Origin and Evolution of the Maracaibo Sedimentary Basin and its Petroleum Resources

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Abstract

Compilation of previous research and exploration data in the Maracaibo Basin has revealed a complex tectonic and sedimentary history culminating in the creation of an extremely hydrocarbon rich foreland basin in the northwestern region of Venezuela. Subsidence in the Maracaibo Basin began with Jurassic continental rifting and terrestrial sedimentation during the early breakup of the supercontinent Pangea. Continued expansion of the Caribbean seaway and resulted in the development of a passive margin on the northern coast of South America, resulting in the deposition of organic-rich Cretaceous carbonates which would later serve as the primary source rocks for the petroleum system (the La Luna Formation). Collision of the Caribbean plate with the South American plate in the Paleocene resulted in the development of a foreland basin, which continued with subsidence and clastic sedimentation until the end of the Eocene, when the basin went through extensive uplift in the Oligocene due to isostatic rebound following flexure. Continued interactions of the South American plate with the Caribbean and Nazca plates resulted in mountain building and further subsidence in the Maracaibo Basin, as well as increased Tertiary sedimentation. Reservoir rocks are then primarily from the Eocene and Miocene. Transpressive conditions and mountain building in recent times due to oblique Caribbean plate collision with South America have seen net shortening in the foreland basin. The end result is a mature, hydrocarbon rich basin with a long history of production that BPP would likely benefit from exploring further.

Introduction

The purpose of this study is to provide a basin-scale outline of the location, geologic setting, history, architecture, and petroleum systems of the Maracaibo basin, located in Northwestern Venezuela. This basin has been extensively explored since the mid- 20th century, and is one of the most prolific producers of hydrocarbons in the region. Over 35 billion barrels have been recovered as of 2006, with an estimated 44 billion barrels remaining to be recovered in the future (Escalona and Mann, 2006). Due to the large economic potential of this basin, extensive studies of its features have been performed over the last few decades. This basin is currently classified as a foreland basin (now inactive), however both seismic and geologic (well data, outcrops, etc.) studies have discovered a remarkably complete record of the basin's tectonic evolution since the Jurassic, from continental rifting, to a passive margin, to a foreland system. This record also describes the subsidence and sedimentation through each of these tectonic events. It is located a widely active tectonic zone defined by the interactions of three major plates, these being the South American, Caribbean, and Nazca plates. This paper will use data and interpretations from multiple previous works on this basin with the intention of providing a complete basin analysis. Well data also provides a comprehensive outline of the basin-wide petroleum system. Determining the validity of continued exploration by BBP is the ultimate goal of this report, and a final recommendation will be presented using this information.

Geographic Location

The Maracaibo basin is located in the northwestern corner of Venezuela, in the extreme northeast of South America (Figure 1). The basin occupies a v-shaped zone between two major intersecting mountain ranges, with the Sierra de Perija located to the northwest and the Méridas Andes being found to the southeast. Lake Maracaibo, a very large shallow lake, covers approximately 30% of the basin surface (Lugo and Mann, 1995). The basin covers a geographical area of approximately 50,000km^2, an area which is naturally marked by the surrounding mountain ranges (Escalona and Mann, 2006). The basin is well outcropped throughout the region, with visible outcrops through the Jurassic to the Neogene (Figure 2). Note that subsidence and basin fill are still occurring in the present day, and that the basin forms a natural topographic depression which acts as a funnel for eroded sediment from the surrounding mountain ranges, meaning that the majority of Mesozoic and earlier rocks are buried beneath Neogene sedimentary rocks and studied through indirect means, such as seismic (Lugo and Mann, 1995). The thickness of the basin ranges from 3.0 to 9.0km, however geological maps (Lugo and Mann, 1995) show that an approximately 7.0km thick section of stratigraphy was preserved from the Jurassic to the Holocene. This provides a mostly complete record of the tectonic history of the basin (Talukdar et al, 1986)

Geologic and Geodynamic Setting

The general geological setting of the basin is rather complex, and defined by multiple different subsidence and tectonic events since the breakup of Pangea in the Triassic - Jurassic. Currently, the basin overlies the Maracaibo tectonic block, which is a triangular shaped section of the South American plate between the Sierra de Perija and Méridas Andes mountains in the Northwest of Venezuela. The basin fill sequence overlies a Paleozoic basement comprised primarily of metasedimentary rocks, which predate initial basin fill during the first phase of sedimentation, which will be discussed further later on. This v-shaped block is geologically bound by a series of basin-scale strike-slip faults, with the Boconó fault to the east (a right lateral fault) and the Santa Marta-Bucaramanga left lateral fault to the west (Duerto et al, 2006). The Maracaibo tectonic block is located in a highly active, large scale tectonic zone (Figure 2) defined by the interactions of three major plates. These plates include the Caribbean plate, the Nazca plate, and the South American continental plate. Due to the geometry of the bounding strike-slip faults in the eastern and western regions of the basin, and the oblique collision of the Caribbean plate resulting in subduction beneath the South American plate, the entire Maracaibo block is currently experiencing net right-lateral motion to the northwest. Due to the v-shaped nature of the Maracaibo block and the type of motion occurring due to these large scale plate interactions, the entire basin displays a near textbook example of “escape tectonics’, where a smaller portion of a plate is squeezed out of a larger plate (the South American plate, in this case) due to strike-slip geometry (Duerto et al, 2006).

The Maracaibo basin belongs to a series of foreland basins occurring along the northwest coast of South America (Figure 3). While the initial evolution of the basin was defined by rifting due to the breakup of Pangea, continued basin evolution and sedimentation is more recently defined by a foreland basin setting, caused by the oblique collision of the Caribbean plate with the South American plate. Seismic data shows that in the west, the collision of these two plates show subduction of the Caribbean plate beneath South America, but as you move eastward, the collision is more oblique, resulting in a strike-slip geometry (Duerto et al, 2006). This contributes to the “escape” of the Maracaibo block. Subduction of the Caribbean plate continues currently, however primary subduction has shifted to the east, and primary sedimentation is now entirely erosional in response to the uplift of the surrounding mountain ranges. Transpression form the strike-slip collision of the Caribbean plate and the South American plate are the primary drivers of sedimentation and deformation at present (Mann and Escalona, 2006). Due to the subsidence of the central region of the basin, the outcrop pattern of sedimentary sequences throughout the basin, and seismic analysis, the general structure of the basin is seen as being synclinal (Figure 4). Deformation in the basin shows phases of extensional faulting, foreland folding and thrusting, and since this basin is believed to have undergone multiple different types of basin evolution, the sedimentary sequences contain within show significant deformation, mostly in the form strike-slip and north – northeast normal faulting. Outcropping of formations is most abundant in the bordering mountain ranges as a result of uplift. Sediment accumulation occurred over a vast time period under varying tectonic settings, with broad settings including rift sedimentation controlled by thermal subsidence, passive margin sedimentation, and foreland basin sediment fill. In summary, the geologic and geodynamic setting of the Maracaibo basin is defined by large scale plate interactions throughout a large portion of geologic time, from the Jurassic to the present day. This has led to a deformed, extensive series of stratigraphic sequences outlining different periods in the evolution of the basin (Duerto et al, 2006).

Subsidence Origin and History

As previously stated, the evolution of this basin has been defined by multiple unique tectonic events through a time period from the Jurassic to recent times, each outlined in the stratigraphic succession preserved in the basin fill. The Maracaibo basin is unique among other basins in this region of South America as it provides a well preserved stratigraphic history of subsidence and sedimentation since its inception. Interpretations of these events have been made using seismic data interpretation, examination of well data from current petroleum plays in the region, as well as outcrop analysis from uplifted units in the basin and surrounding mountain ranges. In this section, each of these events will be outlined from oldest to youngest, and the primary driving force of subsidence for each event will be examined. Note that the nature of the sedimentary fill will not be discussed in great detail here.

Jurassic Rifting

During the Triassic – Jurassic time period, the breakup of the supercontinent Pangea had begun. The main force behind this massive breakup event was large-scale rifting of a few key zones, including the proto-Atlantic rift and the separation of North and South America along what is now the Caribbean rift (Figure 5). During this period, a series of passive continental rifts opened in the Maracaibo basin, resulting in the creation of a series of faulting half-grabens, which are believed to exist due to a rapid change in the thicknesses of terrestrial sediment accumulation as compared to basement rock thicknesses (Lugo and Mann, 1995). This faulting marked the beginning of deformation of sediments in the basin as well. Throughout this time period outcrops of volcanic rocks are also common, and likely emplaced by upwelling due to rifting. The half grabens indicate initial subsidence during this time period was fault controlled, however, as is typical for continental rifts, passive thermal subsidence eventually became the primary driver of subsidence, and saw the emplacement of the volcanic rocks (Lugo and Mann, 1995). Continental rifting continued in this manner, depositing primarily terrestrial sediments, until the late Jurassic, when continental rifting gave way to the creation of the proto-Caribbean seaway. Further extension would then lead to the basin evolving into a passive margin controlled basin. It is worth noting that the rifting recorded in the Maracaibo basin is one of the few places where the effect of this large scale was recorded for this region, as most of the Jurassic rifts were inverted during mountain building beginning in the Miocene (Lugo and Mann, 2006; Duerto et al, 2006).

Cretaceous Passive Margin Rifting

With the continued expansion of the proto-Caribbean seaway, Jurassic rifting controlled subsidence in the Maracaibo basin gave way to passive-margin-controlled thermal subsidence as North and South America separated (Figure 6). This marked the beginning of a period of relative tectonic stability in the region. As rifting continued, the early Caribbean seaway infiltrated the basin, completely altering sedimentation from being terrestrial controlled to shallow marine controlled, as well as vastly reducing the influence of faulting on subsidence (Lugo and Mann, 1995). The passive margin located on the northern coast of South America began to rapidly subside due to rapid cooling following the creation of the seaway. Well data from the region indicates that during initial passive margin thermal subsidence, rates of subsidence were relatively rapid followed by an exponential decay until the Late Cretaceous, where subsidence rates once again increased (Lugo and Mann, 1995). During passive margin subsidence in the basin, inconsistent rates of subsidence can be observed throughout the region, and is believed to be related to the formation of the Mérida arch (Figure 7). What caused the formation of this arch remains poorly understood. The arch consists of uplifted Paleozoic basement rocks and Jurassic-rift related rocks, possibly indicting the formation of the structure is related to passive margin subsidence after Jurassic rifting, however that is speculation. In short, the Mérida Arch represents a Paleozoic high of unknown tectonic origin, and it appears to have strongly impacted the subsidence rates, and subsequent sediment thickness, during this time period as shown on isopach maps of the Cretaceous sediments (Lugo and Mann, 1995).

The thermal subsidence controlled evolution of the Maracaibo basin is believed to have continued into at least the Late Cretaceous, possibly until the Paleocene. The temporal extent of this period appears to be somewhat controversial (Lugo and Mann, 1995), as there is debate as to the existence of a foreland basin sequence east of the Maracaibo basin in the late Cretaceous (Campanian to Masstrichtian). Regardless, the end of passive margin subsidence is marked by an unconformity showing a sudden change from shallow marine (carbonate) sedimentation, to a mixed carbonate and clastic sequence in the Paleocene, indicating a change to foreland basin type subsidence. It is worth noting that these Cretaceous carbonates make up the bulk of the source rocks for the extensive petroleum system that exists in the Maracaibo basin, however the details of this system will be discussed in greater detail further on (Mann et al, 2006).

Paleocene – Eocene Foreland Basin Formation

Tectonic Cause of the Foreland Basin Formation

Following the passive margin dominated subsidence of the Cretaceous, there is a large unconformity marking the end of passive margin sedimentation and the beginning of active margin (subduction zone) sedimentation. This shift in tectonic setting was likely caused by the beginning of a large scale subduction event involving the Caribbean plate moving underneath the northwestern section of the South American plate during the Middle to Late Paleocene. The most widely accepted model of this convergence comes form Lugo and Mann (1995), in which they describe a zone of oblique subduction developing in the northwest of the South American plate. This resulted in the development of an extremely asymmetrical foreland fold and thrust belt, as the developing foreland basin was uniquely constrained by the presence of the South American craton to the south, the closing basin area to the east, and western suture zone caused by the collision of the two plates. This combination of factors resulted in the creation of an asymmetrical, triangular shaped wedge, the result of which is visible in the present day (Mann and Escalona, 2006).

Summary of the Formation of the Foreland Basin

A summary of a series of events culminating in the creation of the foreland clastic wedge, found in the northeastern section of this basin, was defined by Lugo and Mann (1995) and is summarized here. First, movement of the subducting Caribbean plate was generally southwest, which initially caused the development of a foredeep north of the Maracaibo basin. As plate motion continued, these foredeep deposits, along with Cretaceous passive margin deposits were pushed into the cratonic margin of South America, creating a fold and thrust belt. At this point, sedimentation on the cratonic margin was mostly fluvial in nature, but continued foreland basin evolution led to a shift to shoreface and deltaic type sedimentation in the Early Eocene. Since this would result in a higher rate of sediment accumulation, load on the cratonic margin increased dramatically, which is marked by an increase in the rate of subsidence (flexural response) in the basin at this time. As convergence continued, the increased subsidence rates resulted in retrogradation of deltaic sedimentation and a switch to completely shoreface dominated sedimentation. As the foreland basin was pushed further to the southeast, flexure, and subsequently subsidence, diminished due to interactions with the highly resistive Mérida arch, which prevented flexure of the craton. The result of this is visible as a thick (approximately 5km) foreland wedge of sediments in the northeastern section of the basin. At this point, the continued subduction of the Caribbean plate shifted eastward, where further development of other foreland basins in the region, such as the Eastern Venezuela basin, began. Figure 8 outlines the cross-sectional evolution of the foreland basin over time. Isostatic rebound following flexure resulted in uplift and exposure of sediments in the eastern and central areas of the basin, where erosion created the extensive Eocene unconformity. Put simply, the primary control on subsidence of the Maracaibo basin during this time period was lithospheric flexure due to loading from an advancing fold and thrust belt caused by subduction of the Caribbean plate beneath the South American plate (Lugo and Mann, 1995).

Problems with the Foreland Basin model

One known problem with this foreland basin model is that the Eocene foreland fold and thrust belt is seen in seismic analysis to have a northwest going trend, while the Caribbean plate was trending eastward at the time. This suggests an unknown factor must be responsible for a change in orientation of the thrust fault. There are a few possible explanations for this discrepancy. One, suggested by Mathieu (1989), proposes that pre-existing right-lateral strike-slip faulting in the foreland basin area acted as a "ramp" for the thrust belt, offsetting the orientation in relation to the movement of the Caribbean plate. Another possibility is that a change in thrust orientation occurred as a result of the dextral offset of the Boconó fault zone in the eastern margin of the Maracaibo basin (Mann and Burke, 1984), which is contributing to the northern movement and squeezing out of the Maracaibo tectonic block. The primary control would remain controlled by flexure, regardless of the orientation of the fold and thrust belt. Fundamentally, these unsolved questions reveal a controversy relating to the formation of the Eocene clastic wedge (Mann et al, 2006).

