Caño Limón and Caño Yarumal.

During the last several years the Repsol Geological Studies Group conducted a regional multi-disciplinary study of the area. The main challenge was not only to better understand the geologic evolution of the basin and its remaining potential, but also to create a consistent G&G framework. The variable quality of the seismic coming from different surveys, processes and reference datum, the lack of edited wells, and the heterogeneity in the stratigraphic criteria were the main hurdles to generate a coherent database (Figure 2).

The principal milestones of the study were: seismic interpretation, well correlations, petrophysical analysis, reservoir facies mapping, structural restoration, and 3D petroleum system modeling. The studied area includes part of the Foothills for a better timing estimation because a significant part of the hydrocarbon has been expelled below it due to the important overburden in this area.

Llanos Basin Stratigraphy

From Late Devonian to Permian, the area was affected by compressional deformation associated with the inversion of Early Paleozoic and Precambrian extensional basin (Figure 3). The basin development started during a Triassic-Jurassic syn-rift period between the current sub-Andean zone and Eastern Cordillera. This extensional episode was related to the separation of North and South America in the proto-Caribbean. The geometry and distribution of these grabens are not well known, but in general coincide with the orientation of the Eastern Cordillera. The most import extensional event occurred east of the Andean subduction zone, in the current Eastern Cordillera and Magdalena Basin, during Early Cretaceous times. This back-arc mega-sequence was dominated by shallow-marine sedimentation and produced excellent source rock (Gacheta). The accretion of the Western Cordillera stopped the marine deposition during early Maastrichtian.

During early Eocene time, the Llanos Basin and probably the foothills were affected by an erosional event related to tectonic readjustment of the proto Andes. This geologic event probably removed Paleocene source rock, reservoir and pre-Eocene trap in the western part of the basin. Then, deposition of fluvio-deltaic sequence occurred until early Miocene in a pre-Andean foreland basin that covered the Magdalena Valley, Eastern Cordillera, and Llanos Basin.

Early Miocene started the deformation of the Eastern Cordillera that separated the Magdalena Valley from the Llanos Basin and created the accommodation space for the Llanos foreland basin. At the same time a major transgression brought marine mudstones, but the foreland basin was essentially filled by high-energy coarse-grained sediments sourced by fluvial systems coming from the developing Eastern Cordillera (Guayabo Formation).

Cross-Section Restoration and Modeling

Regionally, we have interpreted and analyzed more than twenty-five 2D seismic sections within the basin. Two regional sections across the Foothills and Eastern Llanos Basin (Figure 1 blue lines contoured in red) were restored at different time steps, and source-rock maturity and hydrocarbon migration were calculated.

We do not see clear evidence of deformation in the present-day part of the Llanos Basin until late Eocene (Figure 4). At that time Llanos, the Eastern Cordillera and Magdalena Valley were forming together a pre-Andean foreland basin related to the development of the Western Cordillera. This explains larger thicknesses toward the northwest. Around 29-30 Ma, inversion of pre-extensional faults started; this further developed as shallower thrusting during late Miocene. The thrusting continued and it is believed that the maximum deformation occurred during the last 7 Ma.

Temperature gradient increases eastward, certainly due to a lower cooling effect (less sediment deposition). We also noted that the section in the North was exposed to a lower thermal stress than the one in the South. Less burial is then necessary to mature the source rock in the South; this puts the Rubiales field in a good position for being charged by hydrocarbons through over a 100-km lateral migration pathway.

Geochemistry

More than 90 crude oils samples were analyzed to understand the origin and maturity trends associated with the Eastern Llanos crude oils. The source rock for the Llanos oils is essentially marine shale. The Pristane/Phytane values between 2 and 3 indicate possible deltaic shale contributions. The $\delta^{13}C$ isotopes as well as biomarkers allow us to clearly identify two families of oils. In the North the anoxic conditions increased, and the origin is more marine, whereas in the central and southern part of the basin the terrestrial input increased and the anoxic conditions decreased.

Inside the northern oils, two sub-families can be identified. The Foothills oils, like Capachos could have been charged from Tertiary source rock or different organic facies of the same Cretaceous source but with higher terrestrial input than the oils from the North Llanos foreland basin (as Caño Limón). According to the $\%^{20}S$ versus Ts/Ts+Tm plot the oils found in the southern area apparently reached a lower maturity level than the rest of the oils.

