Regional Tectonics, Stratigraphy, Reservoir Characterization and Petroleum Systems in an Eocene Foreland Basin, Maracaibo Basin, Venezuela*

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Abstract

The Maracaibo basin of Venezuela has produced more than 40 billion BBO since the 1920’s. During the Paleogene, oblique collision between the Caribbean and South American plates produced a 4-km-thick wedge of clastic sediments that serve as the main reservoir rocks in the basin. Interpretation of 2-D and 3-D seismic data in the central and eastern Maracaibo basin reveals two major tectonic features formed during the Paleogene collision:

- The late Paleocene-early Eocene Maracaibo foreland basin.
- The middle-late Eocene Burro Negro lateral ramp fault.

In the Eocene Maracaibo shelf area, intraplate deformation occurs by NNE-striking left-lateral faulting with pull-apart basins localized at fault stepovers (e.g., Icotea pull-apart basin). Extension of the pull-apart basins is localized on pre-existing NW-SE-striking normal faults, formed originally by Paleocene-Eocene plate flexure during the foreland basin period. Detailed sequence stratigraphic interpretation of the central Maracaibo basin was carried out using 2D and 3D seismic data tied to 330 wells. These data reveal that Eocene clastic sedimentation is controlled by tectonic subsidence of the foreland basin and to a much lesser degree by changes in sediment supply and eustasy. Hydrocarbon reservoirs are concentrated in distributary channels and tidal sand bar facies. The most productive areas are structural highs produced by Eocene strike-slip motion along NNE-striking faults.

Introduction

The stratigraphic record of any sedimentary basin is controlled by three variables: eustasy, subsidence, and sediment supply. In foreland basins, high rates of subsidence characterize the main thrust depocenter, formed by downwarping of the foreland plate. Peripheral upwarping forms a “forebulge” as an elastic response to thrust loading.
Sediment supply feeds the foreland basin from either the flexed foreland plate or the overriding thrust belt. Eustasy and sediment supply control the short-term stratigraphic framework, superimposed over lower frequency tectonosequences that are controlled by the asymmetric slope of the basin and the position of the forebulge. The basal unconformity of the foreland tectonosequence is formed by erosion of the progressively migrating forebulge; its upper unconformity is controlled by tectonic rebound.

The Eocene sedimentary record of the Maracaibo basin was formed in a foreland basin setting during an oblique collisional event between the Caribbean and South American plates. As a result of this collisional event, a major depocenter developed in the northwestern area of the basin. The source of shallow-water Eocene clastic sediments was from the south during the early-middle Eocene and from the south and east-northeast during the middle-late Eocene. Depositional environments in the Eocene are highly variable and include fluvial, deltaic, and marginal marine settings with strong tidal influence.

The main objective of this study is to use a dense well database (330 wells) combined with 2-D (500 km) and 3-D seismic (2000 km²) data of a representative area of the Maracaibo basin shown in Figure 1 to:

- Illustrate the overall structure of the Burro Negro zone lateral ramp fault and the two different areas of Eocene sedimentation that the fault separates.
- Analyze intraplate deformation and pull-apart basin formation in the Eocene Maracaibo shelf and its effect on sedimentation.
- Generate a high resolution sequence stratigraphic framework in order to enhance vertical and lateral correlations in a three-dimensional view.
- Understand the interplay between subsidence, eustasy, and sediment supply in a sequence stratigraphic framework.
- Generate maps and evolutionary models for the Eocene clastic section in the central Maracaibo basin.
- Show the distribution and setting of the most productive Eocene reservoirs in central Lake Maracaibo area.