Oligocene – Pliocene Uplift, Erosion, and Subsidence

After the emergence of the foreland thrust belt in the Late Eocene, erosion of the uplifted basin created an Eocene – Late Oligocene unconformity, and primary subsidence in the region had shifted to the east, where the Eastern Venezuela basin was undergoing rapid subsidence (Lugo and Mann, 1995). The northeastern and central areas were, in other words, experiencing an isostatic rebound due migration of the primary subduction zone to the east. During the Late Oligocene, the southern – southwestern portions of the basin underwent extensive fluvial sedimentation. There was no subsidence during this time, as seen in subsidence logs derived from well data (Lugo, 1991).

The Miocene – Pliocene saw the uplift of both the Sierra de Perija mountain range to the east as well as the Méridas Andes to the south and west. Uplift was instigated by the collision of the Panama Arc with northwestern South America (the Andean Orogeny), as well as the continued subduction of the Caribbean plate and onset of the subduction of the Nazca plate beneath South America. The age of this orogenic event has been estimated to the Late Oligocene to the Holocone through the use of fission track dating in surrounding mountain ranges (Lugo and Mann, 1995). In the Maracaibo basin, this event was recorded as east-west compression and the formation of the bounding strike-slip faults in the basin, which are currently contributing to the escape tectonics which now define the Maracaibo block. This uplift resulted in the formation of the basin-wide syncline (Figure 9) seen in the stratigraphy in the present day (Duerto et al, 2006). Rapid subsidence was then seen in the basin due to the mountain building. In response, rapid fluvial sedimentation began, resulting in thick deposits of Tertiary age. At this point, in the early Pliocene, the Maracaibo basin showed a very similar appearance to the present day, and sedimentation due to the rapid Miocene subsidence continues. The present day basin is characterized by this erosional sedimentation, and exists currently as a foreland basin, however since subduction has since moved east, collision of the two plates has evolved into a strike-slip relationship, and the basin is undergoing deformation through transpression. Despite this, the basin is still considered as a foreland basin, and there is little evidence of pull-aprt tectonics (Mann and Escalona, 2006).

Origin and Architecture of the Sedimentary Fill

This section will outline the sedimentary history of the Maracaibo basin as it relates to the tectonic evolution and subsidence previously discussed. Due to the nature of the Maracaibo basin, there are many distinct periods of sedimentation resulting in unique lithologies throughout, some of which would become important reservoir rocks for the petroleum system. Stratigraphic features, such as major unconformities, will be discussed on a basin scale. In addition, the provenance and transport of the deposited sediments in the basin will be explained where known. Much like the phases of subsidence in the basin, the nature of sedimentation over time has been influence by the tectonic environment and evolution, and sedimentation will be discussed as this occurred over the same time periods. The majority of the understanding of the sedimentation history of the Maracaibo basin comes from seismic imaging combining with observed well data from petroleum projects (Escalona and Mann, 2006). Post-Jurassic sedimentation is commonly separated into 4 seismic mega-sequences (Lugo and Mann, 1995), each containing a multitude of formations originally defined by Gonzalez de Juana et al (1980). This is outlined in Figure 10 and Figure 11, as well as the geographical distribution of the formations in relation to present day geographical features (Mann et al, 2006). Present day geographical locations of outcrops by age is pictured in Figure 12. Note that basin fill sedimentation started during the Jurassic, and was deposited over a thick basement composed primarily of metasedimentary rocks of Paleozoic age.

Jurassic Sedimentation

Rifting due to the breakup of North and South America in the Jurassic resulted in the creation of a series of continental rifts in Northern South America. As a result, the majority of sedimentation during this period was derived from primarily continental sources, deposited through fluvial processes. Jurassic units were deposited over Paleozoic metasedimentary rocks (Mucuchachi formation), which predate the existence of this basin and represent a Paleozoic to Jurassic unconformity. Deposit types include alternating alluvial fans with lacustrine deposits. Brackish water deposits are also common during this time period. These deposit types are typical of continental rifting, as lake formation in the rifted zone and fluvial activity is common. Notable formations from this time period include the Early to Middle Jurassic Tinacoa Formation, the Middle Jurassic Macoita formation, and the Middle – Late Jurassic La Quinta formation (Lugo and Mann, 1995). Lithologies from the Jurassic are primary shales and conglomerates, with fine grained sandstones all of which contain freshwater fauna, and lack marine features. Above these Jurassic sediments is a rapid change in depositional environment from continentally derived sediments to shallow marine deposits, which marks the beginning of Cretaceous deposition in the Maracaibo basin. Included within these terrigenous sediments are abundant rift-related volcanic rocks, intruded as dykes. These volcanic rocks were primarily basaltic in nature (Lugo and

Mann, 1995). The existence of continental rifts during this time is inferred through deep wells and seismic interpretation indicating extensional faulting and deposition along half-grabens parallel to the direction of tension (Lugo and Mann, 1995).

Cretaceous Sedimentation

General Cretaceous Depositional Features in the Maracaibo Basin

After continental sedimentation in the Jurassic, basin fill switched from being terrigenous in origin to shallow marine. This was due to the development of a passive rift caused by the separation of North and South America (Lugo and Mann, 1995). The infiltrating Caribbean seaway resulted in the formation of a low-angle continental shelf under shallow water conditions. Due to a poorly understood tectonic process, the Paleozoic high, known as the Mérida Arch, had formed in the southeast-central basin area, likely due to external plate interactions and stresses. This arch greatly affected the geometry of sedimentation throughout the history of the Maracaibo basin. Thicknesses and distribution of the Cretaceous deposits were greatly impacted by the geometry of this arch, resulting in thinner deposits over the high point, and thicker deposits over the flanks, which is shown on isopach maps of the area (Figure 13, Lugo and Mann 1995). The shallow marine environment that dominated this time period resulted in largely carbonate lithologies throughout the Cretaceous, deposited consistently and generally without interruption. In other words, there are no major unconformities during the Cretaceous, and since passive thermal subsidence was the main cause of sedimentation, deformation of these sediments was limited to minor normal faulting due to extension (note that mountain building in the Miocene created an extremely structurally complicated complex along the surrounding mountain ranges, which is beyond the consideration of this report). Shallow marine sedimentation then resulted in the deposition of an extensive sequence of primarily shallow water limestones, with clastic units interspersed between, typical of a clastic – carbonate shelf environment. Carbonate units were, as is expected, sourced from shallow marine life processes, however the clastic units most likely have their provenance from deeper marine sedimentation during transgressive periods (Lugo and Mann, 1995). The shallow carbonate shelf setting led to abundant organic material being included in the limestone and shale deposits, and as a result, formations from the Cretaceous sequence serve as the most important source rocks for the entire basin (Escalona and Mann, 2006).

Cretaceous Sedimentary Sequence

Notable formations from the Cretacous include the Rio Negro Formation (fluvial transgressive clastic deposit), Apon Formation (basal carbonate shelf unit), Lisure Formation (marine sandstone unit), Maraca Formation (fossiliferous limestone), La Luna Formation (black shale and the primary source rock for the entire basin; (Talukdar et al, 1986), and the Colon Formation (micritic limestone). This alternating clastic-carbonate succession through the Cretaceous fits with the passive margin model for subsidence at the time, as these sedimentation patterns are typical of cyclic marine transgression and regression. Note that all of these units are included under seismic Megasequence 1 (de Juana, 1980), with the exception of the Colon Formation, which is included under Megasequence 2 (de Juana, 1980), as it is believed to represent the end of the Cretaceous sea-level high stand responsible for most sedimentation during this time (Lugo and Mann, 1980), as the overlying Paleocene clastic deposits mark the beginning of oblique collision of the Caribbean plate with South America (Escalona and Mann, 2006). There is some debate as to whether or not the Colon Formation could have been formed by a previously undefined foreland basin phase (Lugo and Mann, 1995) from the Campanian to the Maastrichtian, however further study will be required to confirm this (Escalona and Mann, 2006).

Paleocene – Eocene Foreland Basin Sedimentation

Regression of global sea-level following the Cretaceous high-stand and the beginning of oblique collision of the Caribbean plate with South America resulted in reactivation of the passive margin, and deposition of foreland basin type sediments in the Maracaibo basin during the Late Paloecene (Mann et al, 2006). Note that the details of sedimentation as it relates to tectonic evolution of the basin was covered in the subsidence history portion of this paper, as it was necessary to outline the exact controls on subsidence during this phase, due to the sequence of events being very complex. This section will then focus on the general sources of sediments in the foreland phase, as well as notable formations and lithologies contained within.

General Sources of Sediments and their Depositional Environments

As is expected for a foreland basin, the majority of the sediments are clastic, having been sourced from the proto-Maracaibo river which had begun to erode and drain the continent in the region, as well as from erosional processes occurring on the uplifted terrain to the north and east of the basin proper. Due to subduction, the northeastern section of the subsided basin area had been bent down due to lithospheric flexure (Mann et al, 2006). These eroded clastic sediments then began to fill the area of flexure, resulting in a 7.0km thick, asymmetric wedge of sediment (Lugo and Mann, 1995). The geometry of the sedimentation is highly irregular due to the presence of the Mérida arch, which acted to deform and direct the development of the foreland basin as it advanced. The formation of an asymmetric, northeast trending elongate clastic wedge resulted from this (Figure 14). These clastic formations would serve as the most important reservoir rocks in the entire basin, and have been the focus of petroleum exploration thus far (Escalona and Mann, 2006). By the Middle Eocene, the drainage of the continent from the proto-Maracaibo river had developed into a deltaic complex in the interior (present day lake area) of the basin (Maguregui, 1992). This increased sediment load increased the sediment load on the lithosphere, increasing the rate of subsidence and therefore the rate of sedimentation. This is when the majority of the foreland sediments were deposited (Lugo and Mann, 1995). Then, as subduction progressed to the east, isostatic rebound uplifted the basin, causing the retrogradation of the deltaic complex, and shifting to clastic shoreface sedimentation. This shoreface sedimentation was still sourced by fluvial processes occurring on the continent, much like the delta (Mann and Escalona, 2006).

Notable Paleocene – Eocene Formations

As defined by de Juana (1980), the Paleocene sedimentary sequence consists of several distinct clastic units, all primarily composed of fluvial, deltaic, or shoreface sediments. These formations define Megasequence 3, and are capped by the Eocene-Oligocene unconformity (Figure 11), which is a basin wide erosional surface marking a period of non-deposition following foreland basin sedimentation. This unconformity is related to the cessation of foreland progression in the basin, and the beginning of uplift in the region (Lugo and Mann, 1995). The primary formations in this sequence include the Guasare Formation (Paleocene limestone and calcite cemented sandstone), the Trujillo Formation (Early Eocene fluvial/marine sandstone and shale), the Misoa Formation (Middle Eocene deltaic sandstones and shales), and finally the Pauji

Formation (marine shoreface shales). The origins of these units reflect the evolution of the depositional environment and sediment source for the basin during each time period, as outlined above. Sediments formed during the foreland basin phase can be extremely thick (up to 7000m in some areas), contributing to their importance as reservoir rocks (Lugo and Mann, 1995). Sandstone composition studies by Kasper and Larue (1986) and Lugo (1991) indicate that the sediment sources for these rocks are almost entirely continental, with cratonic and recycled orogenic provinces dominating throughout.

Oligocene – Pliocene Sedimentation

Following isostatic rebound and uplift associated with the shifting of subduction of the Caribbean plate to the east of the Maracaibo Basin, external tectonic activity involving both the Caribbean and Nazca plates resulted in the uplift of the mountain ranges surrounding the basin. During the Late Oligocene, uplift had caused the position of the continental shelf to migrate to the north, extending the basin. Mountain building impacted the flow of the proto-Maracaibo river, diverting it temporarily away from the basin, resulting in the majority of sediment transport being carried out by the Orinoco River (Mann and Escalona, 2006). Net uplift during the Oligocene resulted in relatively little deposition, with the lacustrine sourced Icotea formation (de Juana, 1980) being the only major formation from this time period (Figure 11). Moving into the Miocene saw rapid subsidence in response to mountain building, creating the synclinal nature of deposition present through the entire basin (Lugo and Mann, 1995). Sediments are almost entirely continentally sourced, with shales and sandstones dominating the time period. Fluvial transport was the primary method of sediment transport during this time, creating lacustrine deposits as well as deltaic complexes (Mann and Escalona, 2006; Lugo and Mann, 1995). These Miocene sediments include excellent reservoir quality sandstones, and are an extremely important part of petroleum exploration in the basin. By the Pliocene, sediments in the Maracaibo were being sourced almost entirely from the Orinoco River, and the whole erosional system looked very similar to present day. Notable formations from this time period include the La Rosa, Lagunillas, Isnotu, and La Puerta formations, which make up Megasequence 4 (de Juana, 1980). These sediments make up a very large portion of the basin stratigraphic thickness overall (Figure 11).

Petroleum Systems and Hydrocarbon Resources

Now that the tectonic evolution and methods of sedimentation processes of the Maracaibo Basin have been discussed, one more aspect of the basin must be observed. The Maracaibo Basin is a world-class hydrocarbon producing basin, having produced over 30 billion barrels of oil as of 2006, with an estimated 44 billion barrels yet to be retrieved. Production is this basin has been occurring for over 80 years and production has been primarily conducted through conventional (vertical wells) means (Escalona and Mann, 2006). As a result, the petroleum system has been extensively studied and modelled, and there is a very well established understanding of how the large volumes of hydrocarbons came to be in this basin. Using well data, seismic data, and interpretations from previous these previous works on the Maracaibo petroleum system, a basin-scale description of hydrocarbon generation will be outlined here (Figure 15). Important aspects which will be discussed include source rocks, reservoir rocks, sealing formations, and recovery plays both present and future.

Source Rocks

La Luna Formation

As previously mentioned, the primary source rocks for the Maracaibo Basin were deposited during the passive margin sedimentation phase in the Cretaceous. Collectively, these Cretaceous rocks are all included in the La Luna formation (Figure 11, Figure 16), which is estimated to have been deposited over a period of 20 million years, from the Cenomanian to the Campanian (Escalona and Mann, 2006). Lithologically, this formation is primarily composed of organic-enriched limestones and calcareous shales (Talukdar et al, 1986), with thicknesses ranging for 60m to 150m depending on the geographical location in the basin and the relationship with the Paleozoic Meridas Arch. Reservoir studies and geochemical analysis indicate that the La Luna Formation is responsible for 98% of oil generation throughout the basin (Escalona and Mann, 2006). The high organic content (TOC approximately 5.6%) of the La Luna rocks is believed to be related to being deposited on an oxygen-deprived marine shelf or marine slope environment (Talukdar et al, 1986). Anoxic conditions led to high organic content buildup in the sediments as they were lithified, due to the activity of algae and anoxic bacteria (Talukdar et al, 1986). Oil quality and maturity from the La Luna formation is highly dependent on thermal conditions, and is quite variable throughout the reservoir (Escalona and Mann, 2006). Due to these thermal conditions, hydrocarbons are nearly entirely composed of varying quality oil reservoirs, with free natural gas reservoirs being very rare in the Maracaibo Basin. The La Luna formation rocks were buried to depths reaching from 2-6km during and after the foreland basin phase of the basin, beginning in the Paleocene and continuing through the Miocene and Holocene. Multiple subsidence events (lithospheric flexure, isostatic rebound and mountain uplift, all discussed above) during this time were the primary cause of hydrocarbon generation from these source rocks in the basin, and since burial of these source rocks continues today under transpressive tectonic conditions, the La Luna formation is still generating hydrocarbons in a limited state (Talukdar et al, 1986; Escalona and Mann, 2006). Due to its high volume of hydrocarbon generation and lateral extent, the La Luna formation is widely considered to be one of the worlds richest source rocks (Escalona and Mann, 2006; Blaser et al, 1984).