Petroleum System Modeling

The hydrocarbon expulsion pick of the Upper Cretaceous Gacheta source rock was reached during Pliocene. It reached the gas window in the South where expulsion started during Miocene (Figure 5, top left). Hypothetical Lower Cretaceous source rock could have expelled hydrocarbons since Late Cretaceous, but the migration may have been essentially westward, toward the Magdalena Valley. Tertiary source rocks like Los Cuervos and Carbonera are also mature at present day along the Eastern Cordillera, but expelled quantities could be much lower in comparison with Gacheta.

Migration simulations of hydrocarbons expelled from the Gacheta source rock along the continental - shallow marine Eocene sandstones of the Mirador Formation that form the main reservoirs of the area reveal that petroleum expelled in the northernmost part of the basin have migration routes that focus toward Caño Limon (Figure 5), while a large part of the northeast of the Llanos Basin is unlikely to have received hydrocarbons. The most favorable places for long distance lateral migration are in the central part of the foreland basin where the Gacheta source is also the most prolific. In the South, the Gacheta Formation might be too thin to produce important quantities of hydrocarbons.

We calculated that Gacheta expelled to be about 18E+09 tons of hydrocarbon. This value might be underestimated because only petroleum expelled within the studied area is taken into account, whereas Gacheta extends westward under the Cordillera. Nevertheless, the petroleum in place represents more than 10% of the expelled quantity, which could mean that close to 100% of the reserves have already been discovered. This shows that the participation of other source rocks or additional areas is of crucial importance for the exploration of the basin’s remaining potential.

Paleozoic Petroleum System?

The existence of a Paleozoic petroleum system remains unknown. Even though more than 150 wells have encountered Paleozoic rocks, most were suspended at the top of the Paleozoic section.

The Llanos Basin was exposed to transpressive deformations during the Paleozoic. The resulting compressive structures are large and widespread and could have a strong potential for the entrapment of hydrocarbons. New data suggest that the Devonian and Carboniferous strata are present in the Llanos Basin and contain potential source rocks and excellent reservoirs. For example, deep gas probably from the Paleozoic section was found in Tertiary reservoirs. Geochemical and thermal data show that the Paleozoic should be in the early gas window.

