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Tectonostratigraphic evolution of the Gulf of Venezuela

by

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Abstract

TECTONOSTRATIGRAPHIC EVOLUTION OF THE GULF OF VENEZUELA

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The University of Stavanger, 2018

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The Gulf of Venezuela is located at the boundary between the Cretaceous-Cenozoic deformation zone of the South American and Caribbean plates. It is an underexplored area lying between the hydrocarbon-rich Maracaibo Basin and the emergent plays such as the Perla field (Late Oligocene to Early Miocene carbonates) located on the allochthonous terrane. Gravity data, stratigraphy, structural styles, and subsidence plots reveal three main basement provinces in the Gulf of Venezuela: (1) A western Paleozoic basement (Maracaibo province) with continental-affinity similar to those in the Guajira Peninsula and the Maracaibo Basin; (2) a central province covering the area of the Urumaco trough offshore with Meso-Neoproterozoic rocks (Urumaco province); and (3) an easternmost province, with Cretaceous Caribbean arc rocks, related to the Leeward Antilles island arc system (Caribbean province).

Two major interpreted strike-slip faults define the boundary between the main provinces. The Cuiza-Río Seco fault is the western flank of the Urumaco trough offshore and represents a structural and stratigraphic abrupt change that is proposed as the boundary between the Maracaibo autochthonous province and the allochthonous provinces. The Pueblo Nuevo fault is proposed to be the continuation onland of a major interpreted strike-slip fault, defining the boundary between the central and easternmost province. In addition, the Cuiza-Río Seco and Pueblo Nuevo faults accommodate strain

partitioning as well as the Oca- Ancón fault but at different timing, due to oblique compression of the Caribbean plate against the South American plate.

Furthermore, a pop-up structure associated with the Sierra de Perijá is recognized in the southernmost Maracaibo province, allowing to define about ~70-80 km of right-lateral strike-slip displacement along the Oca fault. This fault has a relevant role to the present-day basement configuration, since it has displaced eastwards and segmented the northern part of the basement provinces, resulting in a more complex distribution that needs to be considered to reconstruct the geologic history.

Considering the continuation of the Maracaibo block northwards, this region might hold promising opportunities for hydrocarbons exploration, where the Maracaibo Basin petroleum system might extends offshore into the Gulf of Venezuela.

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1. INTRODUCTION.

Western Venezuela consists of a complex geological deformation zone as result of the Cretaceous–Cenozoic interactions between the Caribbean and the South American plates. In this regard, the Gulf of Venezuela, located in the northwestern most region, represents an important area to understand the uncertain boundary between the hydrocarbon-rich Maracaibo Basin and the gas prone Cenozoic Caribbean-related basins (**¡Error! No se encuentra el origen de la referencia..1**). In 2009, a large giant gas field, the Perla field carbonates (17 TCF of non-associated gas) was discovered, verifying a new play concept of the unknown Cenozoic thermogenic petroleum system (Castillo et al, 2017).

The Gulf of Venezuela comprise different accreted terranes controlled by diachronous Cretaceous to Recent west-to-east collision. Therefore, the boundaries between these provinces are difficult to constrain and are poorly defined. Three main basement provinces have been previously identified: (a) the Paleozoic with continental affinity identified in the Guajira Peninsula and Maracaibo Basin; (b) the northwestern Falcón region with Cretaceous metamorphic rocks; and (c) the Cretaceous Caribbean arc, which is related to the Leeward Antilles arc system (Gorney, 2007). In addition, recent studies based on age dating recognized an allochthonous Meso-Neoproterozoic terrane with continental-affinity at both, La Vela bay and the Falcón Basin, named as Falcónia (Grande, 2013a,b; Baquero, 2015).

Some interpretations and analysis of seismic data have been performed in previous works along this area. A Paleozoic folded belt, continental Jurassic beds (autochthonous) in the western region, and a Mesozoic basement (allochthonous) to the east are proposed (Castillo et al., 2017) with the Urumaco trough as a part of the autochthonous block (Figure 1.2). In contrast, Blanco, (2017) interpreted both, the autochthonous Jurassic basement and the allochthonous Neoproterozoic basement towards the west of the Urumaco trough, while an allochthonous Permian basement towards the east (Figure 1.2).

A ~40 km-wide transition zone is observed on-offshore seismic data. The zone correspond to the Urumaco trough that separates two main tectonic terranes. That condition controls the development of two well-differentiated petroleum systems. First, the allochthonous terrane to the east, characterized mostly by Tertiary terrigenous sediments and carbonate banks and a Cenozoic source rock (Maceralli, 1995), and second, an autochthonous terrane to the west, with

age sediments ranging from Cretaceous to Recent which include a Cretaceous source rock (La Luna Formation) (Escalona and Mann, 2011; Escalona and Yang, 2013; Castillo et al. 2017).

In addition, the right-lateral strike-slip displacement along the Oca fault may have played a relevant role to the Present-day basement configuration. It has displaced at least 80 to 90 km eastward (Kellogg, 1984; Pindell et al., 1998; Escalona and Norton, 2015) and segmented the northern part of the basement provinces, resulting in a more complex distribution that needs to be considered to reconstruct the geological history (Gorney et al., 2007; Escalona and Mann, 2011).

Arguments supporting this configuration include the possible northern extension of the Burro Negro fault zone, which is proposed to be one of the flanks of the Urumaco trough and as far north as the Cuiza fault (Gorney, et al. 2007). This system is suggested as a single aligned fault system prior to the Oca-Ancón strike-slip displacement based on plate tectonics models (Escalona and Norton, 2015). Consequently, the Sierra the Perijá and its characteristic triangle zones (Duerto et al., 2006) and other related structures (e.g. Urdaneta or Icotea faults) in the Maracaibo Basin might have an expression northwards in the Gulf of Venezuela.

These assumptions open up promising exploration opportunities to those plays found in the northwestern corner of the Maracaibo Basin, such as La Paz (fractured basement and Cretaceous reservoirs), Mara and La Concepción (Fractured Cretaceous), and Boscán (Oligocene clastics), within the westernmost part of the Gulf of Venezuela (Escalona and Mann et al., 2006).

1.1. Objectives.

The main purpose of this research is to provide an overview of the Gulf of Venezuela tectono-stratigraphic evolution of, in order to analyze its geological relationship with its neighboring provinces, based on two-dimensional seismic and well data.

This aim will be accomplished by fulfilling the following secondary objectives:

- To study the deformation and depositional framework of the different tectono-sequences defined.
- To improve the paleogeographic knowledge of the study area.

- To analyze the role of the right-lateral strike-slip fault systems, that lead to a complex basement configuration in the region.