Other Source Rocks

Other source rocks for oil generation in this basin are comparatively low volume to the La Luna Formation, however their contributions are significant enough to warrant discussion. The Apon Formation and the Capacho Formation (both Cretaceous in age) are two of these sources (Figure 11). Both are composed of limestones and calcareous shales deposited in a marine shelf environment, and both were buried (along with La Luna) during Paleocene-Miocene subsidence events (Escalona and Mann, 2006). Hydrocarbon generation is lower from these units due to limited lateral extent (the Capacho Formation is only present in the southwestern portion of the basin) and lower average TOC values (Talukdar et al, 1986). Distribution of these formations is also related to the Meridas arch, which may explain their limited extent. The validity of any other potential sources in the basin, such as the Lisure Formation of the Cretaceous, as well as Tertiary sedimentary rocks, remain controversial at this point (Escalona and Mann, 2006; Talukdar et al, 1986).

Reservoir Rocks

The complex structure of the Maracaibo Basin has led to the development of source rocks from a wide range of ages throughout the stratigraphy. Mann and Escalona (2006) recognize three stratigraphic zones, as defined by Mann et al (2006), where accumulations of hydrocarbons have occurred in economic quantities, and they are as follows:

Cretaceous and Paleozoic Reservoir Rocks

Due to the effects of thrusting during the Paleocene foreland basin phase, burial of these Cretaceous and basement (Paleozoic) rocks varies across the basin. These rocks are deeply buried in the southern and central areas of the basin, however the northwestern portion sees them at much shallower depths. Geometry of uplift and faulting resulted in hydrocarbons migrating from the sources along reactivated faults and into fractures (Nelson et al, 2000) and pores of Cretaceous and Paleozoic basement rocks (Figure 17). On a volume basis, these reservoir rocks make up the smallest portion of petroleum accumulations in the basin, due to the geometry and relative permeability of the formations in comparison to the younger clastic reservoirs (Escalona and Mann, 2006).

Eocene Reservoir Rocks

Reservoir rocks from the Eocene are primarily deltaic and shoreface derived clastic sedimentary rocks. They are highly permeable, and overlay the Cretaceous source rocks throughout the area of the basin. Deltaic sediments and shoreface successions allow for extensive accumulation of hydrocarbons, and these reservoir rocks are sealed by the basin-wide Eocene unconformity (Escalona and Mann, 2006). Due to the lateral extent of these sediments throughout the basin, Eocene clastic sediments account for the majority of petroleum accumulations in the basin (Figure 18). Eocene reservoirs are most productive in the central and northeastern areas of the basin, likely due to the increased thickness seen there as a result of lithospheric flexure seen in that area during foreland progression (Escalona and Mann, 2006). The Misoa Formation is the highest producing reservoir in the basin, and consists mostly of Eocene deltaic sands interbedded with sealing shales (Stauffer and Croft, 1995).

Miocene Reservoir Rocks

Composed primarily of fluvial sandstones deposited following foreland basin formation and uplift, these Miocene reservoirs are another high-producing type of reservoir rock found in the basin. Second in volume only to the Eocene reservoirs, these accumulations are most pronounced in the northeastern area, along the shoreline (Escalona and Mann, 2006). Note that, due to the lack of structural traps in some areas (Figure 19) resulted in oil seeping to the surface. These seepages are most common along the edges of the basin. Much like the Eocene reservoir sands, they are also highly permeable and porous sands, but are not capped by the Eocene unconformity, having been sealed by other means (Escalona and Mann, 2006).

Oil Migration, Seals, and Trapping Mechanisms

Due to the structural complexity of this basin, hydrocarbon migration and trapping was heavily influenced by faulting, subsidence, and uplift. After the Cretaceous source rocks were deposited along the passive margin, the initiation of foreland basin sedimentation in the Paleocene – Eocene resulted in the deep burial of these source rocks. Continued foreland basin sedimentation and deformation resulted in the reactivation of normal faults and strike-slip faults initially created during the formative Jurassic rifting phase of the basin. These reactivated faults provided a transport mechanism for hydrocarbons, causing upward vertical motion into the highly enriched Eocene reservoir sands., although the geometry and thickness of the beds resulted in especially productive reservoirs developing in the northeast. Shale layers deposited near the end of the Eocene, preceding the Eocene unconformity, acted as seals for the migrating hydrocarbons. (Escalona and Mann, 2006). Following that, erosion due to isostatic rebound (Eocene unconformity) resulted in the loss of some oil which had migrated to the surface. This continued into the Oligocene. This rebound inverted many of the structures responsible for hydrocarbon movement in the Eocene, creating structural traps. As the uplift from this rebound continued through the Oligocene, it is assumed that many hydrocarbon reserves were lost as they were forced to the surface, where they degraded (Escalona and Mann, 2006).

Following Oligocene uplift of the basin, tectonic interactions between the Caribbean plate and South America resulted in the uplift of the Sierra de Perijá and Mérida Andes mountain ranges, which in turn resulted in rapid subsidence and formation of the synclinal structure seen in the basin today (Lugo and Mann, 1995). Geometrically, this caused a shift in sedimentation in the basin to the southwest, and reactivation of Cretaceous source rocks (Escalona and Mann, 2006). A second period of hydrocarbon movement then occurred, which followed faulting systems in Eocene rocks and stratigraphy created by the formation of the syncline in the Miocene formations. Large accumulations of hydrocarbons then occurred in Miocene rocks, particularly in the northeast. Reservoirs in the Miocene are generally trapped by stratigraphic pinch-outs, inversions associated with uplift, and surface seeps along the margins of the mountain ranges (Escalona and Mann, 2006). Accumulations also occurred in the south and southwestern portions of the basin, although these are generally not as well explored (Escalona and Mann, 2006; Stauffer and Croft, 1995).

Known and Potential Production Plays

As seen in Figure 20, producing petroleum fields are concentrated in the northeastern and western – southwestern regions of the basin, along the flanks of the synclinal structure. Oil seepages to the surface are quite common along the flanks of the mountain ranges, where the stratigraphy has been uplifted and eroded by mountain building. The most significant oil fields are located near the northeastern coast, and is known as the Bolivar Coastal Complex, which contains fields such as the Tia Juana, Cabimas, Lagunillas, and Bachaquero fields (Stauffer and Croft, 1995). Collectively, the Bolivar coastal complex is one of the largest oil producing fields in the world (Stauffer and Croft, 1995). Bounded by faulting and the Eocene unconformity, most of the production in this complex is derived from Eocene sands, with lesser amounts in the Micoene. Since the reactivation of these fields by Exxon, Shell and Petroleos de Venezuela in 1995 (Stauffer and Croft, 1995), extraction in this complex has consisted of both conventional vertical wells, as well as cyclic steam drainage. Other plays include, for example, the Lama and Lamar fields south of the northeastern complex (conventional and steam assisted), Centro and Lago fields in the central region (seepages and vertical recovery), and the La Paz and Mara fields (Cretaceous light oil reservoirs, conventionally recovered), as well as a multitude of other fields throughout the region (Stauffer and Croft, 1995). These plays are responsible for much of the 35 billion barrels of oil recovered as of 2006 (Escalona and Mann, 2006), and consist of a mixture of conventional and unconventional recovery techniques (Stauffer and Croft, 1995).

Potential future plays in the region are difficult to determine specifically, as there are large, poorly explored regions in the basin, particularly in the south-central basin area. The lateral extent of source and reservoir units indicates there is likely a large potential for future production from these areas. This of course, is not considering the reserves remaining in the known plays, which is estimated at over 45 billion barrels (Escalona and Mann, 2006). The recent advances in unconventional extraction are also likely to contribute to the potential of this basin. In short, the Maracaibo basin will most likely see significant future development, however specific plays are subject to further exploration. Overall, the Maracaibo basin is a very mature, proven, producing basin with great potential for future expansion and development.

Discussion

The Maracaibo basin is a very complex geologic region, from both a tectonic and sedimentary standpoint. It shows a somewhat convoluted, but well recorded, subsidence history since its inception in the Jurassic, through continental rifting, passive margin development, and foreland basin advance, all of which culminates in what is seen today. Through this complex subsidence history, deposition of organic rich sediments led to the development of an extensive, extremely enriched petroleum system. We see this through previous studies on the stratigraphic, tectonic, and petroleum aspects of the basin. Based on observations in seismic, well data, and outcrops, the complete history of the basin has been outlined by researchers, showing a highly economically viable basin. Study of the geodynamics and stratigraphy of the basin provides an excellent resource to use in future exploration projects. Previously researched data, from sources such as those used for this report (and this report itself), are an excellent resource on the lithology (source rocks, reservoir rocks), structure (traps, seals, etc.), and evolution of the basin. The presence of this previous research would make any future exploration far more feasible and cost-effective. Petroleum production has also been proven throughout the region over the last decades, particularly following the involvement of corporations such as Shell and Exxon, with

35 billion barrels of oil having already been recovered (Escalona and Mann, 2006). The estimated presence of 45 billion barrels still in-place is by itself adequate reason to consider further exploration by BPP.

Despite the extensive studies on certain oil fields and the geodynamic setting of the basin, there still remain portions of the basin which are relatively unexplored. Considering the lateral extent of the extremely rich source rocks of the Cretaceous La Luna Formation, and the presence of reservoir grade rocks from The Eocene and Miocene throughout the basin, it is reasonable to believe that new, untapped production opportunities exist in the basin. The structural complexity of the basin caused by faulting, thrusting, and rapid subsidence would suggest that reservoirs and traps could exist in abundance in the unexplored areas. New data (seismic, exploration wells, mapping, etc.) would need to be collected by BPP in order to definitively conclude whether exploration of these areas (the southern region, in particular, see Figure 20) would be economically viable. There also remains controversy over the presence of other, poorly studied source rocks in the region, which, if proven significant, could present BPP with other opportunities in the basin (Escalona and Mann, 2006).

Certain challenges would present themselves in the event of future exploration by BPP, mostly related to the surface environment of the basin itself. As seen earlier, Lake Maracaibo covers approximately one-third of the surface of the basin. From an economic and environmental standpoint, this would cause difficulties in hydrocarbon exploration and extraction, assuming a reservoir of interest existed under the lake. Export of oil recovered would be heavily reliant on ocean transport due to the surrounding mountain ranges as well. Geological challenges also exist, particularly in the structure of the basin, the complexity of which could pose some difficulties when it comes to drilling and recovery. These, however, would likely prove no more significant than other basins (the Western Canadian Sedimentary Basin, for example) worldwide. Overall, the expansion of an exploration, and possibly production project by BPP would very likely see positive results, considering the information compiled in this report.

Conclusions

As a final recommendation to BPP, exploration of the Maracaibo Basin in Venezeula would likely yield positive results, and should be seriously pursued. Subsidence history of the basin, from Jurassic rifting, Cretaceous passive margin development, and foreland basin evolution have been extensively studied by previous researchers, and is well recorded and understood. These studies have since revealed a massive hydrocarbon producing complex, resulting from an extremely rich source rock system, the La Luna formation. Extensive sedimentation and structural evolution of the basin through time has provided an abundance of trapping mechanisms for these hydrocarbons resulting in very large accumulations of hydrocarbons in Eocene and Miocene clastic deposits. Previous research and exploration provide an excellent resource from which BPP can base its own exploration program, both in well studied oil fields, as well as in relatively unexplored areas within the basin which are likely to yield further discoveries. In short, the data available on the Maracaibo indicates it is a mature, well explored, hydrocarbon producing basin which BPP could very likely see positive results from exploring further.

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Figure Captions

Figure 1: Geographic Location of the Maracaibo Basin (Mann et al, 2006), Figure 2: Geodynamic and Tectonic Setting of the Maracaibo Basin (Mann et al, 2006), Figure 3: Basins of Northern South America (Mann et al, 2006), Figure 4: Outcrop Pattern in the Maracaibo Basin (Mann et al, 2006). Note that the outcrops for Paleozoic and Cretaceous units are mirrored in the surrounding mountain ranges., and that Eocene and Miocene units are outcropped mostly in the NE., Figure 5: Locations of Jurassic rifts in the Maracaibo Basin (Lugo and Mann, 1995). Rifts are filled in gray, and the area uplifted by the Merida Arch filled with the striped pattern. Note the location of the present day Lake Maracaibo overlain in black., Figure 6: Cretaceous Passive Margin Setting (Mann et al, 2006). Map is simplified on the top image, with depositional settings outlined in the bottom image., Figure 7: Cross-sectional structure of the uplifted Meridas Arch in the Maracaibo Basin (Lugo and Mann, 1995). The arch includes the white coloured zone, which has thinned the stratigraphy above it., Figure 8: Foreland Basin Evolution through time (Lugo and Mann, 2006)., Figure 9: Basin-wide cross-section showing syncline formation following the Oligocene (Mann et al, 2006)., Figure 10: Generalized stratigraphic outline of the Maracaibo basin (Lugo and Mann, 1995; Lugo, 1991)., Figure 11: Stratigraphic Column and Geographical Distribution of Maracaibo Basin Formations (Lugo and Mann, 1991), Figure 13: Isopach Maps of various Cretaceous formations (Lugo and Mann, 1995). Note the thinning of units in the gray area above the Meridas arch., Figure 14: Development of the Paleocene asymmetric foreland thrust belt and clastic wedge (Lugo and Mann, 1995)., Figure 15: Outline of Hydrocarbon Generation in the Maracaibo Basin (Escalona and Mann, 2006)., Figure 16: Stratigraphy of the Cretaceous Formations of the Maracaibo Basin (Escalona and Mann, 2006. Note the La Luna source rock of the Late Cretaceous., Figure 17: Cretaceous and Paleozoic Reservoirs in Cross-Section (Escalona and Mann, 2006)., Figure 18: Eocene Reservoirs in Cross-Section (Escalona

and Mann, 2006), Figure 19: Miocene Reservoirs in Cross-Section (Escalon and Mann, 2006). Black dots indicate reservoirs., Figure 20: Locations of major oil fields, Gas seeps, and oil surface seeps in the Maracaibo basin area (Escalona and Mann, 2006).