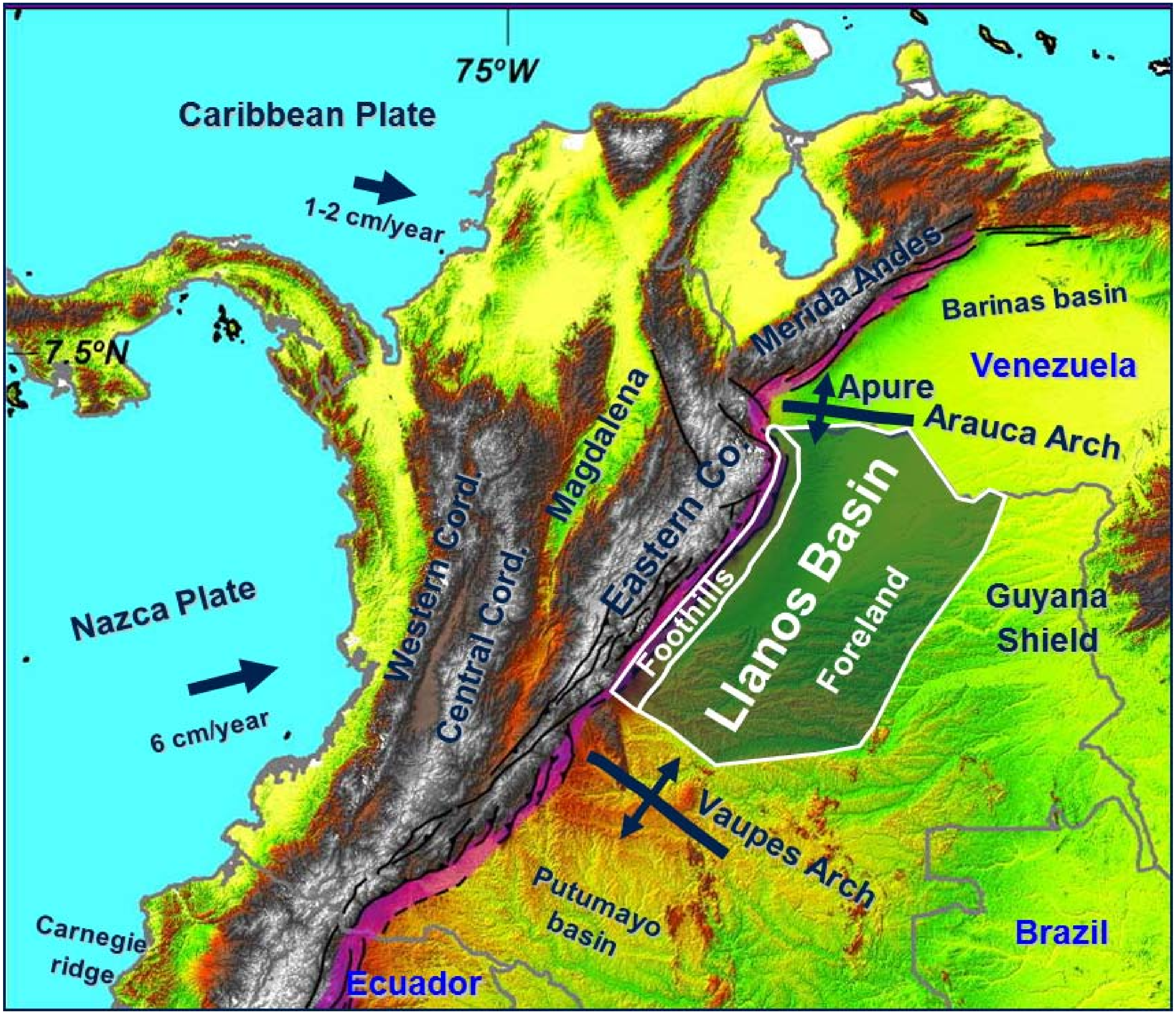

Figure 1. Index map of the Llanos Basin and its main tectonic elements.