**Paleogene Tectonic Setting of Northwestern South America**

**Late Paleocene-Early Eocene**

The Maracaibo basin began to downwarp in response to tectonic loading on its north and northeastern margins as the Caribbean plate started to collide with northern South America during late Paleocene time (Figure 2A). Eocene clastic input from the south and southwest infill the basin and onlap the Paleocene platform as tectonic loading continued. A flexural bulge formed in the central part of the basin and migrated southward in response of to west-to-east thrusting. Lower Eocene rocks onlap the forebulge. NNE-striking faults (e.g., Icotea fault and Pueblo Viejo) were reactivated as left-lateral strike-slip faults developing pull-apart basins along their traces. The platform margin was located along the Burro Negro fault zone.
Middle Eocene-Oligocene (Figure 2B)

Tectonic loading ended in central and south Maracaibo basin, producing the regional “Eocene unconformity” by tectonic rebound. Collision of the Caribbean plate moved SE-to-E and induced right-lateral strike-slip motion on the Burro Negro lateral ramp fault zone.
Eocene Clastic Wedge

The lower Eocene clastic wedge of the Maracaibo basin pinches out in the central part of the present-day Lake Maracaibo and thickens to more than 4 km at the NE margin of the basin (Figure 3). To the south, the Eocene wedge onlaps against a folded Paleocene high (forebulge). Back-stepping onlap of Eocene sequences toward the south suggest subaerial exposure of upper Paleocene rocks. The clastic wedge is divided into two main sections by the Burro Negro fault:

- To the SW, fluvio-deltaic sedimentation took place in a shelf setting with NW-striking normal faults and formation of pull-apart basins.
- To the NE, deep-marine, Eocene-Miocene sediments were highly deformed by folding and thrusting; Oligocene and Miocene syntectonic sub-basins are bounded by structural highs characterized by chaotic reflections (Figure 3).

Sequence Stratigraphy

The Eocene tectonosequence is confined between two major unconformities:

- The basal Paleocene unconformity with an age of ~54 Ma.
- The Eocene unconformity which separates middle Eocene (< 44 Ma) from early Miocene sedimentary rocks (~25.2 Ma).

The Eocene succession in central Lake Maracaibo is characterized by an aggradational succession of sandstone above the Paleocene unconformity overlain by a major retrogradational succession of shale and sandstone with few progradational units and an aggradational succession of sandstone near the top of the tectonosequence. Using high-resolution well correlations, five genetic sequences, one depositional sequence and seventeen parasequence sets were interpreted. Assuming linear interpolation between the few age controls from core data, the duration of parasequence sets is on the order of 300 to 900 ky.
Evolution of the Eocene Maracaibo basin platform:

The stratigraphic evolution of the Maracaibo basin during the Eocene is controlled by the oblique collision between the Caribbean plate and passive margin of South America in western Venezuela (Figure 2), and to a much lesser degree by sediment supply and eustasy. Small changes in the oxygen isotope record and the lack of major continental ice caps during the early-middle Eocene greenhouse period suggest that eustasy played a minor role in high frequency cycles observed in the Maracaibo basin. The lateral and vertical continuity of facies associations indicates that the Eocene shelf was never subaerially exposed. The evolution the Eocene Maracaibo shelf can be summarized as follows (Figure 4):

1. **Late Paleocene ~ 60 Ma** (Figure 4A): The Maracaibo basin was a passive, mixed carbonate-clastic margin that underwent tectonic loading from the NNW as the Caribbean plate and arc system approached western Venezuela (Figure 2A). The shelf edge was located along the Burro Negro fault, and subsidence rates increased rapidly across this fault.

2. **Early Eocene ~54 Ma** (Figure 4B): Tectonic loading from the north induced higher subsidence rates on most of the shelf. Flexural loading created a forebulge to the south, exposing the Paleocene platform and forming the Paleocene unconformity. Clastic input began to infill the basin. Turbidites were deposited in the deeper water Maracaibo basin, northeast of the Burro Negro fault.

3. **Early-middle Eocene ~49 Ma** (Figure 4C): Tectonic loading reached its maximum with high subsidence rates (150 m/my) across the entire basin. The forebulge migrated progressively southward and clastic sediments onlapped the Paleocene unconformity, inducing retrogradation of the Eocene tectonostratigraphic sequence. Forebulge uplift is estimated in 10 m/my.