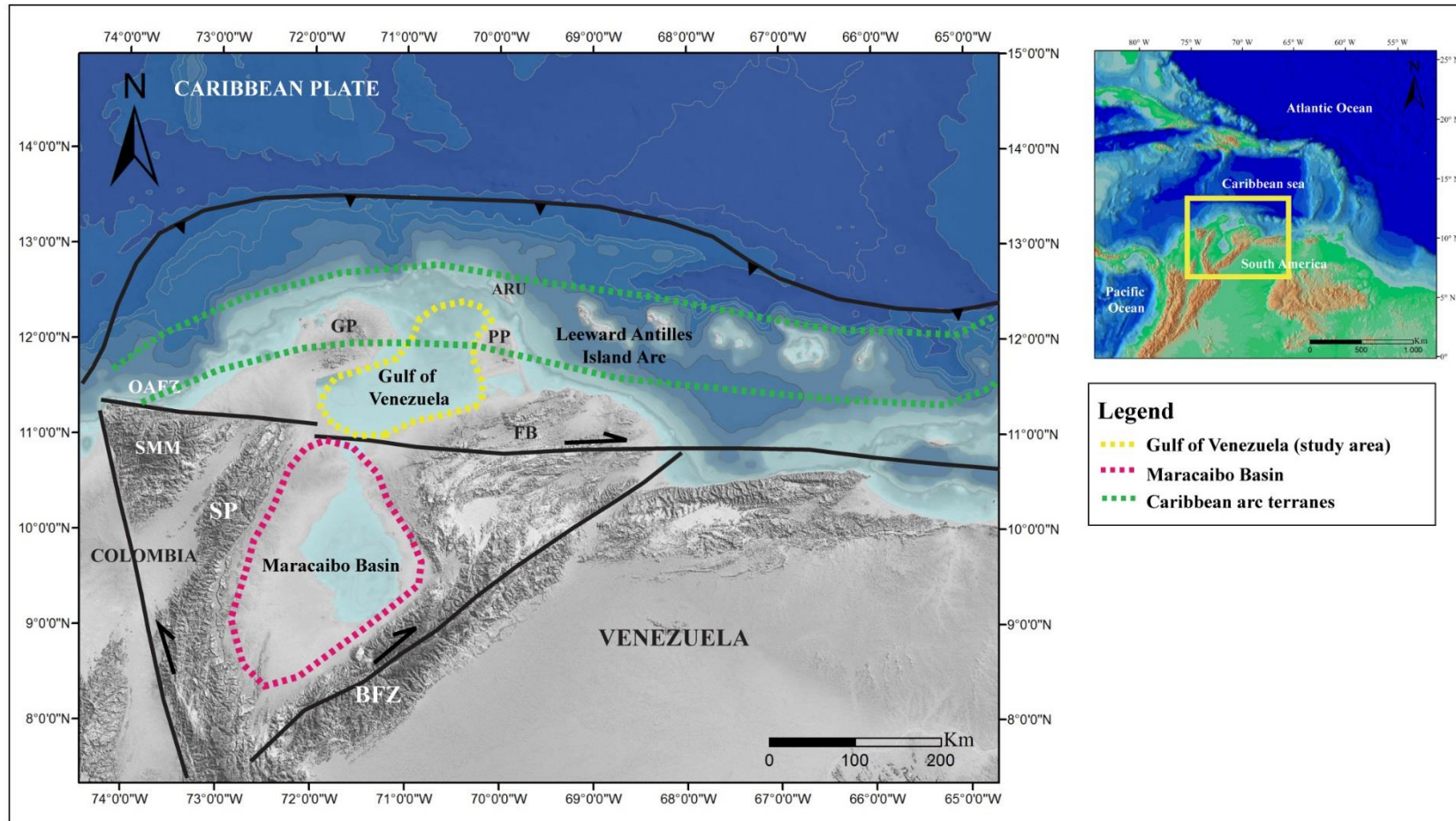


Figure 1.1. Map showing the location of the study area and the main neighboring terranes. Pink dashed lines indicate the location of the Maracaibo Basin. Yellow dashed lines indicate the location of the Gulf of Venezuela. Green dashed lines indicate the location of the Caribbean arc.

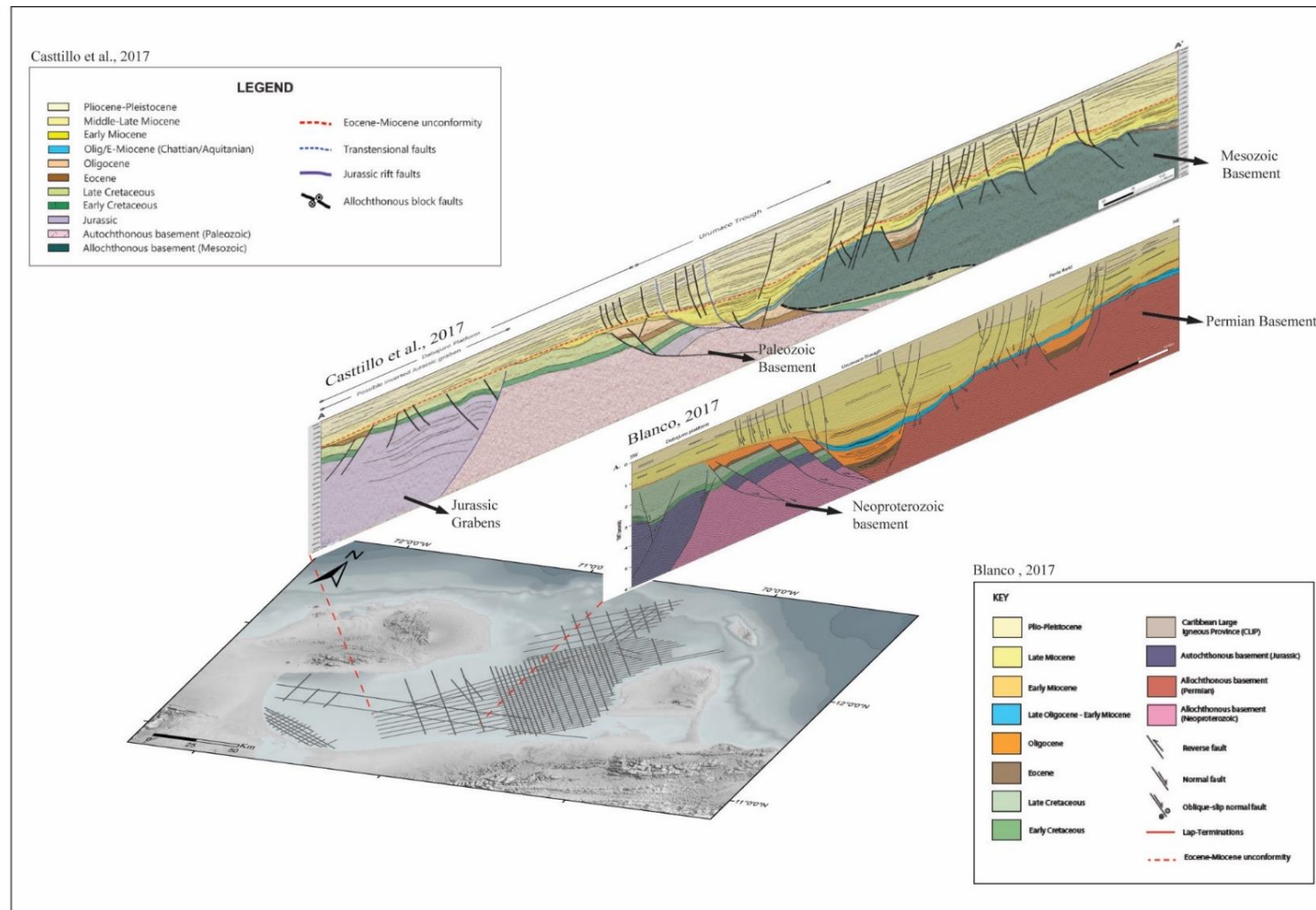


Figure 1.2. Diagram showing two NE-SW seismic lines interpreted by previous authors. Different ages for the basement in the same province have been established. Seismic lines were taken from Castillo et al. (2017) and Blanco (2017).

