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Structural and Thermal Evolution of the Cordillera Oriental, Colombia

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Introduction

Important hydrocarbon deposits exist within Tertiary and Late Cretaceous reservoirs in both the eastern and western foothills of the doubly vergent Cordillera Oriental fold-and-thrust belt of Colombia. We carried out a regional study to investigate the relationship between the evolution of the fold-and-thrust belt and the thermal history of the source rocks and reservoirs which are present in various structural settings across the Cordillera. This study incorporated structural data from seismic surveys, surface geological maps, and wells together with thermal maturity and bottom-hole temperature measurements, fluid inclusion analyses from the sandstone reservoirs both in the surface and the subsurface, and apatite fission-track data of surface samples. These data was provided by the members of the SUBTRAP consortium managed by IFP.

Mesozoic-Cenozoic Evolution of the Cordillera Oriental:

The Colombian Andes are located at the NW corner of the South American plate near a long-lived triple plate junction. Complex intraplate deformation has resulted from interactions with the Pacific, North America, and Caribbean plates. The Mesozoic to Recent tectonic history of the area now occupied by the Cordillera Oriental can be summarized as follows:

1) *Extensional stage*-During Late Triassic to Early Cretaceous the area underwent an episode of rifting and basin formation (Etayo et al., 1969). This extensional deformation concentrated east of a continental arc system caused by subduction of Pacific lithosphere under the west margin of South America. Both back-arc processes and a failed rift related to the opening of the North Atlantic may have contributed to the extension. During late Jurassic and Early Cretaceous up to 5 km of sedimentary rocks accumulated in the Bogota Basin which covered the central and northern portion of the Cordillera (Fabre, 1987).

2) *Thermal subsidence stage*- Once active rifting ceased subsidence rates diminished across the Bogota Basin from Albian to Paleocene as the mantle isotherms re- equilibrated (Fabre, 1987). During this period the main source rocks (Cenomanian to Santonian marine black shales) where deposited. By the latest Cretaceous deltaic and even continental facies prevailed.

3) *First compressional stage*- In the Magdalena Valley, which lies between the Cordillera Oriental and the Cordillera Central, there is evidence for the onset of compressional deformation during Maastrichtian to Paleocene time. Although the deformation probably was concentrated in the Cordillera Central, the petrography of Tertiary sandstones (Fabre, 1981; Guillande, 1988; Sarmiento, 1989) and $^{40}Ar/^{39}Ar$ dating of emerald-bearing vein systems (Cheilletz et al. 1994) suggests that shortening also affected the Bogota Basin.

4) *Pre-Andean foreland basin stage*- From Late Eocene to Early Miocene, a new episode of basin subsidence affected a large region extending east into the Llanos basin. Subsidence was driven by tectonic loading in the Central Cordillera (Cooper et al. 1996). East-vergent thrusting also affected the Madgalena Valley, and apatite fission-track ages from the Floresta massif of the Eastern Cordillera suggest that tectonic uplift and denudation started at about 20 Ma (Toro, 1990). The sandstone of the Mirador Formation, the principal hydrocarbon reservoir of the eastern foothills of the Cordillera Oriental, was laid down at the onset of this stage.

5) *Andean Stage*- Starting in Late Miocene the imposing topographic relief of the present day Cordillera Oriental was created. There was major basin inversion, tectonic uplift, and shortening. Thick foreland basin deposits filled the Llanos basin.

Structural Style

The major range-bounding faults of the Cordillera, such as the Guicaramo-Santa Maria system or the Boyaca fault, were controlled by Jurassic-Early normal faults that defined the Bogota Basin and the paleo-Magdalena Basin. This is demonstrated by the great thickness of the Jurassic and Early Cretaceous units found on the hanging walls of the major thrusts relative to the footwalls (Fig. 1). The dominant structural style is one of major east-vergent thrust faults that involve basement (Cooper et al. 1995). There are also secondary thin skinned structures detached within the Cretaceous units. Overall, shortening is moderate: about 100 km in the broadest portion of the Cordillera at the latitude of Tunja (our northern transect) (Colletta et al. 1990), and about 55 km south of Bogota where the mountain range narrows considerably (our southern transect, Fig. 1). West-vergent thrusts found in the western foothills and Magdalena Valley appear to be subordinate, although the seismic data available does not permit an unambiguous interpretation of the linking of the two fault systems at depth.

Although shortening started in the latest Cretaceous, the bulk of the deformation took place during the Miocene to Recent Andean phase.

Kinematic and Thermal Modeling

On the basis of seismic, well, and surface data we made two balanced cross sections of the Cordillera, one extending from the Floresta massif to the Llanos (northern transect) and a second one from the Magdalena Valley to the Llanos south of Bogota. The kinematic evolution of these two sections was modeled with the THRUSTPACK 4.0 software (Sassi and Rudkiewicz, 1996) which uses an algorithm based on the kink-band method for fold-bend folds of Suppe (1983). A reasonably good fit to the observed structure was obtained in spite of the restrictions imposed by the fold-bend fold model. Once we had produced a series of kinematic stages which accounted for the timing constraints, the major erosional unconformities, and the observed thickness and geometry of syntectonic sedimentary series, we calculated the 2-D thermal structure of each stage. The first step in this process was to carry out 1-D back stripping and conductive thermal modeling of wells located near each structural transect using the GENEX software until the models matched the thermal maturity values observed in the wells. This allowed us to constrain basal heat flow across the regional sections. Given rock thermal properties, radioactive content, surface temperature, and basal heat flow THRUSTPACK grids the section and solves the 2-D conductive heat equation for all the nodes on the grid. Both transient and equilibrium solutions were tested. Convective heat transfer due to groundwater circulation was documented in the Bolivar well, located in the internal part of the Cordillera along the northern transect, and in the Coporo well, located between the two transects. However we did not attempt to model convective effects in the regional sections due to lack of adequate knowledge of the distribution of permeability. The final step in the modeling was to calculate the predicted maturation of source rocks in each stage of the structural model.