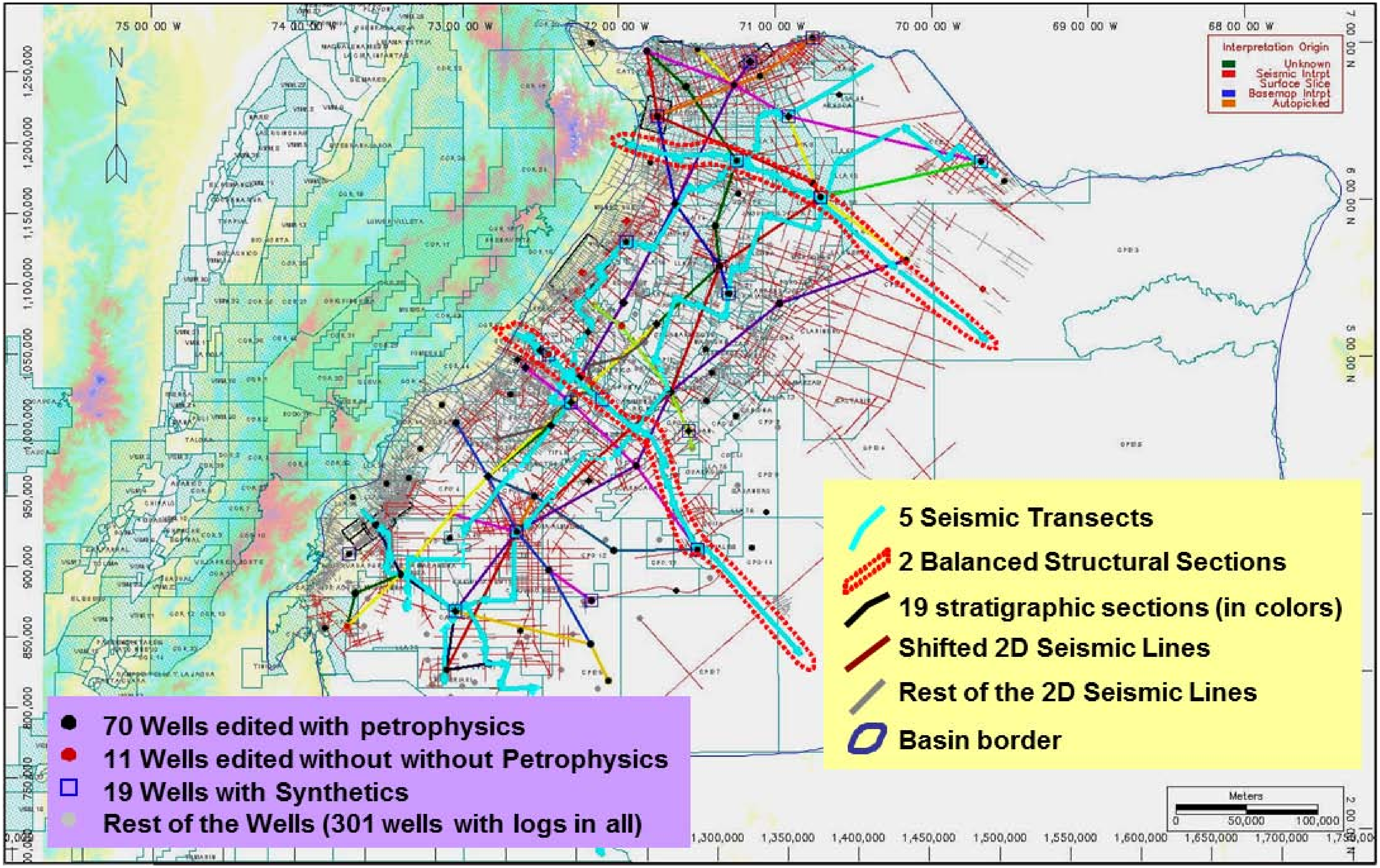

Figure 2. Llanos database map and products.