2. GEOLOGICAL SETTING.

2.1. Present tectonic setting of the study area.

The Caribbean plate evolution has been a controversial topic for many years. At present, there is a large agreement on its Cretaceous origin as a thick basaltic oceanic plateau in the Pacific Ocean and later it has drifted relatively northeastward towards its present location between the Americas (Pindell and Dewey, 1982, Pindell and Barret, 1999, Escalona and Mann, 2011). It reached the northwestern South America by Late Paleocene subducting the oceanic crust of the Proto-Caribbean (Pindell, 2005). GPS-geodetic information indicates a progressive eastward displacement at the present day of the Caribbean at a rate of 20 mm/year whose boundaries are strongly controlled by this regional plate motions (Perez et al., 2001; Weber et al., 2001; Trenkamp et al., 1995). The result of this progressive and continue collision of the Caribbean and South America plates is a complex geometry with 100 km wide zone of diffuse deformation that can be observed today. The Caribbean region might be divided in different tectonic provinces: (1) Venezuela Basin; (2) Aves ridge–Leeward Antilles Ridge; (3) Grenada–Bonaire–Falcón basins; (4) Lesser Antilles–Cordillera de La Costa; (5) Tobago–Carupano basins; (6) Barbados accretionary prism–Eastern Venezuela–Maracaibo foreland basins (Escalona and Mann, 2011) (Figure 2.1).

On the other hand, the Gulf of Venezuela is an underexplored area that records important geological evidence of the tectonic interactions between the Caribbean and South American plates. It has been proposed to be part of two main tectonic provinces, with different characteristics and origin: an autochthonous terrane associated with Maracaibo Basin and allochthonous terrane associated with the Caribbean (Gorney et al., 2017).

2.2. Basement provinces.

The different basement provinces present in the Gulf of Venezuela is an important aspect of the subsurface geology in order to understand the petroleum systems developed in this region. Some authors have considered that the Late Cretaceous source rocks and the most prolific hydrocarbon basins in northern South America overlie the South American continental crust, whereas the less-prolific hydrocarbon basins overlie the crust of the Great Arc of the Caribbean (GAC) in Venezuelan coastal areas or in the offshore islands (Gorney et al., 2007; Escalona and Mann, 2011). There has been a substantial debate about the exact location of the GAC and South America plate boundary and this uncertainty remains to the date.

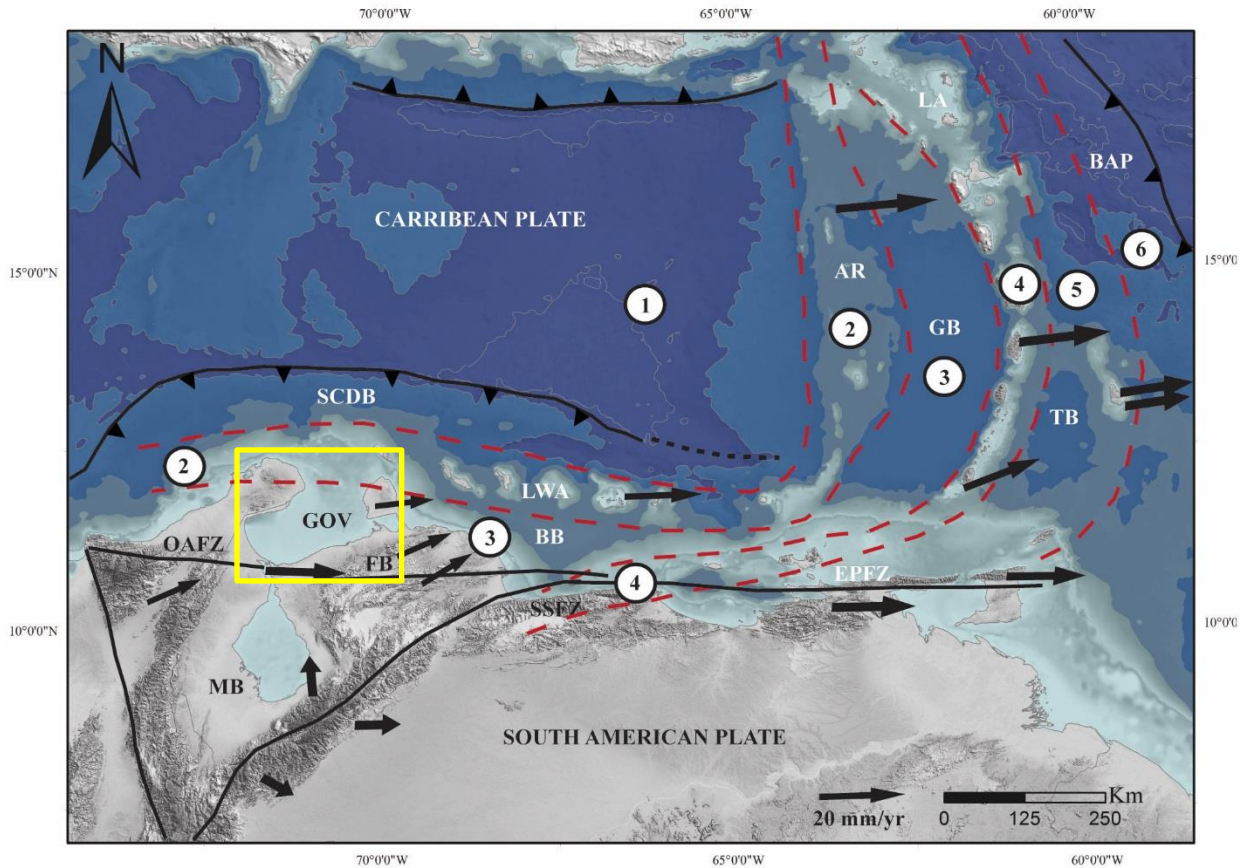


Figure 2.1. Regional map showing major faults and tectonic provinces (represented by numbers); GPS measurements (black arrows) and the area of study (yellow box) are also observed (Perez et al., 2001; Weber et al., 2001; Trenkamp et al., 2002). Numbered label for the tectonic provinces as follows: 1: Venezuela Basin; 2: Aves ridge–Leeward Antilles Ridge; 3: Grenada–Bonaire–Falcón Basins; 4: Lesser Antilles–Cordillera de La Costa; 5: Tobago–Carupano basins; 6: Barbados accretionary prism–Eastern Venezuela–Maracaibo foreland basins (modified from Gorney et al., 2007; Escalona and Mann, 2011). Abbreviations: AR: Aves Ridge; BAP: Barbados accretionary prism, BB: Bonaire Basin, FB: Falcón Basin, GB: Grenada Basin, GOV: Gulf of Venezuela, LWA: Leeward Antilles ridge, EPFZ: El Pilar fault zone, MB: Maracaibo Basin, OAFZ: Oca- Ancón fault zone, SSFZ: San Sebastian fault zone, TB: Tobago Basin, SCDB: South Caribbean Deformed Belt.

Previous works have identified three main basement provinces in the study area based mainly on well data and outcrops dating (Gorney et al., 2007): (1) Paleozoic with continental-affinity revealed in the Guajira Peninsula and the Maracaibo Basin (Feo-Codecido (1984); (2) the northwestern Falcón with Cretaceous metamorphic continental intra-arc rocks, revealed in wells onshore Falcón and La Vela bay (Gonzalez de Juana et al. 1980; Feo Codecido, 1984; Macerralli, 1995); and the Cretaceous Caribbean arc that is related to the Leeward Antilles arc system, recognized in wells drilled in Aruba (Curet, 1992) (Figure 2.2a).