Conclusions

The diverse histories of burial (both tectonic and sedimentary) and denudation found in different structural positions within the thrust belt lead to very different time-temperature paths for the rocks, and in consequence to very different thermal maturation histories (Figs. 1 and 2). We could differentiate four distinct settings:

1. *Cordillera Oriental interior*- The thermal evolution of the Cordillera was strongly influence by the location of Mesozoic extensional basins. Thermal gradients were higher in the interior of the Bogota basin than in the flanks through out its history. During the Early Cretaceous a high geothermal gradient prevailed due to the effects of active rifting. Higher thermal gradient persisted in the basin during Tertiary time due to the blanketing effect of the thick, low conductivity sedimentary pile. As a result, the maturation values at equivalent depths are higher in the interior of the Cordillera, which is the now inverted Bogota Basin, than in the margins of the Llanos. Peak sedimentary burial occurred in the mid-Tertiary during the pre-Andean foreland basin stage leading to an early phase of hydrocarbon maturation and migration that pre-dated the Andean traps. Uplift and erosional denudation started at about Oligocene time thus arresting the maturation process. The subsequent history has been of continued deformation, uplift and erosion, although some frozen hydrocarbon kitchens were preserved by early uplift. See thermal history points 4 and 5 in Figures 1 and 2.
2. *Llanos Foothills*- This area was characterized by continued flexural subsidence and syntectonic sedimentation through the Miocene and Pliocene. Because both the thermal gradient and the thickness of pre-Miocene stratigraphic units were less than in the central part of the Bogota basin, thermal maturity of the source rocks was delayed relative to the interior of the Cordillera. Burial of rocks on the hanging wall of the frontal thrusts (i.e. Cusiana, Yopal, and Guavio faults) ceased when these faults became active. Prospects in the foothills are viable when connected to active kitchens in the underthrust zone. Contrast the thermal histories of points 2 and 3 (Figs. 1 and 2).
3. *Llanos foreland*- As in the foothills the thermal gradient has been lower than in the Cordillera. Today the basin is at maximum burial, however because the thickness of the

stratigraphic section decreases rapidly away from the thrust-front, the source rocks are for the most part immature (curve 1 in fig. 2). Traps in the Llanos require long distance migration.

4. *Magdalena Valley*- The thermal regime of the western flank of the Cordillera is cooler than the interior of the range while the structural history is more complex. Along our southern transect an active kitchen is located in the underthrust zone of the west-vergent thrust belt of the Cordillera Oriental (point 5 in figures 1 and 2). In the Magdalena Valley there are local kitchens only where a thick section of syntectonic units is present in basin lows. The timing of hydrocarbon generation is strongly influenced by local conditions.

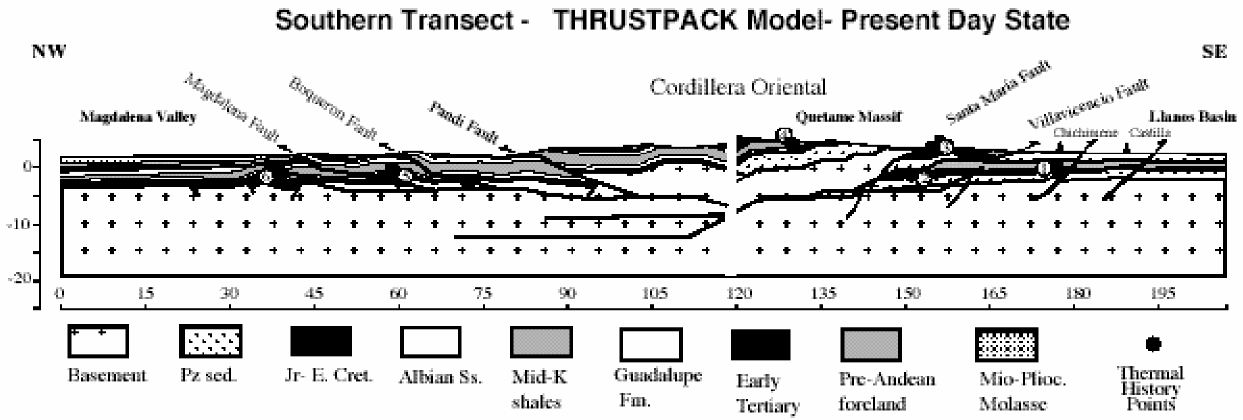

Figure 1. Structural cross section of the Cordillera Oriental south of Bogota modeled with THRUSTPACK. The kerogen maturation histories of selected points, which characterize distict structural settings along the transect are shown on Fig. 2.

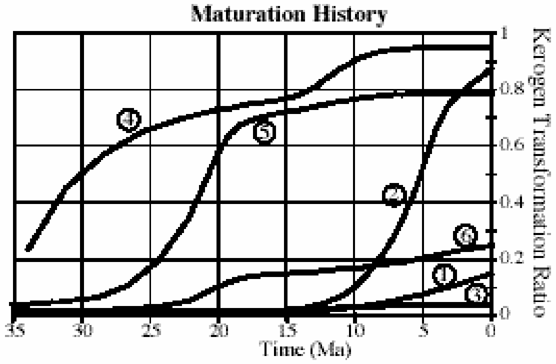

Figure 2. Kerogen maturation histories for Late Cretaceous source rocks of the Cordillera Oriental modeled using a 2D thermal model of the cross-section. Each curve corresponds to a point located in Figure 1.