Introduction

The right understanding of the tectonic setting is a fundamental key in the exploration phase. According to this principle, the Mesozoic structural configuration plays an important role in the development of the Eastern Cordillera, an orogen that originated as a Mesozoic graben and was inverted and uplifted during the Cenozoic (Cooper, 1995, Sarmiento, 2001., Mora, 2006.). Inversion was unusually strong, generating high elevations and steep topographic relief. The Eastern Cordillera is located in the northern Andes where the Nazca, Caribbean and South American tectonic plates interact (Taboada, 2000). Both margins of the Eastern Cordillera were thrust over adjacent basins during the inversion, the Llanos Foothills to the East and Middle Magdalena Valley in the West, producing a complex combination of thick-skinned and thin-skinned structures.

The Eastern Cordillera is a slightly asymmetric mountain range with a steeper eastern flank. Its axial part is dominated by a wide 2.6 km high plateau. The highest elevations of up to 4 km occur in the Sierra Nevada del Cocuy (Sarmiento, 2006).

The extent and development of the rift successions at depth has been deduced by seismic programs that aim to image shallow or other targets. However, exposed Mesozoic structures and stratigraphic units are accessible to field work and allow collecting stratigraphic and structural data as well as validating and evaluating the kinematics of these structures and their influence on the basin evolution. The integration of surface and subsurface mapping permits to assess the timing and the evolution of the structures in the Middle Magdalena Valley through structural modeling.

The correct analysis and understanding of the structural configuration in rift basins is an essential component for the proper understanding of the petroleum systems, given that the formation of the traps and thicknesses of lithostratigraphic units were influenced by the formation of these structures.

Geological Framework

Our project analyses an area extending from the central part of the Eastern Cordillera in the east to the eastern side of the San Lucas range in the west (Fig. 1), and is aimed at the reconstruction of the structures which were present in the rift basins to understand the architecture and their implications for the development of new exploratory concepts. This project also aims to interpret structures observed at the surface and controlled by subsurface data and to correlate them with similar structural configurations in the Middle Magdalena Valley basin.

The Mesozoic units in the Eastern Cordillera and Middle Magdalena Valley have been analyzed by different authors (e.g., Julivert, 1963., Cedia, 1968., Clavijo, 1995., Kammer, 2006., Sarmiento, 2001) and internal studies by companies such as Ecopetrol, ICP and ANH. These units are defined as a continental sequence for the Triassic to Jurassic, with a succession of intercalated sands, conglomerates, red beds and ashes typical of rift domains, according to the lithology, mineral composition and coarse grain distribution. By contrast, the Early Cretaceous units are defined as a transitional domain with the presence of a succession of shales and fine-grained sands, mainly attributed to a fluvial or shallow marine environment, and without associated volcanism.

The major Mesozoic normal structures were generated by stretching events related with the North America and South America separation (Jaillard, 1990., Cooper, 1995., Mojica, 1996). From the Triassic until the Early Cretaceous the basin development occurred in response to rifting. Two rift sub basins were generated in the Eastern Cordillera, the Cocuy basin to the east and the Tablazo-Magdalena basin in the west, both separated by the Santander and Floresta massifs.

The structural evolution of the Eastern Cordillera is fundamentally associated with the inversion of the normal faults such as the Guaicaramo fault to the east and La Salina fault in the west. Both structures are part of the reactivated borders of the Eastern Cordillera. Another important feature in the study area is the presence and location of anticlines that probably reveal the position of the Mesozoic normal faults and (half-)grabens before the reactivation as inverse structures.

Different researchers argue that with minimum reserves and few important discoveries, Colombia is approaching the limit of its petroleum resources and will have to explore outside of Colombia or
import oil and gas soon (IHS, 2012). Moreover, the Eastern Cordillera has been an area of limited exploration throughout the history of exploration in Colombia. In some cases, it has been considered a frontier basin for oil and gas exploration. However, in 2011 the ANH reported the discovery of two oil production wells in the Buenavista block (70 km NE of Tunja, Boyacá). Over a century of exploration in the Middle Magdalena Valley basin has yielded important results, such as the giant field of La Cira-Infantas and many billions of barrels of reserves discovered in oil and gas fields (IHS, 2012).

**Fig. 1.** Left. Geodynamical map of the northern Andes. The black square comprises the Eastern Cordillera and Middle Magdalena valley basins. Right. Geological map of the study area. Structures are color-coded as follows: Red: Synclines, Blue: Anticlines, Black: Faults, the black square is the area of this project.

**Methods**

Our main objective is to integrate the surface information such as maps, samples, new age data, and stratigraphic columns available in the area with the subsurface information such as boreholes and seismic lines provided by the National Agency of Hydrocarbons in Colombia, in order to produce a geological model of the area.

We selected the study area according to the lithological disposition and the presence of the main structures. Focusing on the areas where the units from the Triassic until the Early Cretaceous are well exposed, with the aim to constrain the model, petrographic analysis were carried out to select samples for geochronological dating through U/Pb in LA-ICP. The generation of a dense grid of cross sections, employing the existent surface data and the new measurements collected within this work as well as the subsurface mapping using the seismic and petrophysics interpretation in time and depth domains, allows generating a geological model that integrates all the information available for the study area, and also employing new modeling facilities through the software packages Petrel and Move (see Fig. 2).

**Results**
The units analyzed in this work allow to generate and constrain a possible Mesozoic geological model.

Lithologically the units analyzed represent a continental sequence with the presence of conglomerates, sands, effusive and pyroclastic volcanism for the most basal formations in the northern and central parts of the Eastern Cordillera and Middle Magdalena Valley. Intercalation of fine sands and black mudstones indicate a shallow marine environment atypical for that time. The ashes that sporadically appear in some units are correlatable with intermediate volcanism. During the Early Cretaceous the absence of tuffs and the intercalations between sands and mudstones reflect a transitional domain to shallow marine conditions.

**Fig. 2.** Left. Geological pseudo-3D model of the Eastern Cordillera and Middle Magdalena Valley, that integrates the surface and subsurface data available. Right. Location of the geological model.

The geochronological age dating done in the tuffs and ashes of the basal units, aims to define the temporal evolution of the basin during the Mesozoic and its relation with the rifting phase. The youngest ages obtained in the area are Rhaetian to Hettangian. Based on the lithology of the samples previously dated these ages could be associated with the depositional age. Following the sequence in another geological unit there are ages ranging from Sinemurian to Pliensbachian for the volcaniclastic succession. The youngest ages obtained for the tuffs are Toarcian, being considered as the last volcanic event.

The geological modeling of the area allows to constrain the geometrical variations between blocks and the stratigraphic sequences recording the activity of the Mesozoic normal faults. For instance, the La Salina fault system is considered as a master inverted normal fault that presents clear evidence of thickness variations between the hanging wall and footwall for the Mesozoic units. Fault displacement on the La Salina fault increases progressively to the south, as is the case of the Suarez fault system, whereas displacement of the Boyaca fault system decreases towards the south of the project area.

**Conclusions**

The Mesozoic evolution of the Eastern Cordillera reflects stresses associated with lithospheric stretching. According to the type of volcanism the rifting could have occurred in a back arc setting, from the Late Triassic until the Early Jurassic. The lack of clear evidence for volcanism during the Early Cretaceous allows to infer that after the initial rifting event the basin had entered the cooling period, and the thickness variations for the uppermost units were produced by mechanical accommodation. A tentative inference based on the U/Pb geochronology is that the rifting evolved from south to north according with the ages obtained.
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