On the other hand, high-grade metamorphic rocks were recognized in the Falcón Basin and La Vela bay terranes with Putumayo/Grenvillian continental-affinity, reporting a Meso-

Neoproterozoic age, named after as the Falcónia terrane (Grande and Urbani, 2009; Grande, 2013a, b). Recent studies based on zircon age dating and provenance, confirmed these Meso-Neoproterozoic metamorphic rocks located in the Falcón Basin and La Vela bay (Figure 2.2b) (Baquero et al., 2015). Therefore, this allochthonous basement in this region is not related with either the Amazonia craton or the Cretaceous oceanic Caribbean terranes (Grande and Urbani, 2009; Grande, 2013a,b; Baquero et al., 2015). These evidences suggest a Putumayo orogeny (Ibanez and Mejias, 2011), where the northern boundary of the Amazonia craton collides with the passive margin of the Baltic crust, associated with the assembly of the supercontinent Rodinia. During the Caribbean oblique collision, these Putumayo fragments were accreted into the northwestern continental margin of South America from the Colombia–Guajira Peninsula to the eastern Falcón forming the Falcónia terrane (Baquero, 2015) (Figure 2.2b)

In addition, another continental allochthonous basement with Permian age (U-Pb dating) was identified in the L-well located in the Gulf of Venezuela (Baquero et al., 2015).

Several authors have integrated gravity, magnetic, seismic reflection, surface geology, and dated basement rocks to define the suture between the GAC and South America. Vence, (2008) proposed a 280-km-long western extension of the GAC along the continental margin of Colombia. In contrast, a boundary located north of the Chimare suture through a right-lateral strike-slip fault with a strong vertical component is proposed by Londoño et al. (2015). In addition, Blanco et al., (2015) propose a new location for the suture, which coincide with the Pueblo Nuevo fault previously interpreted in the Paraguaná Peninsula (Figure 2.3).

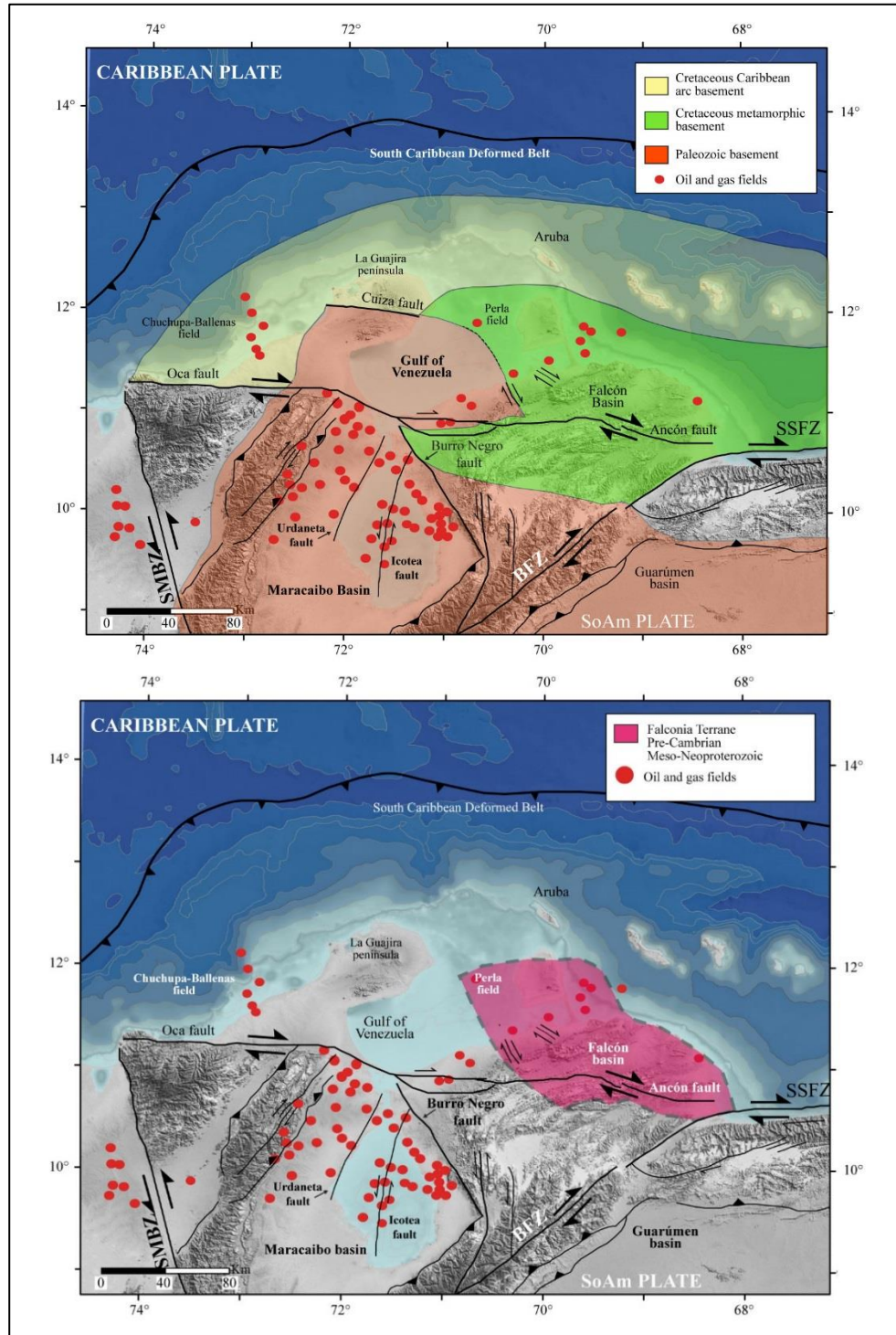


Figure 2.2. Maps showing different provinces proposed in the study area. (Top) Three main provinces observed: Paleozoic with continental-affinity identified in the Guajira Peninsula and Maracaibo Basin; the northwestern Falcón region with Cretaceous metamorphic rocks; and the Cretaceous Caribbean arc, which is related to the Leeward Antilles arc system (Gorney et al., 2007). (Bottom) Pre-Cambrian terrane in La Vela bay and Falcón Basin with continental-affinity, named as Falcónia (Grande, 2013a,b; Baquero, 2015; Baquero et al. 2015).