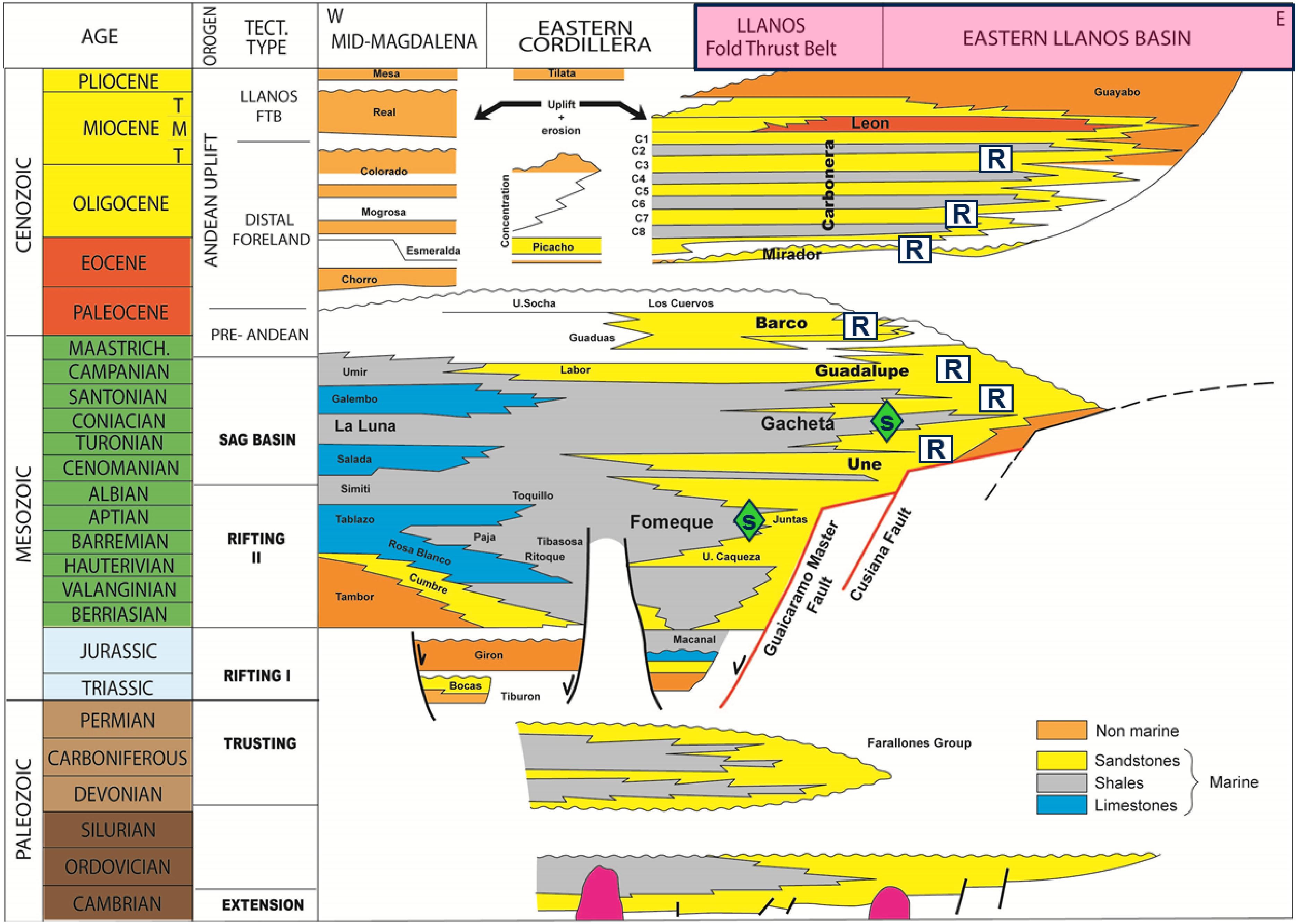

Figure 3. Regional stratigraphy chart.

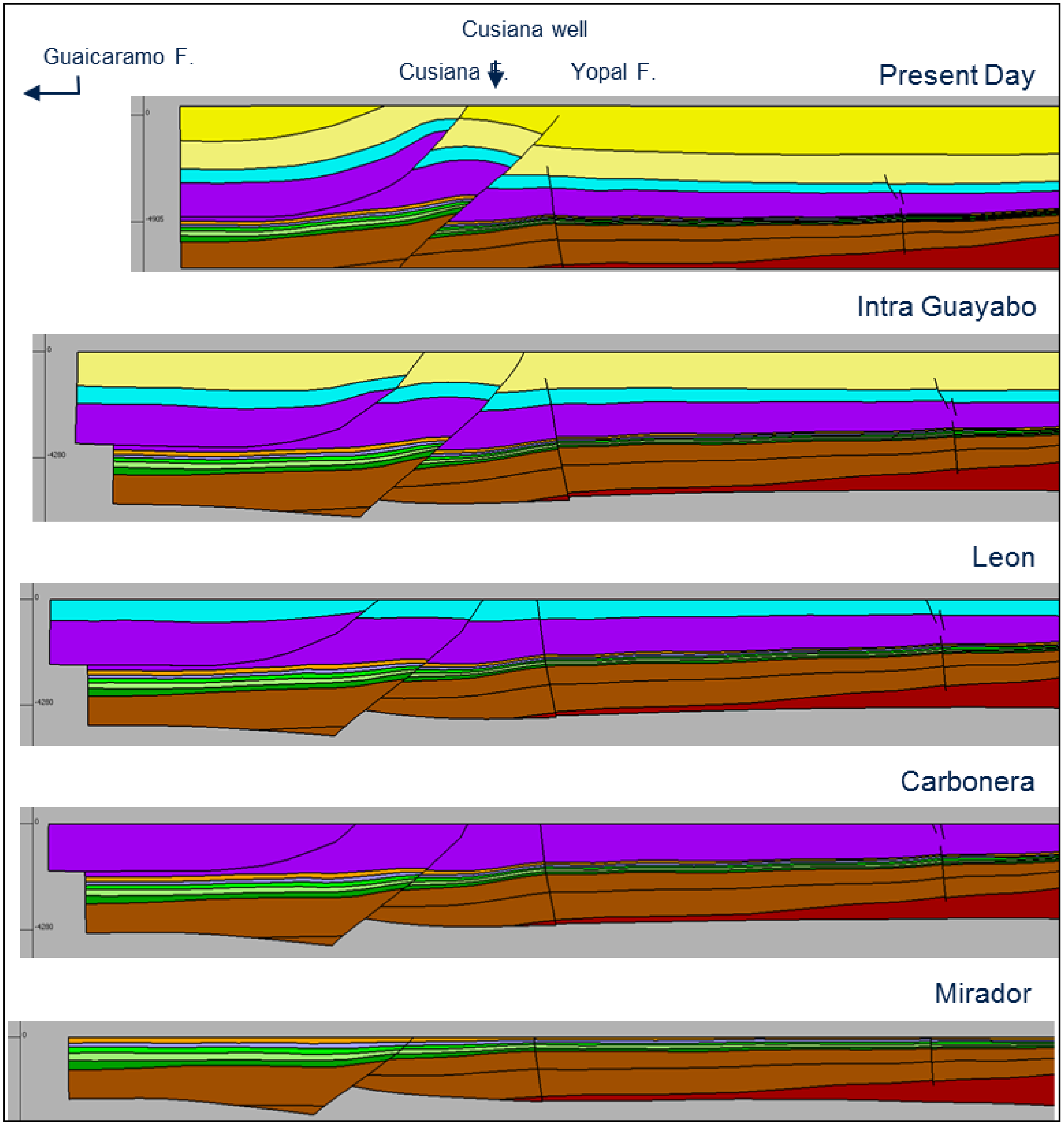

Figure 4. Restored 2D cross-section.