Figures

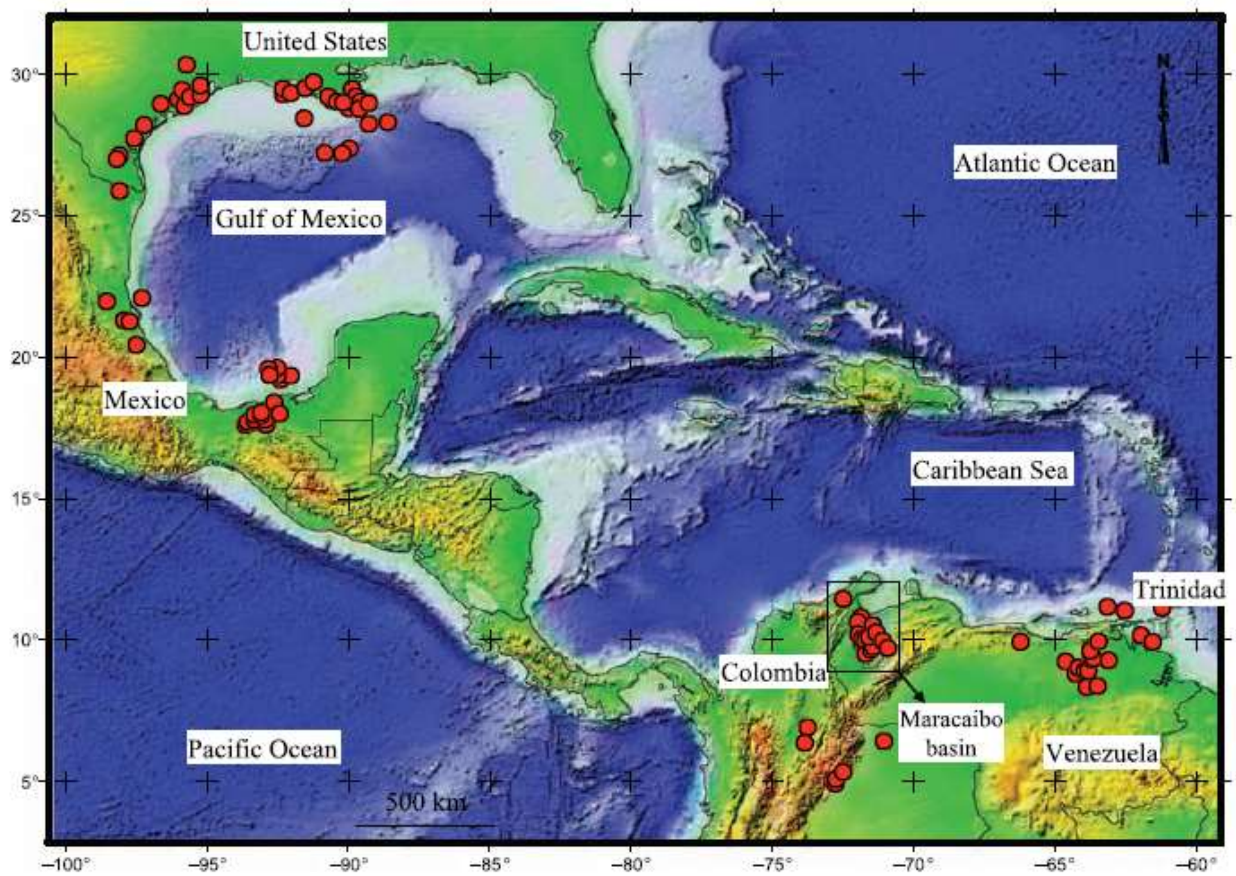


Figure 1: Geographic Location of the Maracaibo Basin (Mann et al, 2006)

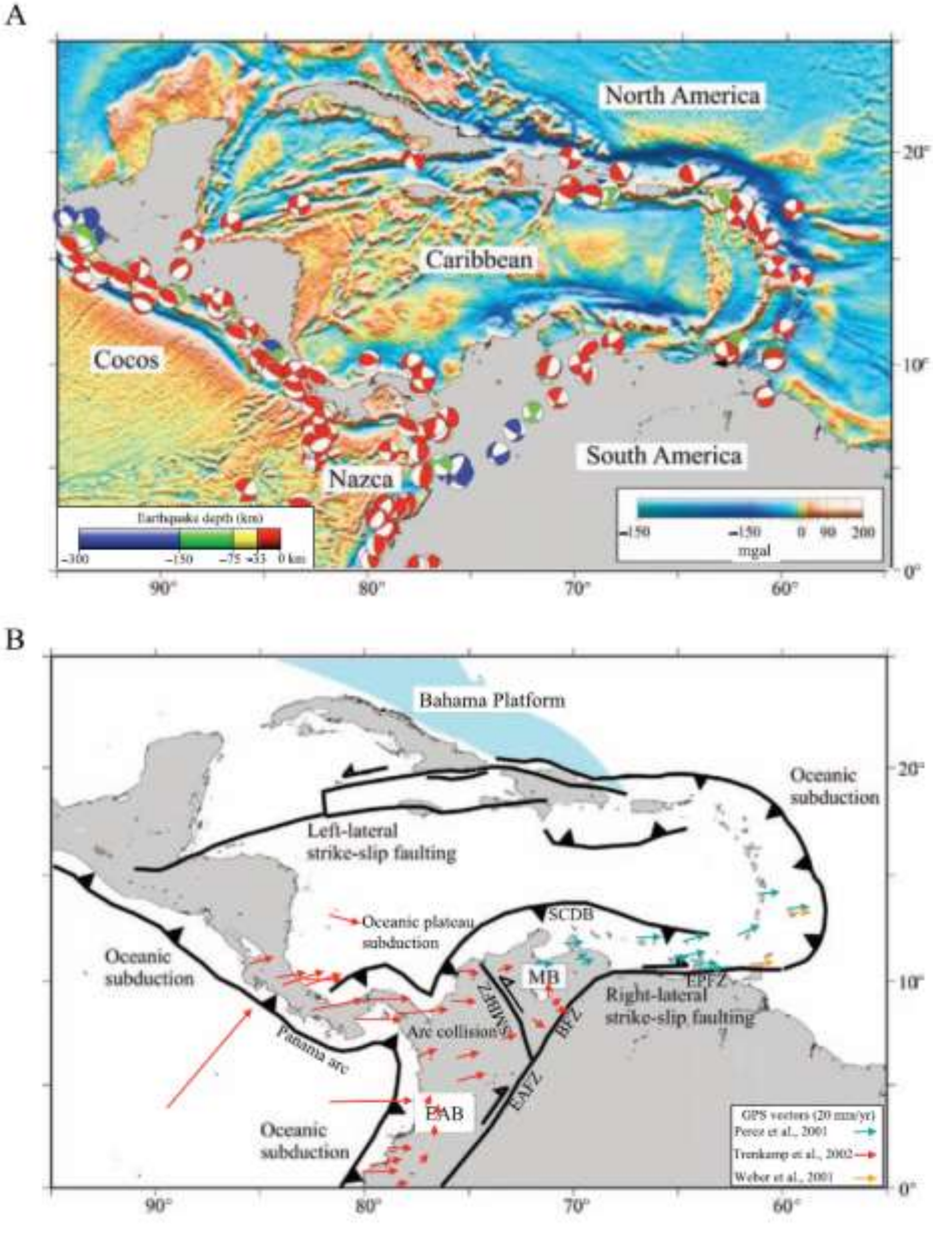


Figure 2: Geodynamic and Tectonic Setting of the Maracaibo Basin (Mann et al, 2006)

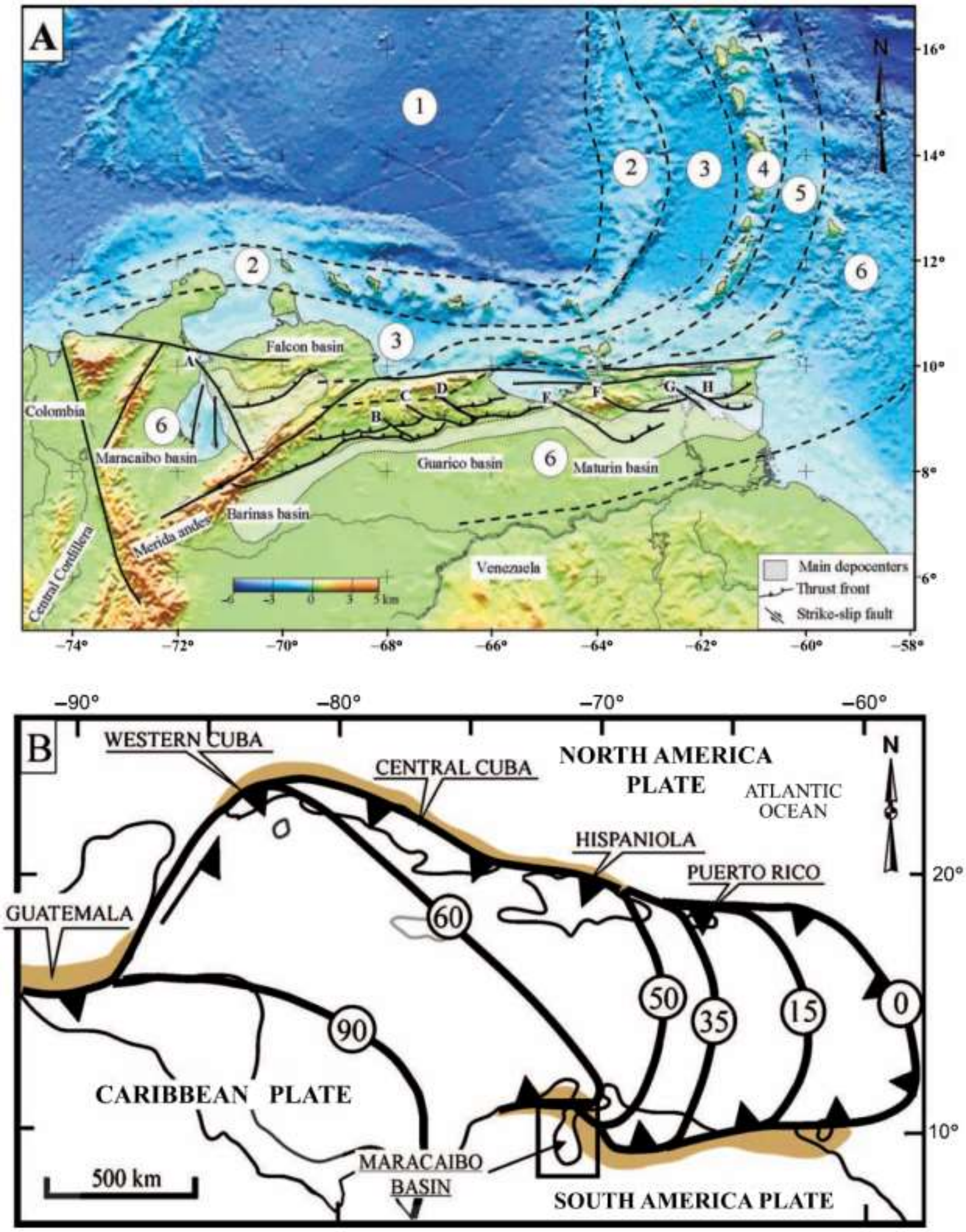


Figure 3: Basins of Northern South America (Mann et al, 2006)

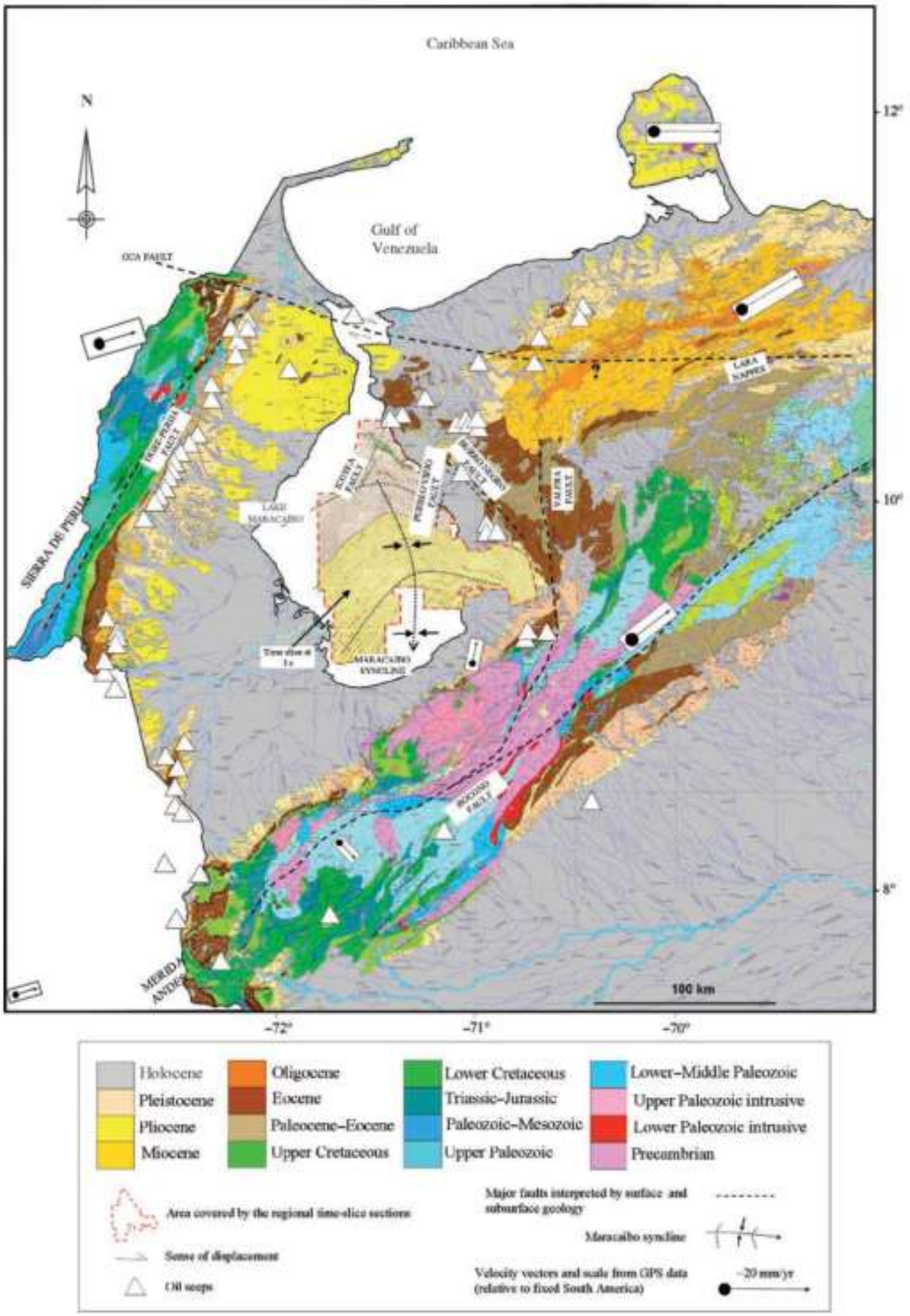


Figure 4: Outcrop Pattern in the Maracaibo Basin (Mann et al, 2006). Note that the outcrops for Paleozoic and Cretaceous units are mirrored in the surrounding mountain ranges., and that Eocene and Micocene units are outcropped mostly in the NE.