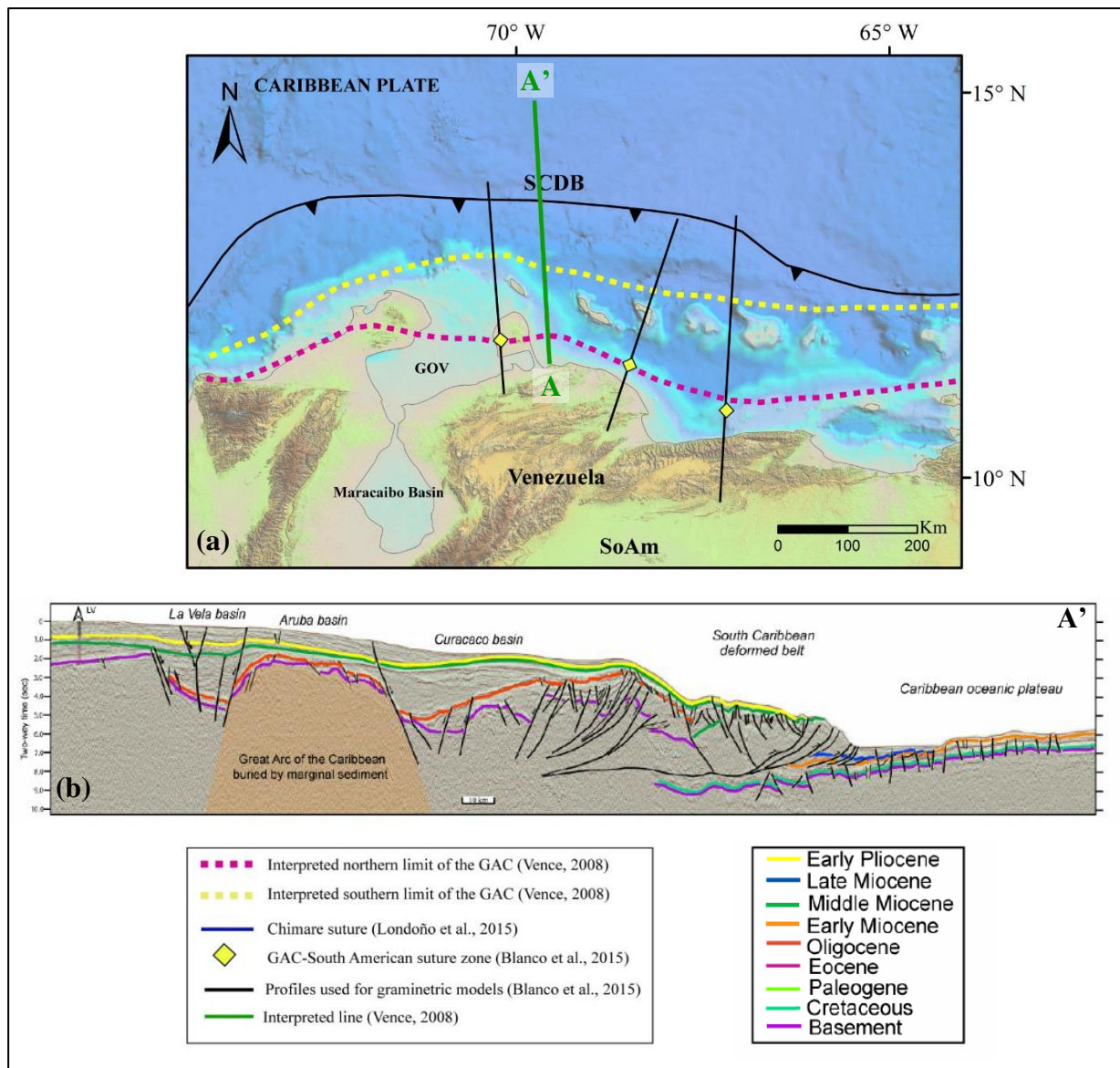


Figure 2.3. (a) Map showing different boundaries proposed for the Great Arc of the Caribbean (GAC). Location of the interpreted seismic line is also showing (green line) (Vence, 2008; Londoño, 2015). (b) Seismic line N-S interpreted (Vence, 2008). Yellow rhombus defined the suture zone proposed by Blanco et al., (2015). Abbreviations: SCDB: South Caribbean Deformed Belt; SoAm: South Caribbean Deformed Belt; GOV: Gulf of Venezuela.

2.3. Active tectonic in the Gulf of Venezuela.

Western Venezuela has a very complex geodynamic setting involving South America and Caribbean plates and the interaction of these major plates with several crustal blocks or microplates (Audemard, 1993).

The major active strike-slip faults in this convergence margin are Oca–Ancón, Boconó, San Sebastián, and El Pilar, from the southernmost region of the Mérida Andes until the Trinidad

Island (Figure 2.1). The main evidence of the active tectonics involved some earthquakes in the Gulf of Venezuela, generated by different fault ruptures process reported in the region and confirmed by focal mechanism solutions (Figure 2.4). The Oca-Ancón fault is the most important right-lateral strike-slip fault system in the study area, extended from Colombia to the southeastern most part of Gulf of Venezuela and the Falcón Basin. In addition, the important Cuiza fault interpreted in the Guajira Peninsula might represent a continuation of the fault observed onland in the Falcón Basin named as Río Seco (Audemard, 2001).

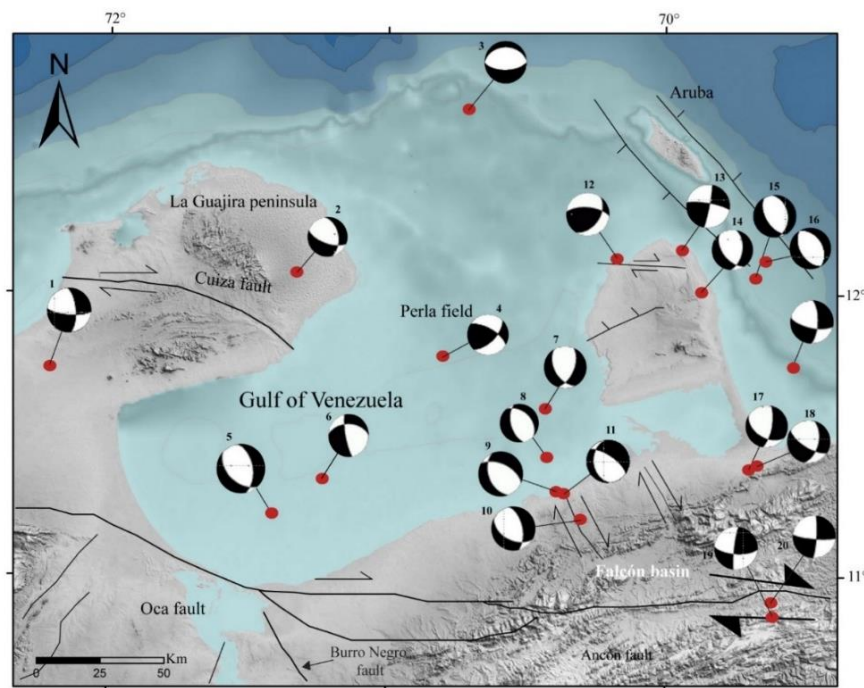


Figure 2.4. Focal mechanism solutions in the study area, indicating active tectonics and a complex configuration represented by different movements (after the Venezuelan Foundation for Seismological Research seismicity catalog).

Strike-slips offsets of both faults have been calculated (Table 1.1) by some authors that were summarized by Blanco (2017). Feo-Codecido (1971) and Tschanz et al. (1974) worked with well correlations and outcrop information from the Santa Marta Massif, while Kellogg (1984) restored Oligocene isopachs. Escalona and Norton (2015) made plates tectonic reconstructions of the Caribbean region, while Blanco (2017) used structural restoration of regional maps of magnetic data. For the Cuiza fault zone, Gomez (2001) used offshore seismic data to infer its offset, while Alberding (1957) showed displacements of rock units in map view. Alvarez (1967, 1971) calculated its offsets from regional structural trends in eastern Colombia.

Table 1.1. Different displacements calculated for the Oca and Cuiza faults from different authors and methods (modified from Blanco et al., 2017).

Fault	Author	Displacement
Oca	Feo-Codecido, 1972	15-20 km (9-12 mi)
Oca	Tschanz et al., 1974	50-60 km (31-37 mi)
Oca	Kellogg, 1984	90-100 km (55-62 mi)
Oca	Pindell, 1998	90 km (55 mi)
Oca	Escalona and Norton, 2015	70-90 km (55-70 mi)
Oca	Blanco, 2017	50-78 km (31-48 mi)
Cuiza	Alberding, 1957; Alvarez, 1967; Alvarez, 1971	15-25 km (9-15 mi)
Cuiza	Gomez, 2001	5-15 km (3-9 mi)

Different ages have been proposed for the initial displacement of the Oca fault. Kellogg (1984) proposed that the Oca-Ancón fault activity started during Middle to Late Oligocene. In contrast, Feo Codecido (1971) suggests an Eocene age, with mainly vertical displacement to later change for horizontal displacement. In regard to Cuiza fault, it starts to move during the Late Eocene-Oligocene (Vence, 2008). However, the strike-slip component occurred during the Early Oligocene (Benkovics and Asensio, 2015).