4. **Middle-late Eocene ~40 Ma** (Figure 4D): Tectonic loading moved eastward. The lithosphere responded by tectonic rebound characterized by uplift rates of 60 m/my. Rebound affected the entire Eocene Maracaibo shelf, forming the Eocene unconformity.

5. **Late Eocene-Oligocene ~35-25 Ma** (Figure 4E): The entire basin was subaerially exposed, and intra-basinal erosion cannibalized a large amount of clastic sediments.

**Petroleum Systems**

Distribution of hydrocarbons reservoirs in the Maracaibo basin are mostly concentrated between the Icotea and Pueblo Viejo faults SW of the Burro Negro fault zone. Figure 5 is
a transverse, E-W interpreted seismic line in the central Maracaibo basin showing the main features of the basin’s petroleum system from Cretaceous source rock to Eocene and Miocene reservoirs.

Figure 4. Paleogene subsidence history of the Maracaibo foreland basin and its effect on stratigraphic architecture.
Source Rocks

Hydrocarbon source rocks in the Maracaibo basin are Cretaceous carbonates of the La Luna Formation (Albian-Coniacian) and to a lesser degree, Eocene and Miocene shales. Hydrocarbon generation most likely occurred during the Paleogene, when Cretaceous rocks were deeply buried in a foreland setting and reached thermal maturation. Miocene inversion of the Maracaibo basin deeply buried Eocene and Miocene rocks in the southern part of the basin (Maracaibo syncline) and led to thermal maturation of Eocene-Miocene shale source rocks.

Migration and Trapping

Hydrocarbon migration and trapping occur in two main phases:
- Paleogene oblique collision.
- Post-Eocene inversion.

During Paleogene oblique collision, a wedge of fluvial-deltaic Eocene rocks was deposited in a foreland basin (Figure 4). Pull-apart basins controlled by reactivated Jurassic N-S-trending faults within the Maracaibo basin formed. These faults served as vertical pathways for hydrocarbon migration from the Cretaceous source rocks to Eocene reservoirs (Figure 5). Vertical displacements along major faults allowed lateral contact between Cretaceous source rocks and Eocene reservoir rocks and contributed to increased upward hydrocarbon migration (Figure 5). Hydrocarbon traps are associated with anticlines formed during creation of the pull-apart basins structures and are compartmentalized by NW-striking faults (Figure 5). Regional NNE dip of the basin also contributes to updip oil migration into Eocene reservoir facies and trapping beneath the Eocene unconformity in the central Maracaibo basin.

Post-Eocene inversion was characterized by uplift of the Sierra de Perijá and the Mérida Andes, formation of the N-S Maracaibo syncline, and inversion of Eocene structures in the central basin. Hydrocarbon migration occurred along fault zones at the Eocene unconformity and in places where post-Eocene reservoir rocks are in contact with Eocene reservoirs. The Miocene depocenter was located in the southern Maracaibo basin. Miocene continental facies pinch out to the NE, forming a major stratigraphic trap for hydrocarbons that have migrated upward (Figure 5).
Reservoirs in Central Maracaibo Basin

Hydrocarbons in Eocene reservoirs of central Lake Maracaibo have API gravity between 20 and 30 and are classified as medium oil. The reservoirs are located on structural highs and in parasequence sets with high sandstone content (Figure 5). The structural highs were formed by strike-slip and inversion of N-NE-striking normal faults. NNW normal faults separate the main anticlines into discrete blocks. Structural lows to the east and west tend to be wet reservoirs outside the main anticline areas. Most oil production is located in the central and southern areas. To the north these areas are less productive due to increase in shale content related to an increase of tidal influence. Oil is most likely to be concentrated in the main continuous distributary channel facies and sand bars. The southern and central areas have been intensely drilled over the main anticline structure. The northern area and flanks of the main anticline are poorly drilled and open the opportunity for exploration of untested stratigraphic traps in the central-west part of the study area.