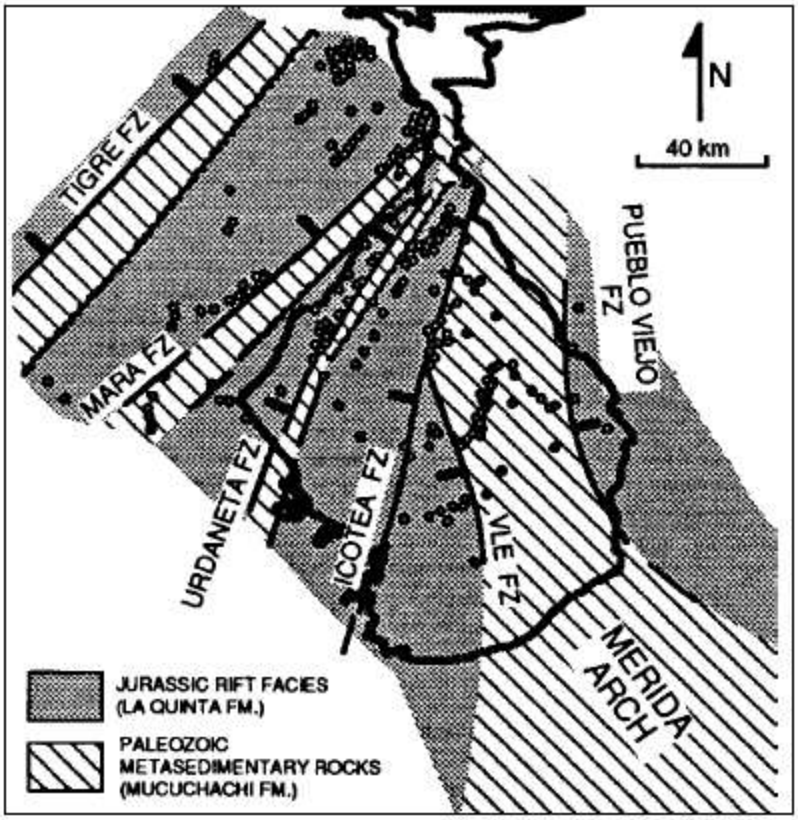


Figure 5: Locations of Jurassic rifts in the Maracaibo Basin (Lugo and Mann, 1995). Rifts are filled in gray, and the area uplifted by the Merida Arch filled with the striped pattern. Note the location of the present day Lake Maracaibo overlain in black.

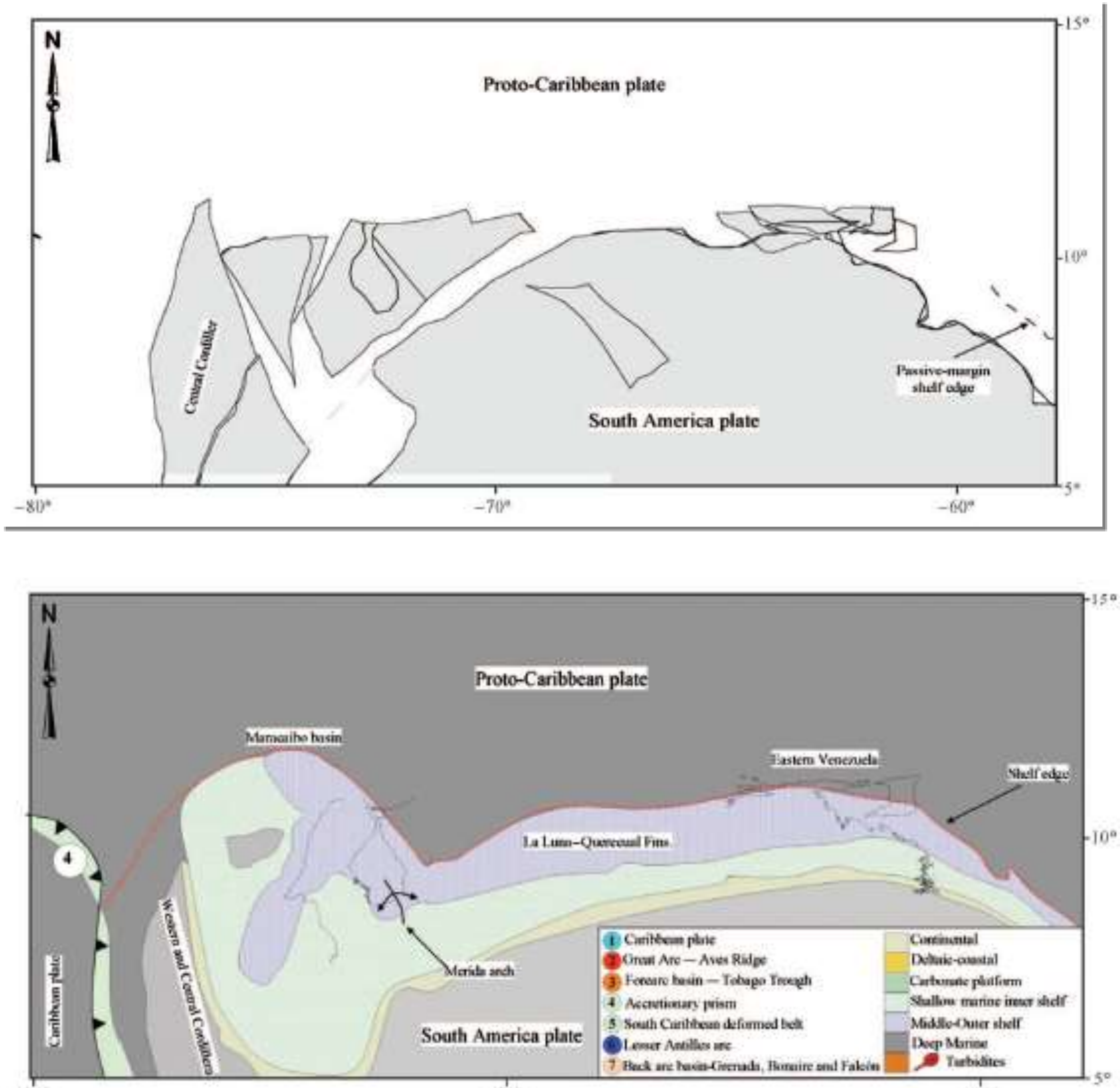


Figure 6: Cretaceous Passive Margin Setting (Mann et al, 2006). Map is simplified on the top image, with depositional settings outlined in the bottom image.

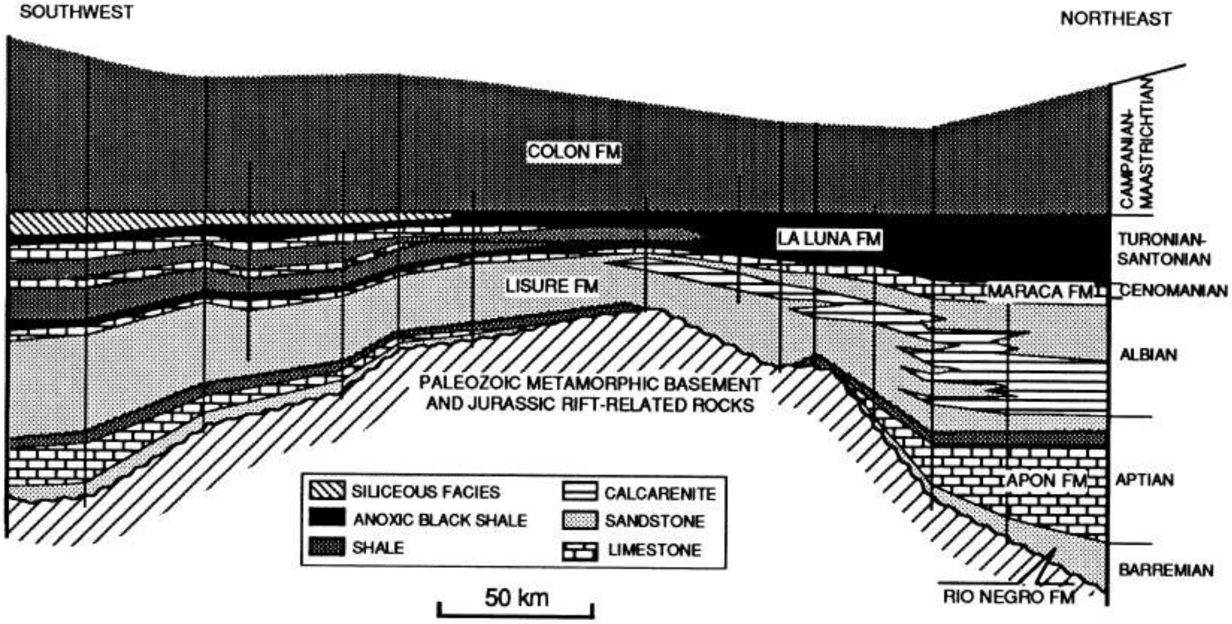


Figure 7: Cross-sectional structure of the uplifted Meridas Arch in the Maracaibo Basin (Lugo and Mann, 1995). The arch includes the white coloured zone, which has thinned the stratigraphy above it.

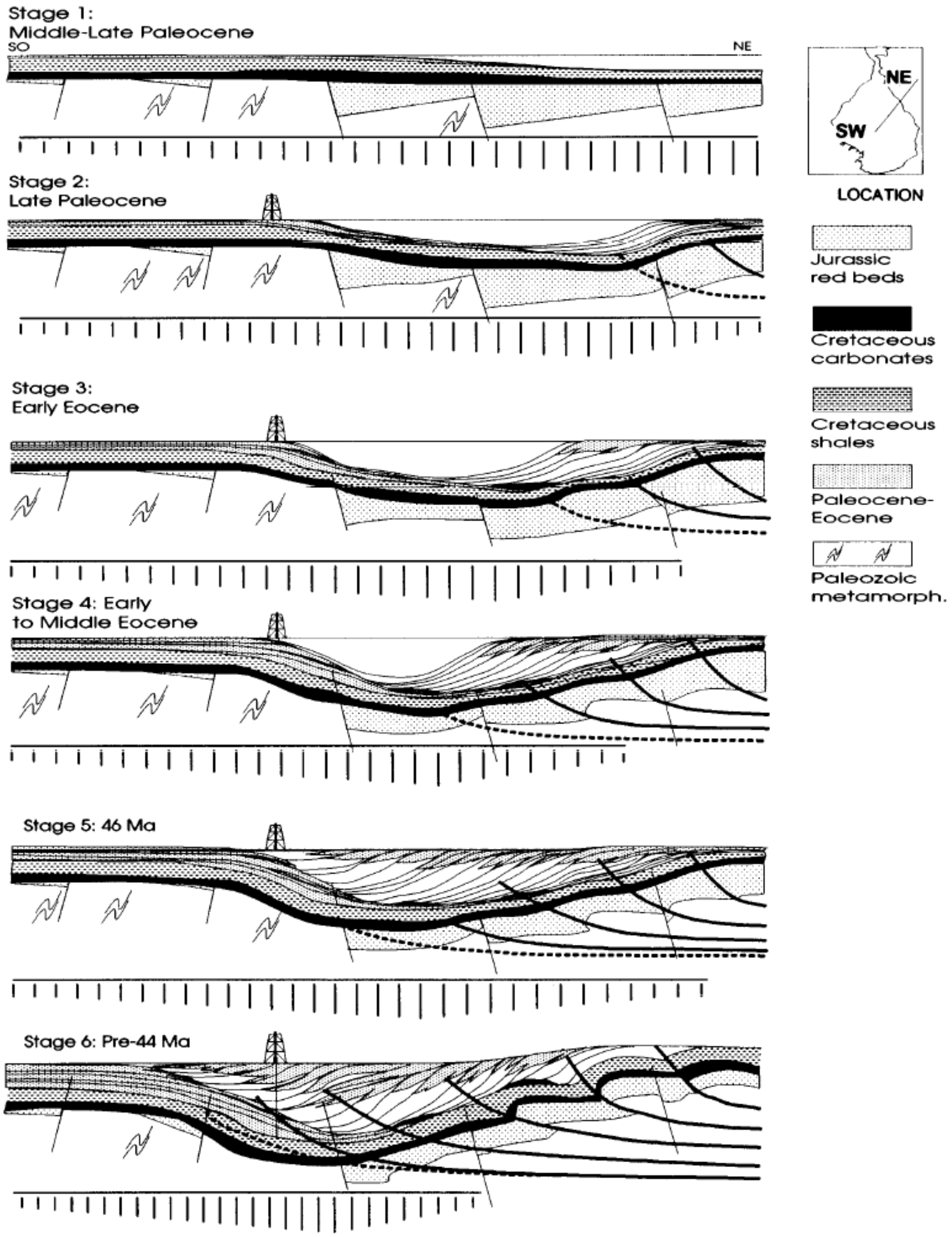


Figure 8: Foreland Basin Evolution through time (Lugo and Mann, 2006).