2.4. Evolution of the region.

In the study area, different phases of deformation have developed a very complex configuration. The Gulf of Venezuela is confined by the Caribbean plate to the north, the Maracaibo Basin to the southwest, the Falcón Basin to the southeast, and the Guajira Peninsula to the west (Figure 1.1).

The sedimentary history in the region started in Middle to Late Jurassic when Gondwana broke up from North America (Laurentia) developing the Proto-Caribbean; northwestern South America was separated from the present area of the northern Gulf of Mexico and Yucatan Peninsula (Pindell and Barret, 1999; Meschede and Frish, 1998; Mann, 1999). This rifting process allowed the deposition of Jurassic sequences in structural grabens related with a series of NNE-trending faults, filled predominantly with continental deposits with subordinate mafic to ultramafic volcanic rocks (e.g. La Quinta Formation) (Maze, 1984). These rocks crop out in different localities: The Sierra de Perijá, Mérida Andes, and the Guajira Peninsula (Case and Holcombe, 1980; Maze, 1984).

The Early Cretaceous to Paleocene periods corresponded to a thermal subsidence and quiescence that developed a passive margin associated with the rifting between South and North America, while the Yucatán Block took place (Pindell and Kennan, 2001; Mann, 1999; Mann et al., 2006; Escalona and Mann, 2011) (Figure 2.5a). This period is characterized by a broad, mixed carbonate-clastic shelf which was deposited along an extensive area of the middle to outer shelf of Cogollo Group (Apon, Lisure, and Maraca formations) and La Luna Formation (Cooper et al., 1995; Escalona and Mann, 2006c) (Figures 2.5a).

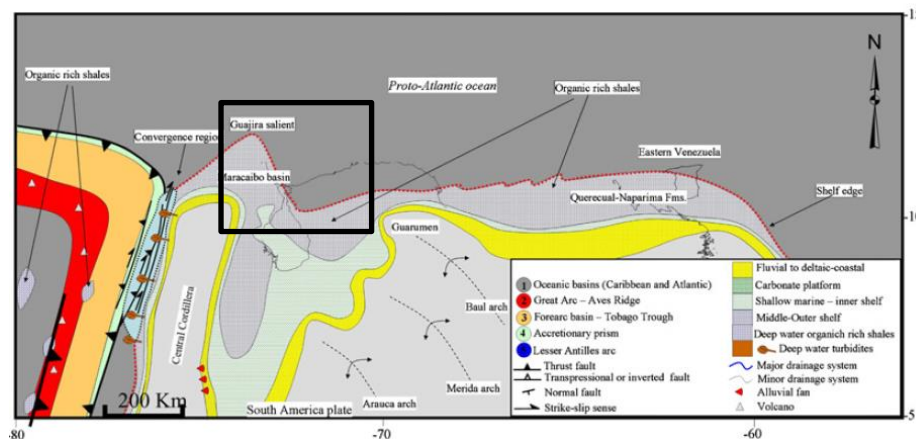
The Paleocene marked the end of the passive margin, when convergence of the Great Arc of the Caribbean against the Gulf of Venezuela started (Figure 2.5b). A foreland basin in the northeastern part of the Maracaibo Basin is generated, and a thrusting-imbricated system started to emplace as the Lara Nappes, controlling sedimentation and deformation in the region (Stephan, 1982; Pindell and Barret, 1990; Lugo and Mann, 1995) (Figures 2.5c and 2.6). The displacement of this allochthonous block is associated with a right-lateral southeastward movement of the thrust (east of the Burro Negro tear fault) (Stephan, 1980, 1982) (Figures 2.5b and 2.5c).

In addition, the magmatic Lesser Antilles arc related with the oblique subduction of the Proto-Caribbean beneath the Caribbean plate is developed, during the migration of the Great Arc of the Caribbean (Audemard, 1993, 1999). The displacement eastwards of this arc originated the Grenada, Blanquilla, and Falcón back-arc basins (Audemard, 1993, 2009, Gorney et al., 2007, Escalona and Mann 2011).

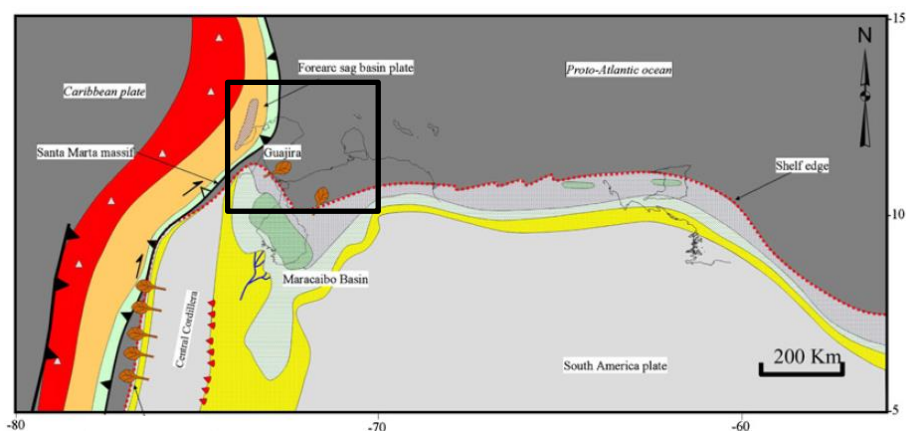
By Middle Eocene, the tectonic setting is similar to the Paleocene period, with a compressional setting along the margin. In addition, a slab-pull of the underlying South American slab occurred possibly during this time (Escalona and Mann, 2011) and the Falcón and Bonaire basins started to open in a back-arc rift system (Figure 2.5c).

The Maracaibo Basin was developed during the Eocene as a foreland basin by thrusting and an associated Burro Negro tear fault is also generated by this time (Figure 2.5c). A thick fluvial deltaic sedimentation wedge represented by Misoa Formation was deposited where the most important reservoirs of the region are trapped.

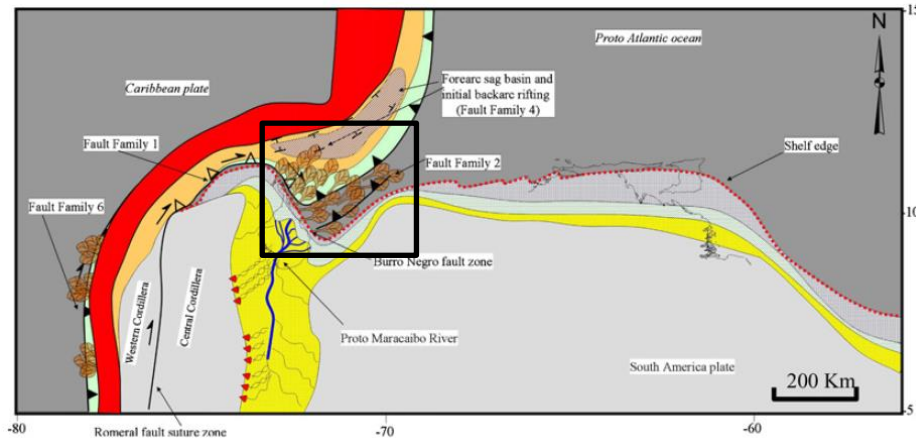
A Late Cretaceous (~80 Ma)