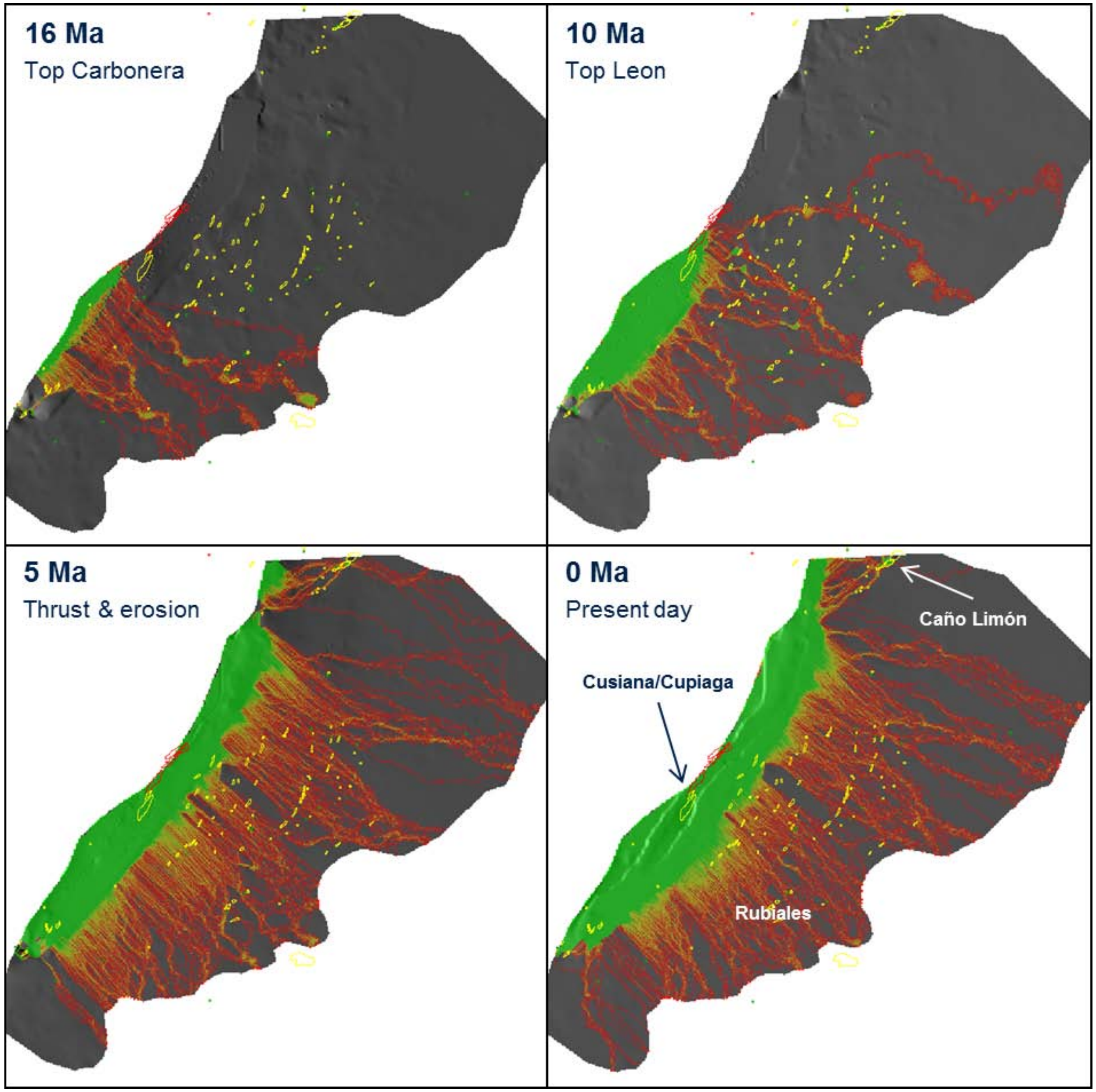

Figure 5. Migration routes along top Mirador (Eocene) of hydrocarbon expelled from Gacheta. Red lines show the less likely migration routes, whereas migration has higher chance to happen along the yellow/green lines.