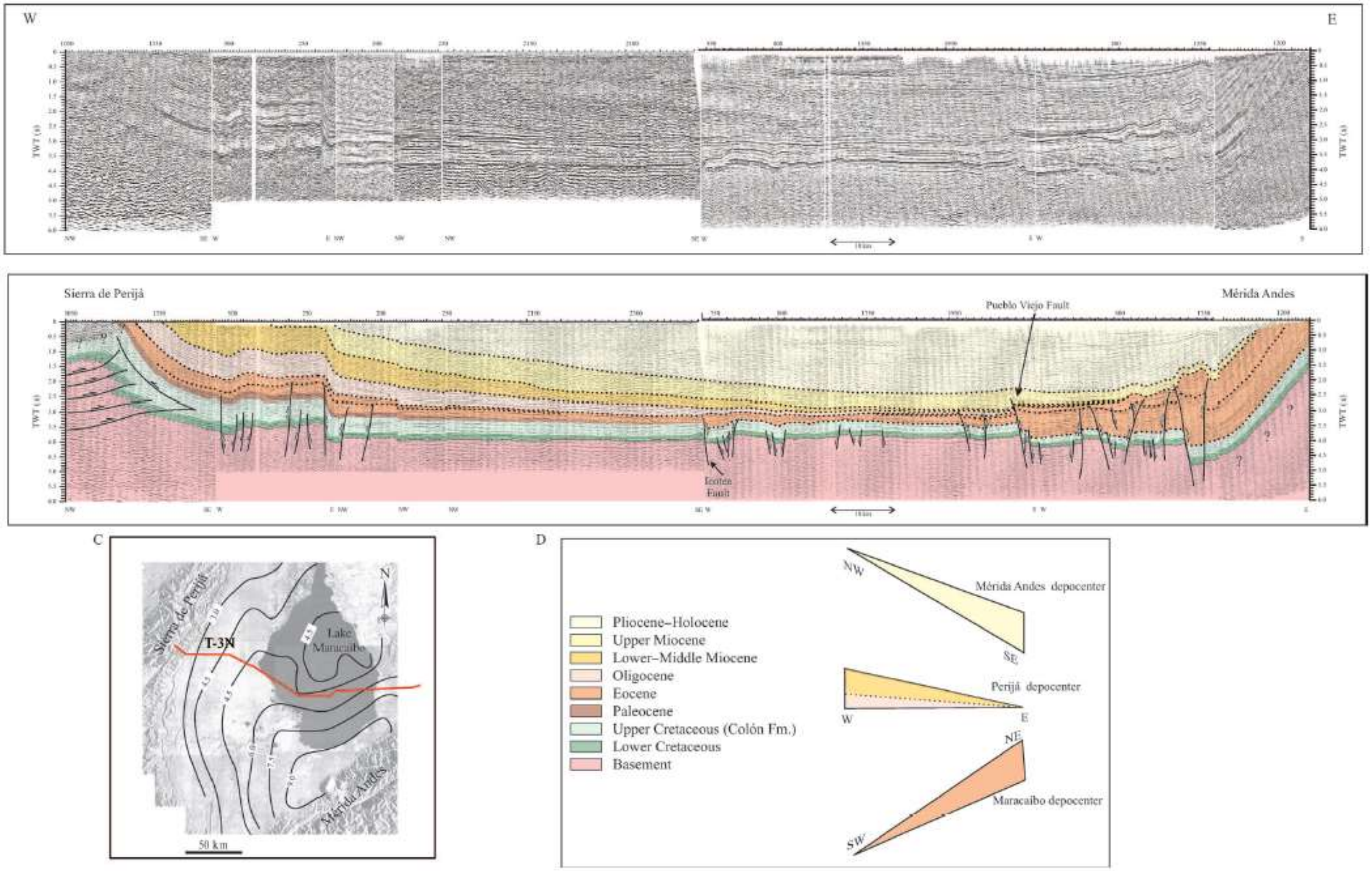
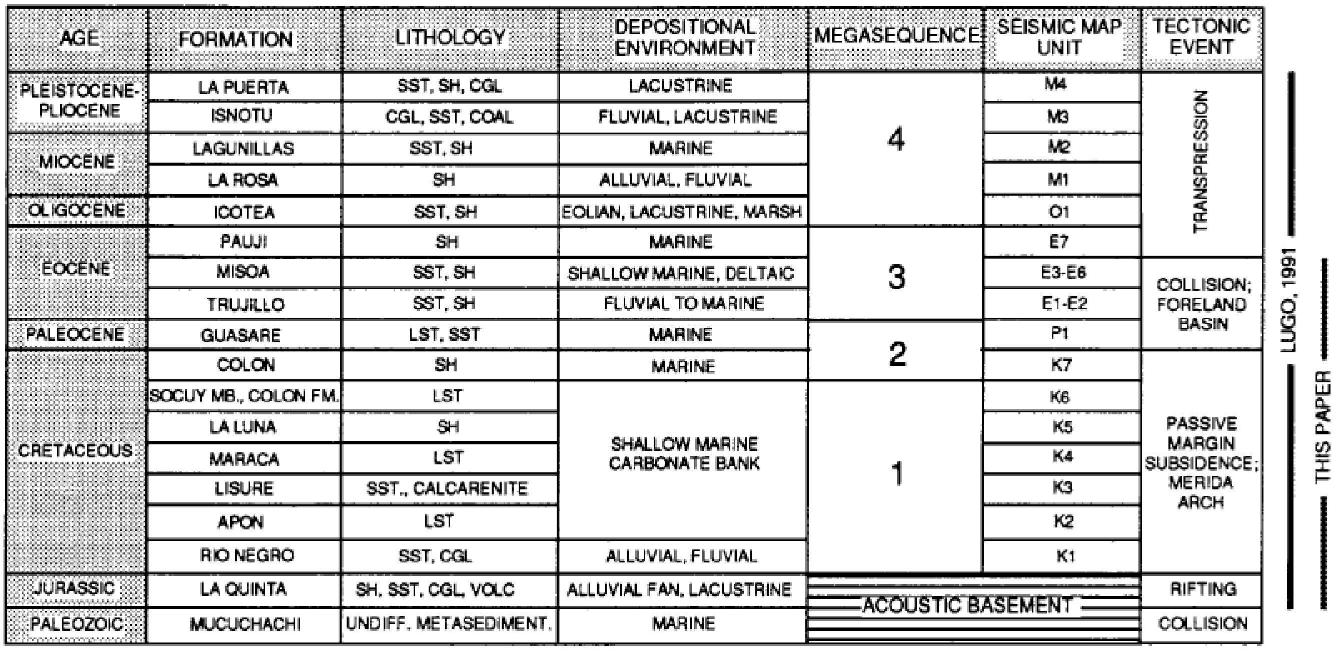


Figure 9: Basin-wide cross-section showing syncline formation following the Oligocene (Mann et al, 2006).



AGE	FORMATION	LITHOLOGY	DEPOSITIONAL ENVIRONMENT	MEGASEQUENCE	SEISMIC MAP UNIT	TECTONIC EVENT
PLEISTOCENE-PLIOCENE	LA PUERTA	SST, SH, CGL	LACUSTRINE	4	M4	TRANSPRESSION
	ISNOTU	CGL, SST, COAL	FLUVIAL, LACUSTRINE		M3	
MIOCENE	LAGUNILLAS	SST, SH	MARINE		M2	
	LA ROSA	SH	ALLUVIAL, FLUVIAL		M1	
OLIGOCENE	ICOTEA	SST, SH	EOLIAN, LACUSTRINE, MARSH		O1	
EOCENE	PAUJI	SH	MARINE	3	E7	
	MISOA	SST, SH	SHALLOW MARINE, DELTAIC		E3-E6	COLLISION; FORELAND BASIN
	TRUJILLO	SST, SH	FLUVIAL TO MARINE		E1-E2	
PALEOCENE	GUASARE	LST, SST	MARINE	2	P1	
CRETACEOUS	COLON	SH	MARINE		K7	PASSIVE MARGIN SUBSIDENCE; MERIDA ARCH
	SOCUY MB., COLON FM.	LST	SHALLOW MARINE CARBONATE BANK	1	K6	
	LA LUNA	SH			K5	
	MARACA	LST			K4	
	LISURE	SST., CALCARENITE			K3	
	APON	LST			K2	
	RIO NEGRO	SST, CGL	ALLUVIAL, FLUVIAL		K1	
JURASSIC	LA QUINTA	SH, SST, CGL, VOLC	ALLUVIAL FAN, LACUSTRINE	ACOUSTIC BASEMENT		RIFTING
PALEOZOIC	MUCUCHACHI	UNDIFF. METASEDIMENT.	MARINE			COLLISION

Figure 10: Generalized stratigraphic outline of the Maracaibo basin (Lugo and Mann, 1995; Lugo, 1991).

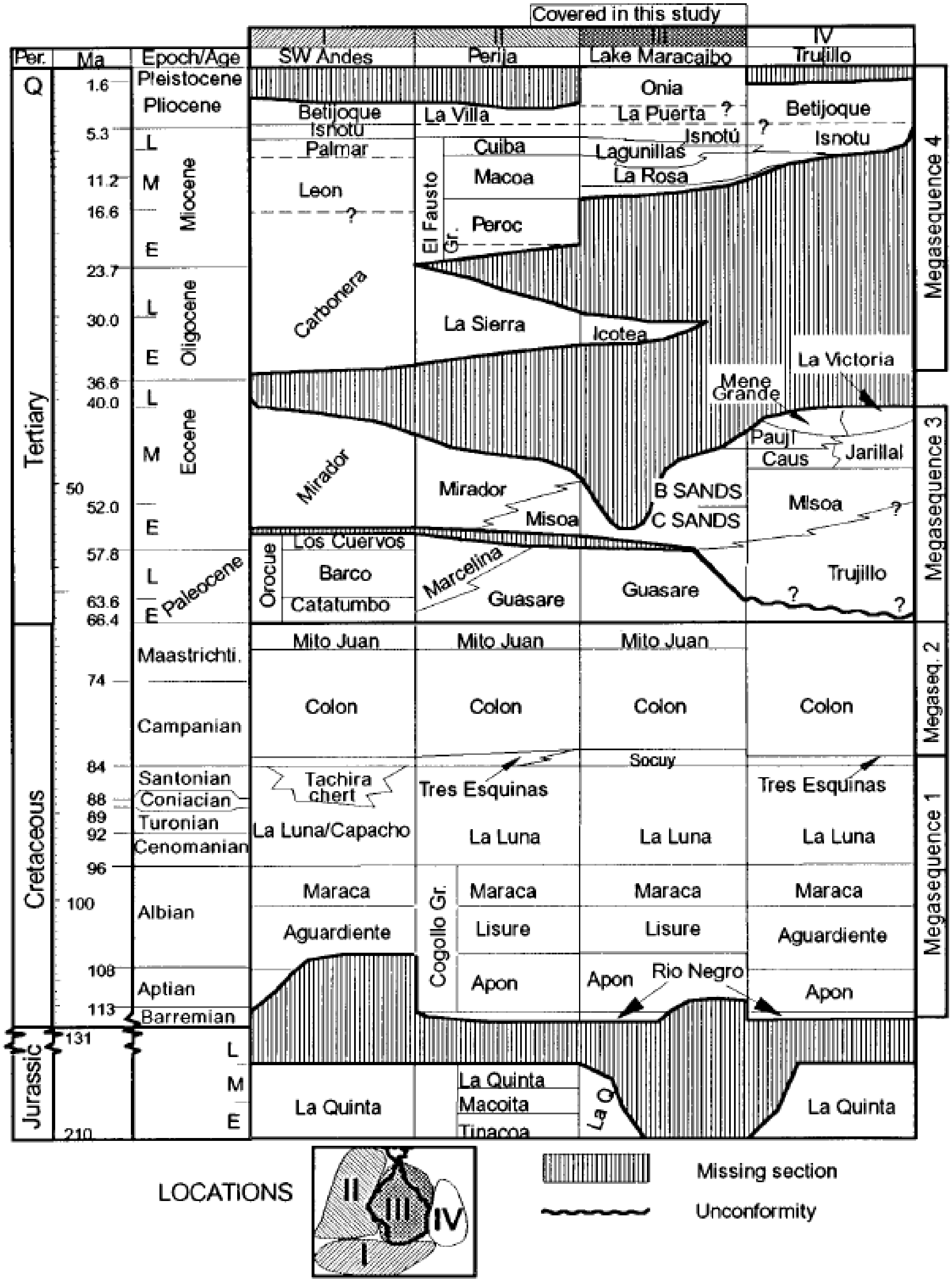


Figure 11: Stratigraphic Column and Geographical Distribution of Maracaibo Basin Formations (Lugo and Mann, 1995). Note localities listed at the top of the column.

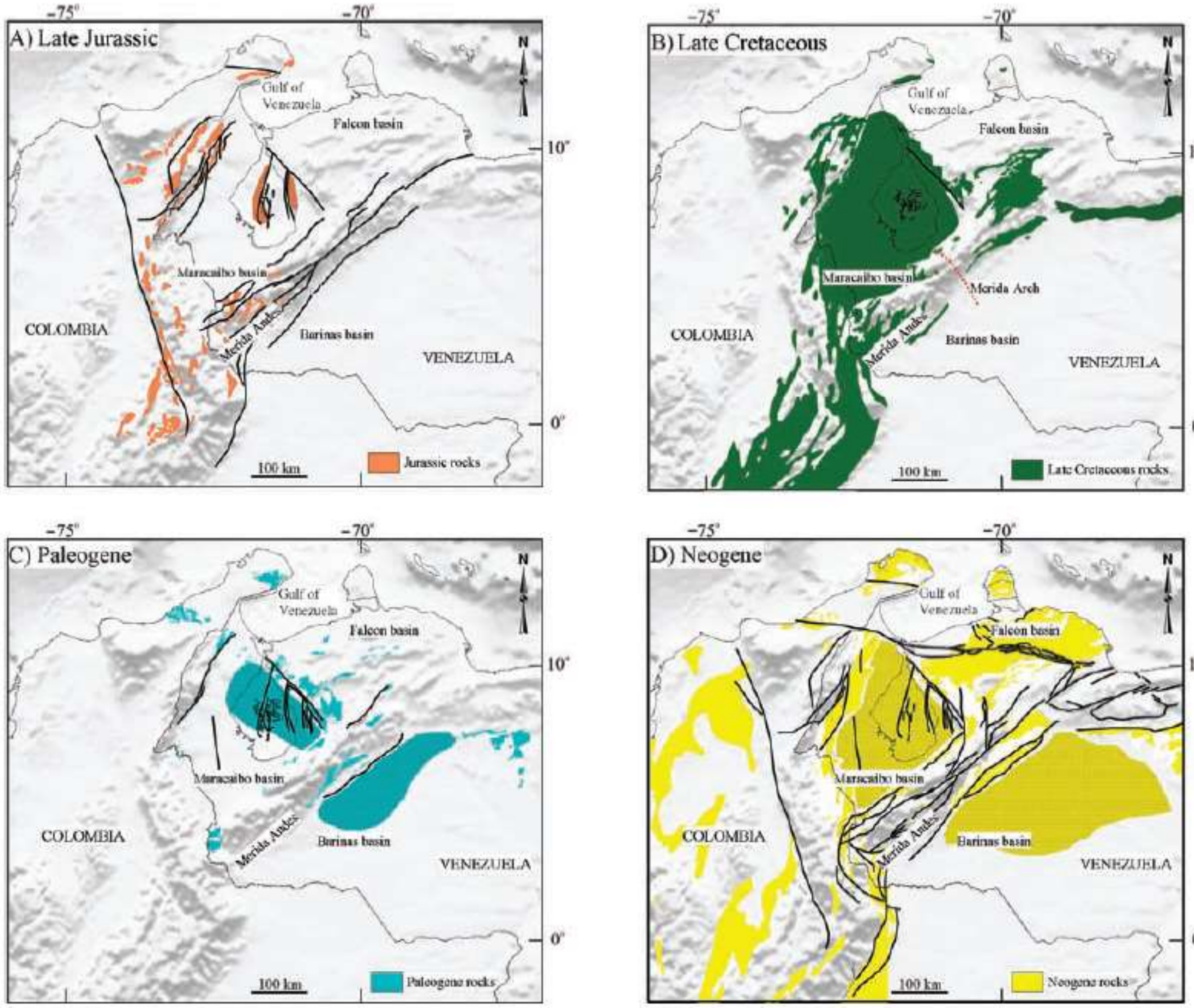


Figure 12: Present day geographical locations of outcrops by age (Mann et al, 2006).