B Middle Paleocene (~60 Ma)



C Middle Eocene (~44 Ma)



D Middle Oligocene (~30 Ma)

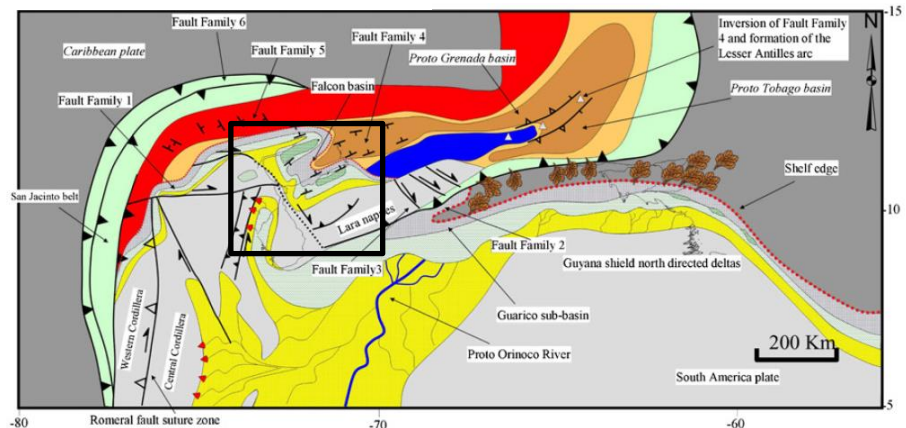


Figure 2.5. Maps showing the regional evolution of the region affected by the Caribbean-South American oblique collision. Black square indicates the location of the study area. **(a)** Paleogeography by Late Cretaceous (~80 Ma), **(b)** Middle Paleocene (~60 Ma), **(c)** Middle Eocene (~44 Ma). **(d)** Middle Oligocene (~30 Ma) (Escalona and Mann, 2011).

During the Oligocene, the Caribbean-related regime changed from a convergent to a transtensional margin. A strain partitioning initiated with the incipient Oca-Ancón right-lateral strike-slip fault system emplaced along this zone (Figure 2.5d). During this phase, a significant crustal thinning is produced (Late Oligocene-Early Miocene). This thinning facilitated intrusion of basalts along the main axis of the Falcón Basin (Muessig, 1978, Baquero, 2015). This crustal thinning was later confirmed from deep seismic studies (Guedez, 2007; Bezada et al., 2008; Mazuera et al., 2016). The intra-arc rifting decreased and the igneous intrusions ceased by the Early Miocene along the Falcón Basin (Gorney et al., 2007).

Another important deformation occurred at the end of the Early Miocene, when the Sierra de Perijá thrust-belt emerged as a positive structure. This major structure is characterized by complex triangle zones as a result of imbricated basement thrust and detaching along the Upper Cretaceous shales units and propagating mountainward. In addition, during this compressional event, the Jurassic half-grabens were partially inverted (De Toni and Kellogg, 1993; Duerto and Escalona, 2006).

On the other hand, the Middle Miocene transpression affected the northwestern South America with the Falcón Basin inversion as its more significant event (Audemard, 2001). Therefore, the present geodynamic setting of the northwestern most Venezuela is controlled by a low-angle subduction process of the Caribbean beneath the northwestern most corner of the South America plate, and continues eastward movement of the Caribbean plate (van der Hilst and Mann, 1994; Duerto et al., 2006; Escalona and Mann, 2011; Mazuera et al., 2018).

Finally, the evolution of the Gulf of Venezuela started at the Early Paleogene with the tectonic coupling of the eastward-escaping Caribbean plate and the South American plate. Two distinctive geologic provinces controlled this evolution (Castillo et al., 2017) sharing common sedimentary records until Present (Flinch and Castillo, 2015). A very well preserved passive margin deposition characterized the western province (Figure 2.6) that started with a transgressive phase during the Early Cretaceous (deposition of the Cogollo Group, Luna and Colon formations). In contrast, the sedimentary history in the eastern province started with the deposition of Eocene sequences along the Urumaco Trough, capping the allochthonous basement (Castillo et al., 2017). A wide shallow-water platform was developed during the Oligocene-Early Miocene in the eastern province that deepens toward the west. This event is very important for the petroleum system developing at eastern Gulf of Venezuela since

carbonate reservoir rocks were deposited under shallow water conditions, while the source rocks deposition and preservation took place in the deeper water environments of the Urumaco Trough (Figure 2.6).

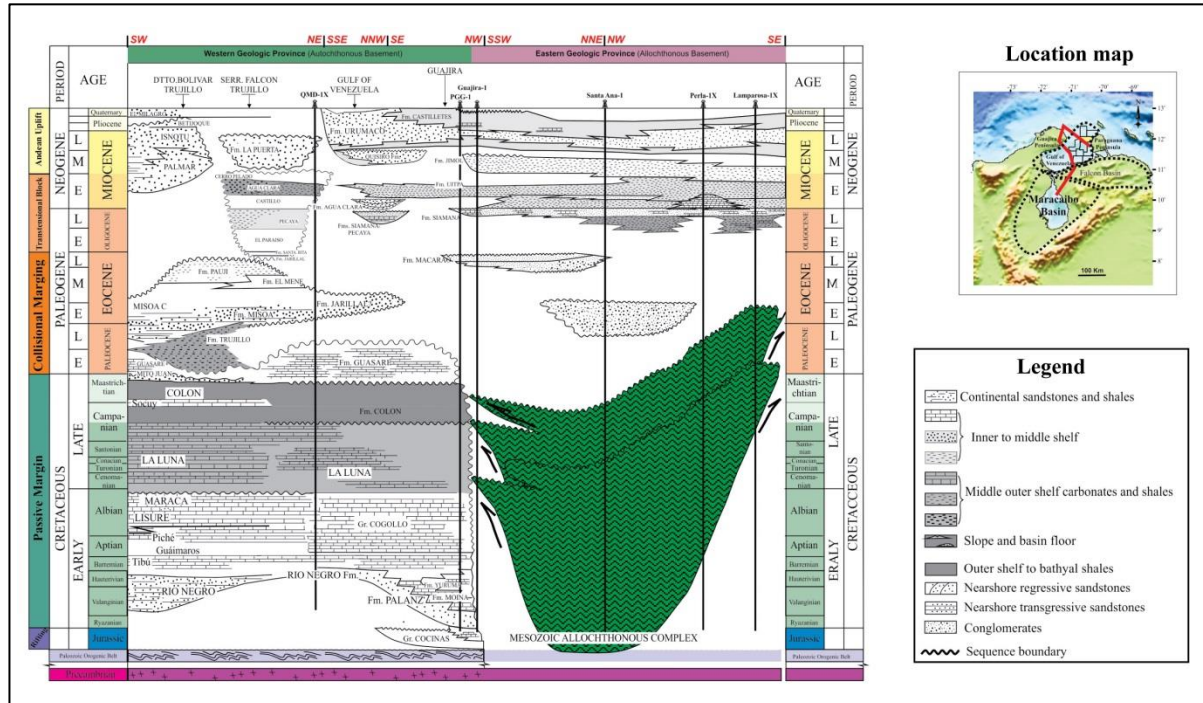


Figure 2.6. Chronostratigraphic chart showing the northeast Maracaibo, northwest Falcón, and Gulf of Venezuela basins. Seismic data, exploration wells, surface geology, and additional information are included on this chart. Significant differences on the lateral and vertical stratigraphic evolution are shown on both, the autochthonous and the allochthonous provinces (Castillo et al., 2017).