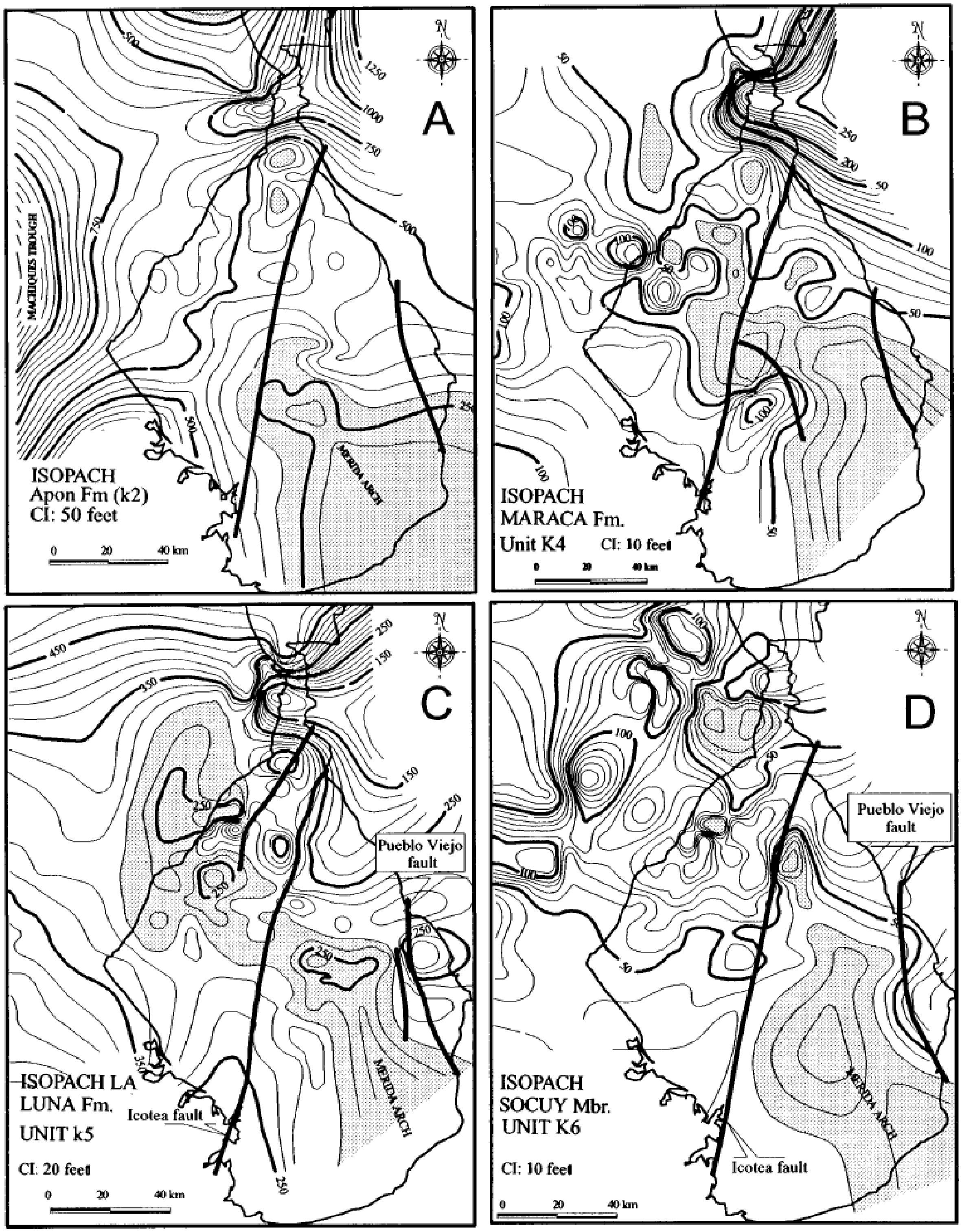


Figure 13: Isopach Maps of various Cretaceous formations (Lugo and Mann, 1995). Note the thinning of units in the gray area above the Meridas arch.

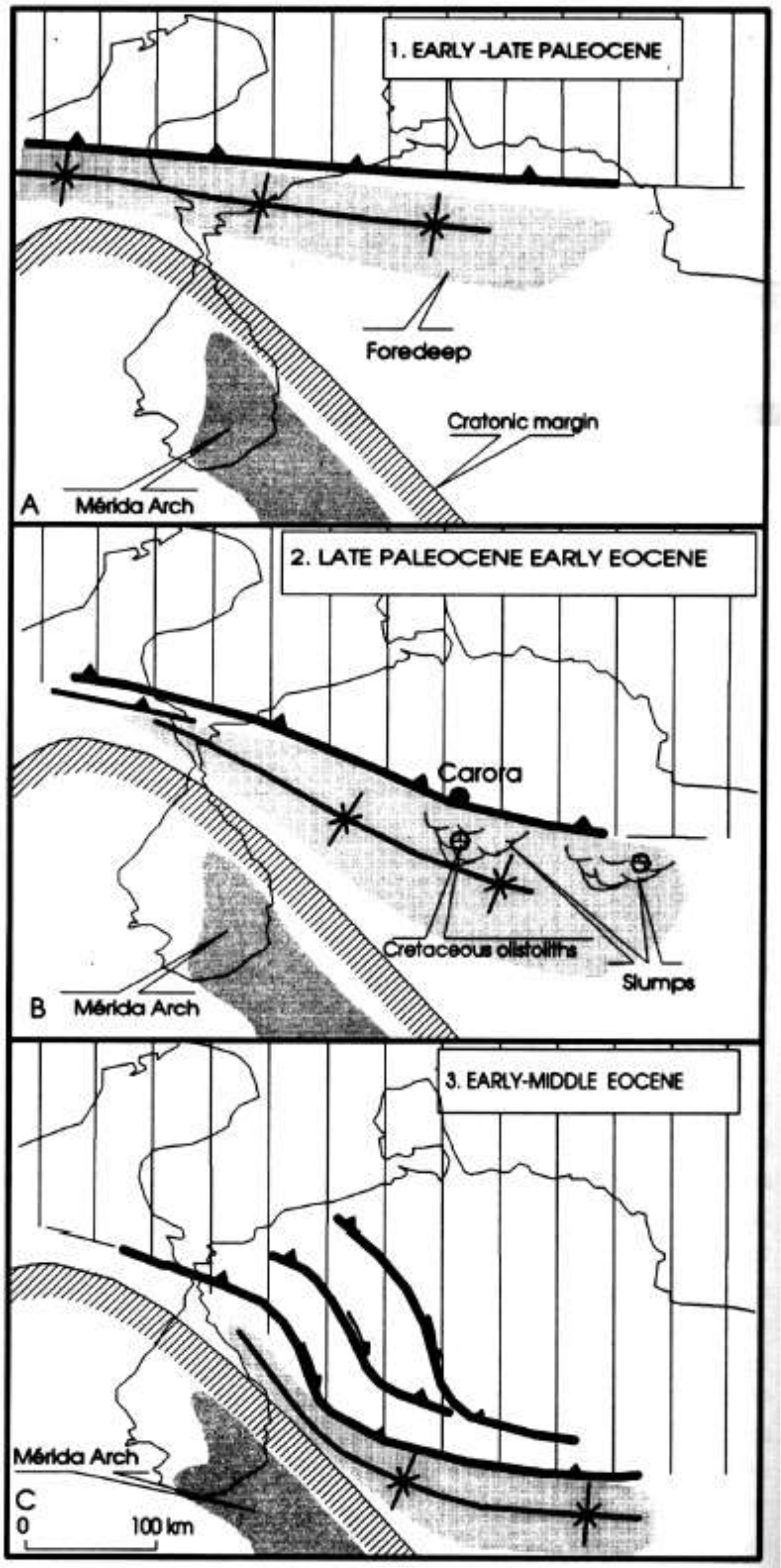


Figure 14: Development of the Paleocene asymmetric foreland thrust belt and clastic wedge (Lugo and Mann, 1995).

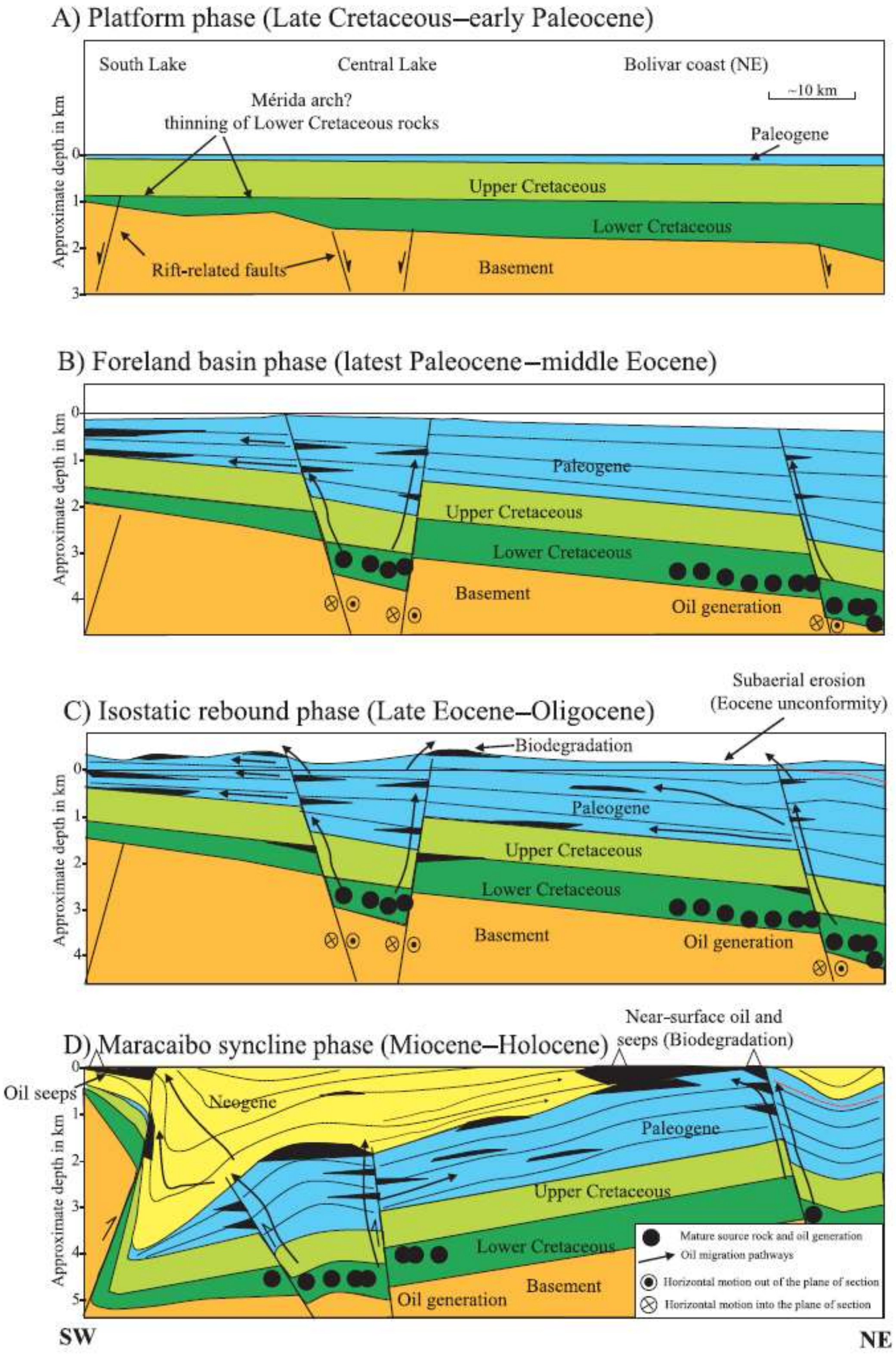


Figure 15: Outline of Hydrocarbon Generation in the Maracaibo Basin (Escalona and Mann, 2006).

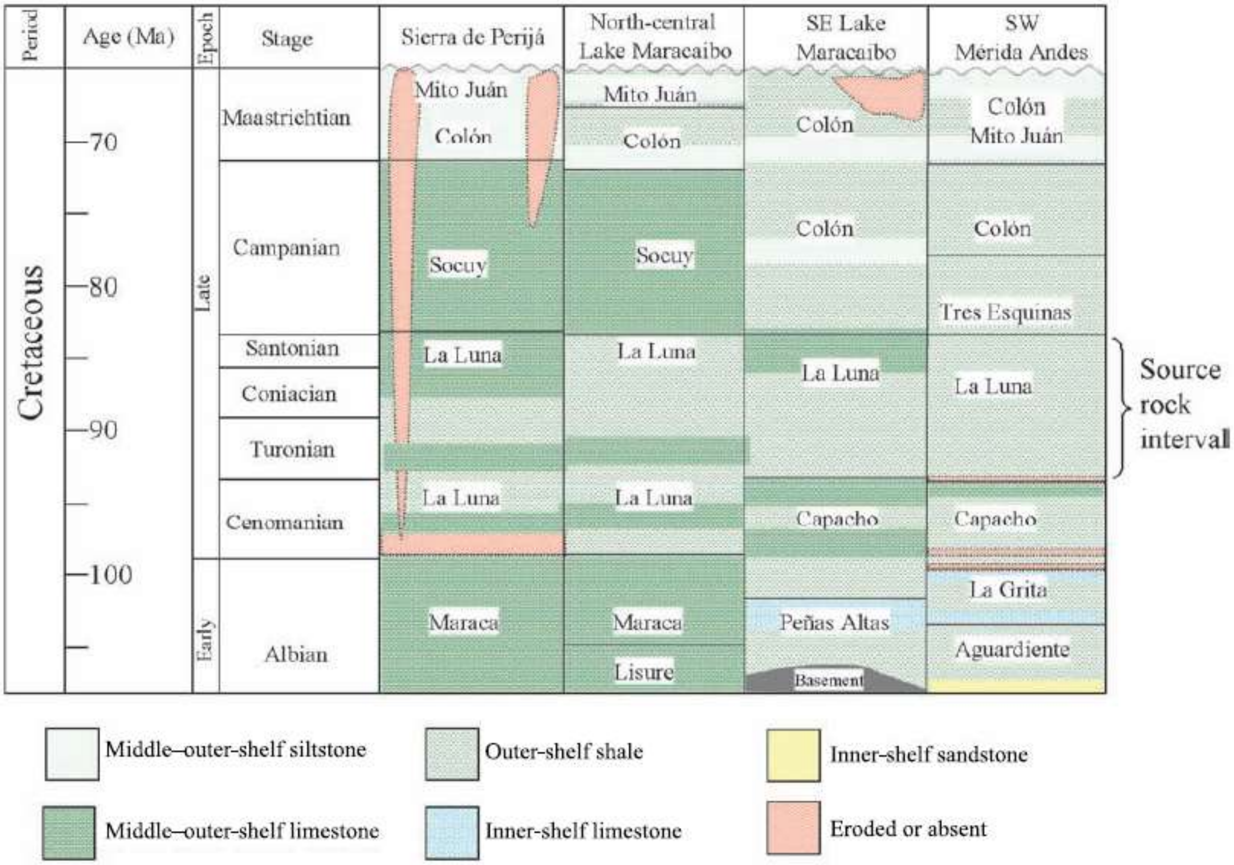


Figure 16: Stratigraphy of the Cretaceous Formations of the Maracaibo Basin (Escalona and Mann, 2006). Note the La Luna source rock of the Late Cretaceous.

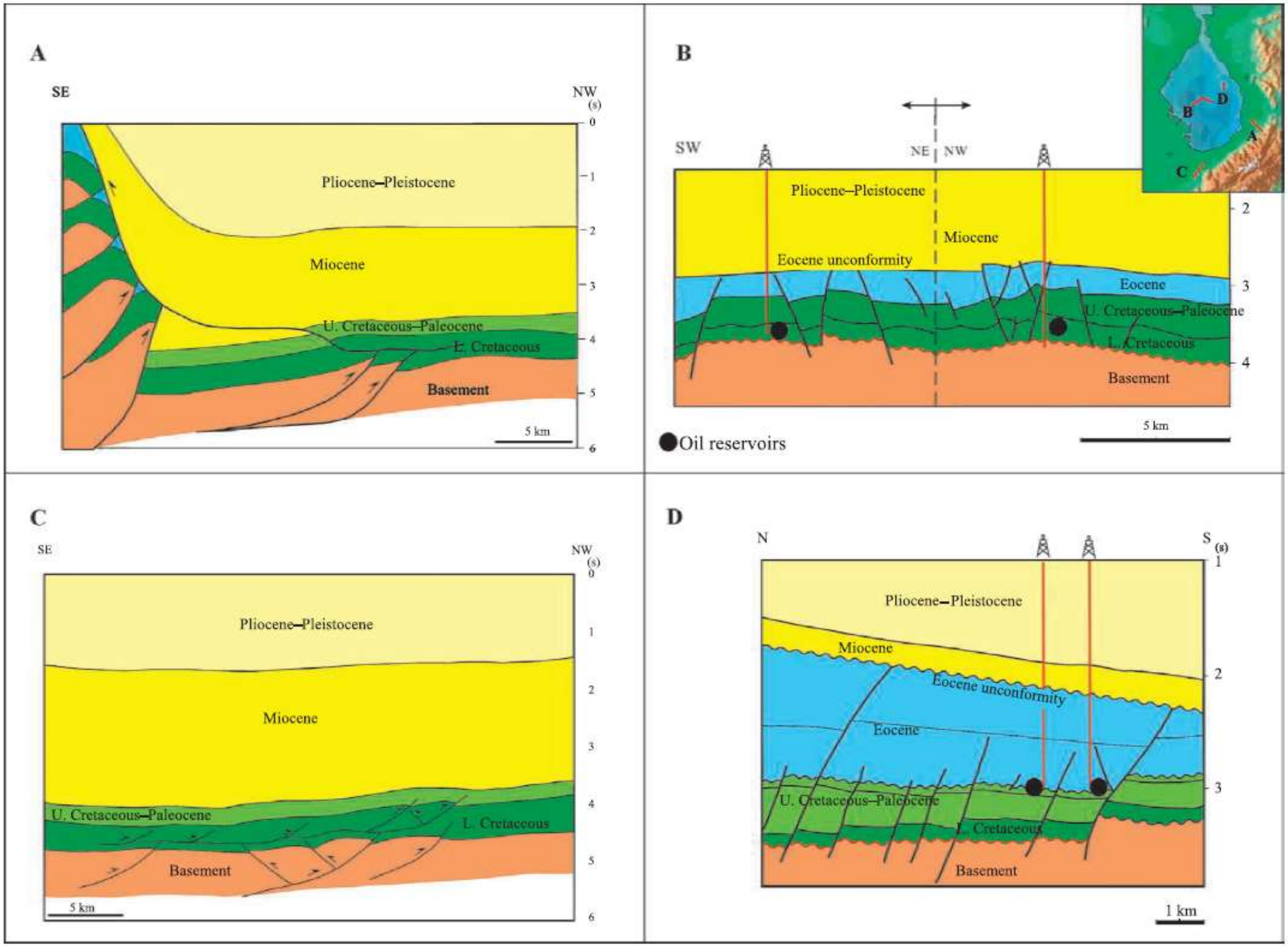


Figure 17: Cretaceous and Paleozoic Reservoirs in Cross-Section (Escalona and Mann, 2006). Black dots indicate reservoirs.

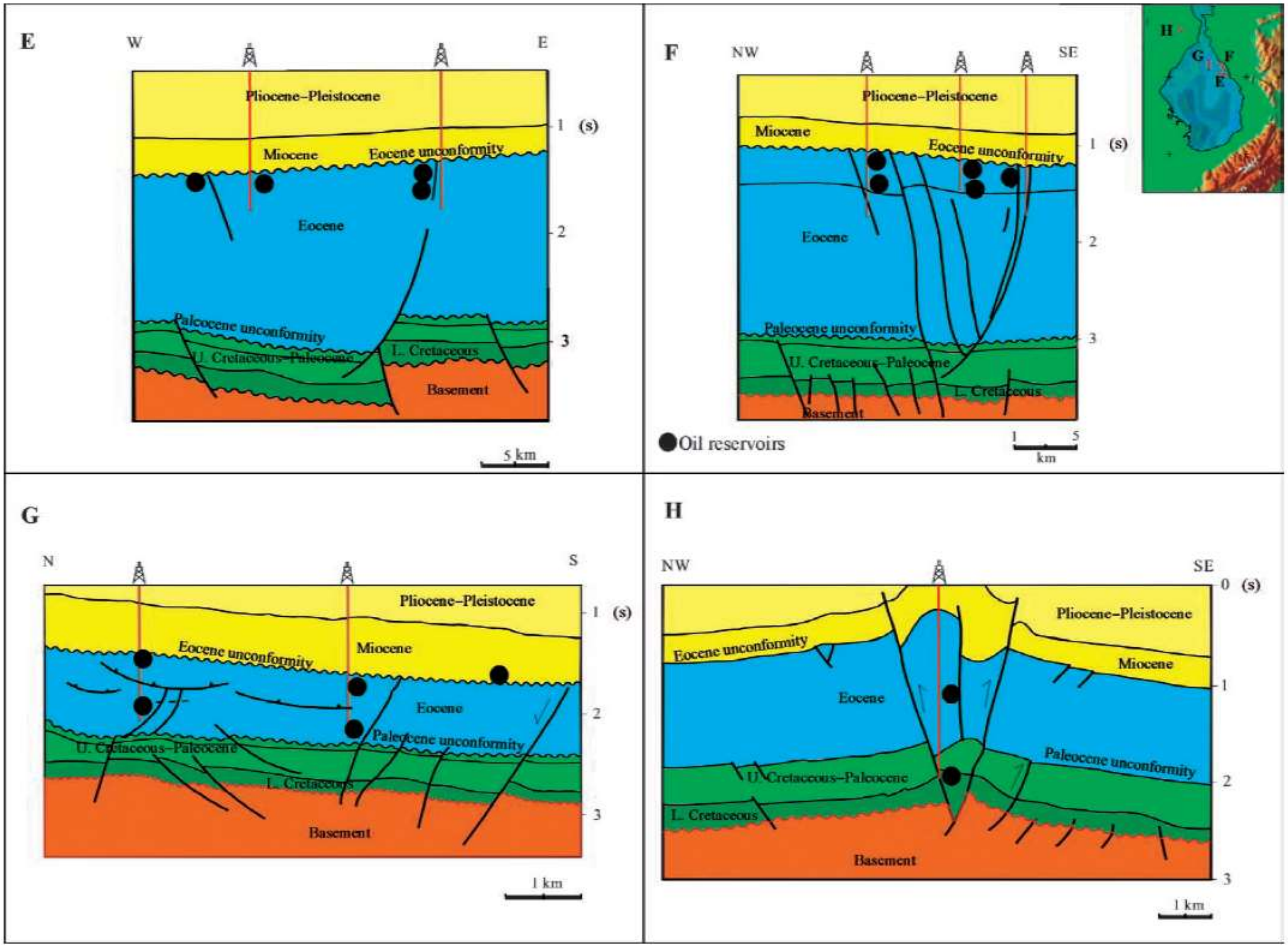


Figure 18: Eocene Reservoirs in Cross-Section (Escalona and Mann, 2006). Black dots indicate reservoirs.

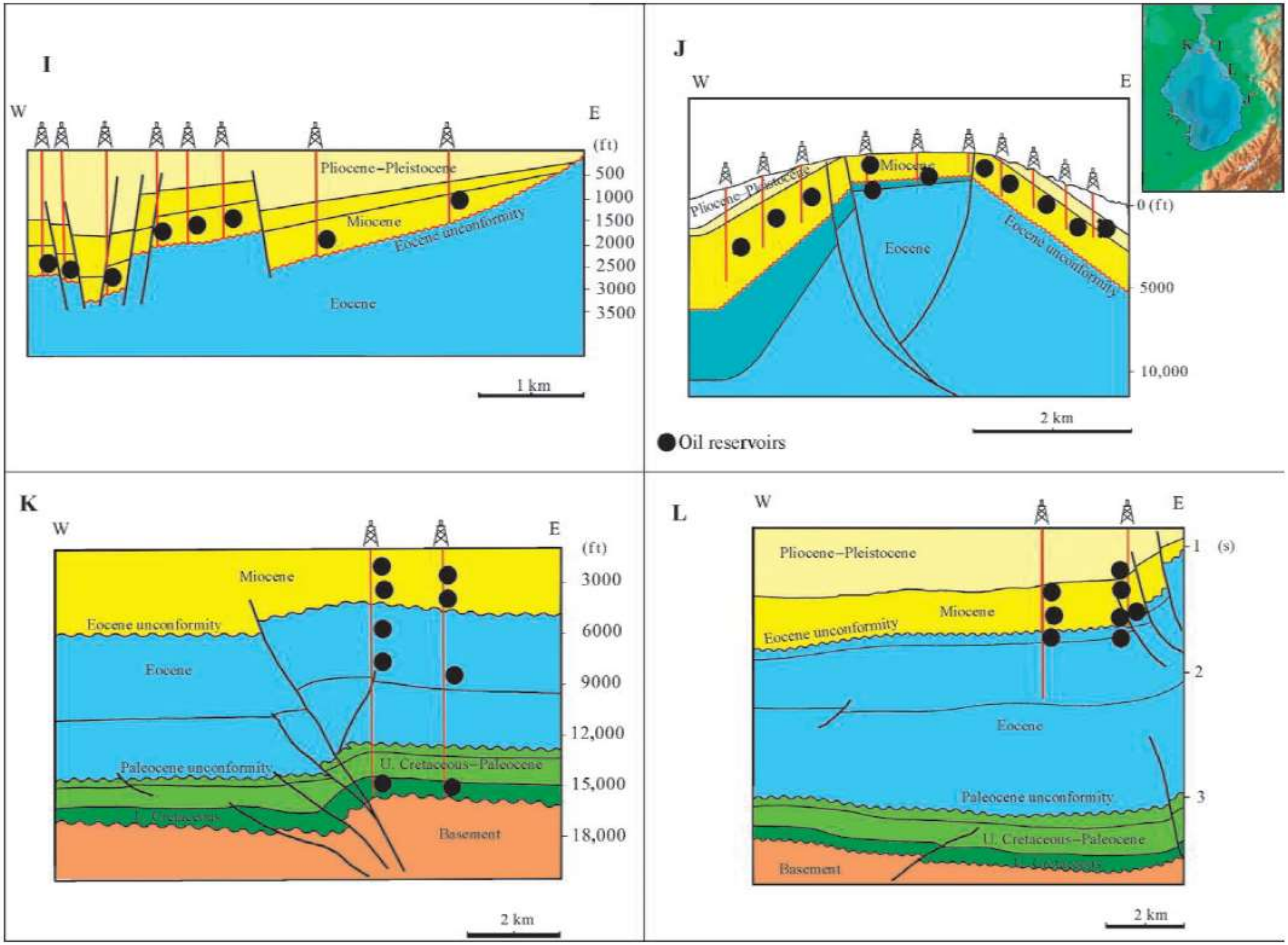


Figure 19: Miocene Reservoirs in Cross-Section (Escalona and Mann, 2006). Black dots indicate reservoirs.

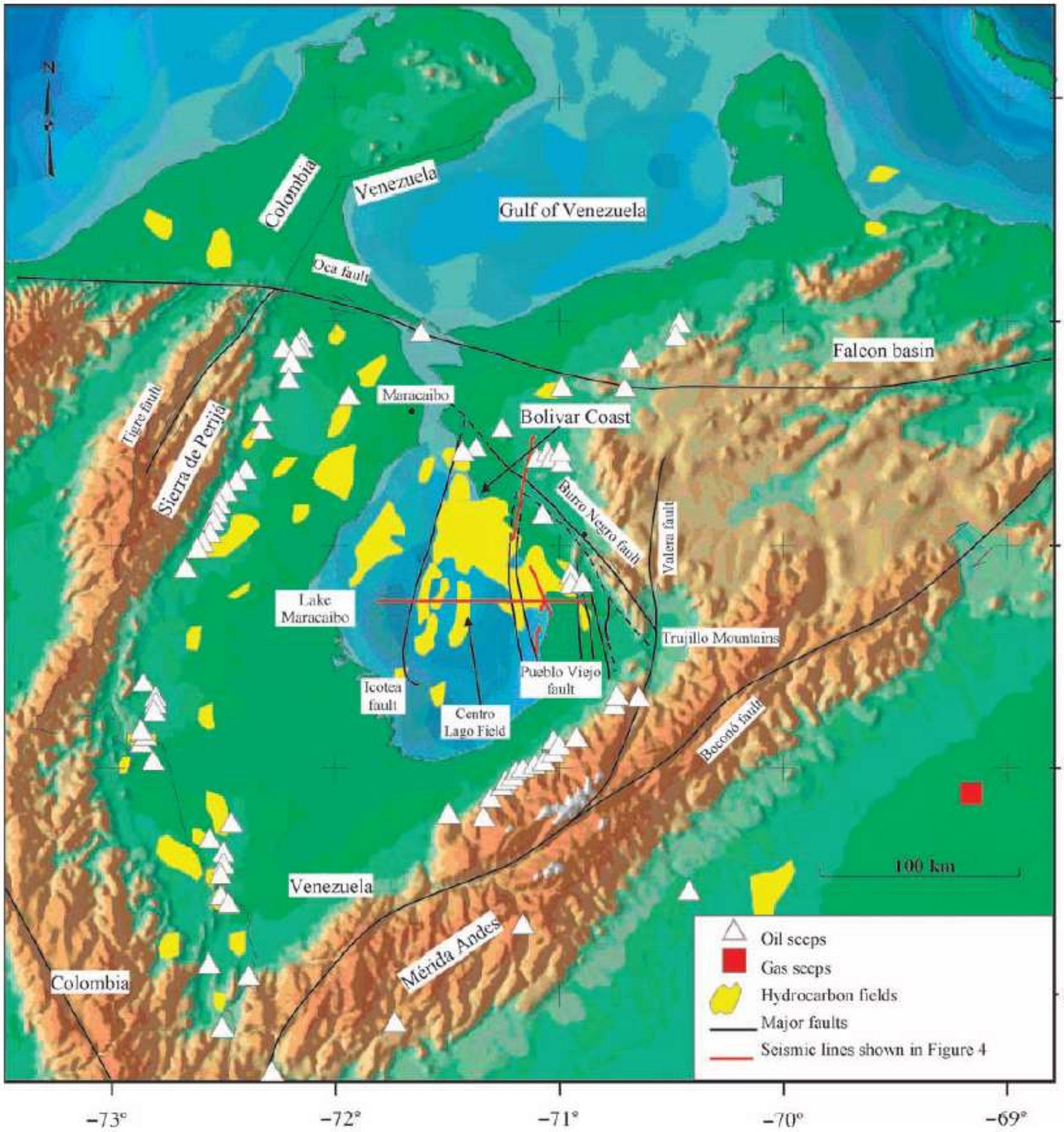


Figure 20: Locations of major oil fields, gas seeps, and oil surface seeps in the Maracaibo basin area (Escalona and Mann, 2006).