2.4.1. Tectonic models.

Two major tectonic models have been proposed for northwestern on- and offshore Venezuela: (1) First, some models are based on a Cenozoic pull-apart basin configuration (from Early Miocene) which opened a long east-west orientation, plate-margin parallel, right-lateral strike-slip faults system (Muessig, 1978, 1984a; Boesi and Goddard, 1991; Macellari, 1995; Sisson, et al., 2005; Weber et al., 2009; Cardona-Molina et al. 2010, 2014). This pull-apart-related system (Muessig, 1984a) is integrated by stable basement highs (Paraguaná, Dabajuro, and Guajira) and larger subsidence zones (Falcón basin, Urumaco Trough, La Vela bay, and Bonaire basin). A later stage related with transpressive deformation during the Late Miocene–Present deformed the pull-apart system by folding and thrusting (Figure 2.7a).

(2) In contrast, some models related to an extensional aperture of an east-west oriented, back-arc basins in a shallow-subduction context are proposed (Figure 2.7b) (Audemard, 1993, 2009; Audemard and Giraldo, 1997; Porras, 2000; Gorney et al., 2007; Bezada et al., 2008; Baquero et al., 2009; Escalona and Mann, 2011) or just a back-arc basin formed as a response to a north-south subduction zone that rotated into its current east-west trending configuration (Skerlec and Hargraves, 1980).

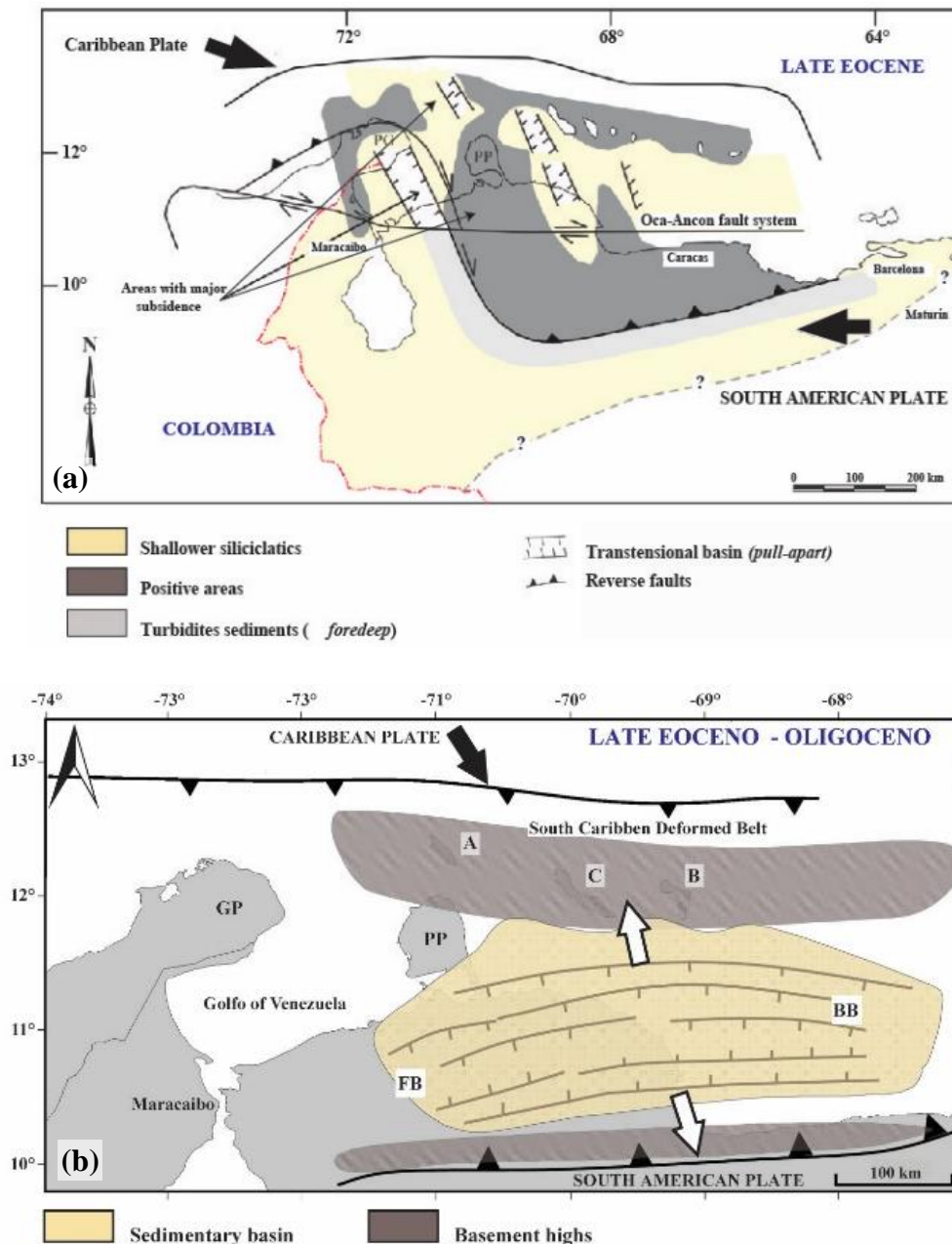


Figure 2.7. (a) Eocene-Oligocene pull apart model in northwestern Venezuela associated with the strike-slip displacement of the Caribbean eastwards migration. The figure shows areas with major subsidence (modified from Maceralli, 1995; Baquero, 2015). **(b)** Paleocene-Eocene back-arc basin opening model for the Falcón and western Bonaire basins (modified from Porras, 2000; Gorney et al., 2007). Abbreviations: PP: Paraguana Peninsula; GP: Guajira Peninsula; A: Aruba, C: Curaçao, B: Bonaire, BB: Bonaire Basin, FB: Falcón Basin.

3. DATA AND METHODOLOGY.

3.1. Dataset.

3.1.1. Seismic data.

The data set used for this research consists of approximately 6405 km (3979 mi) offshore and 1195 km (742 mi) of 2D seismic data, covering an area of 25,000 km² (9653 mi²) (Figure 3.1). The data was provided by the state-oil company Petróleos de Venezuela (PDVSA) and is composed of several surveys, acquired at different times, different acquisitions parameters, and quality. In general, the biggest and relevant survey was acquired in 1989, with 5,557 km², 10x20 km grid (6x12 mi) and normal polarity. It covers most of the study area offshore, showing good to high quality in the western areas and decreasing towards the south. The vertical resolution is 22 m (73 ft.) at shallower sequences and 71 m (233 ft.) at deeper sequences.

3.1.2. Well data.

Well information from fifteen (15) wells was used (Figure 3.1). The data include conventional well logs (gamma ray, density, sonic, resistivity, spontaneous potential, and others), master-logs, check shots, cores description, and drilling reports for the wells recently drilled. PDVSA also provided biostratigraphy reports with the bio-markers information; paleontological data and descriptions, and chrono-stratigraphic interpretations were used to correlate with seismic for age control and subsidence plots.

3.1.3. Gravity data.

Bouguer anomalies map was obtained from spectral decomposition of gravity data, a. The data was acquired from the EIGEN-6c4 model, and some pre-processing steps were applied using ICGEM from GFZ Potsdam research center (<http://icgem.gfz-potsdam.de>). Some corrections were calculated to transform the values from observed gravity to Bouguer anomalies reduced to the ellipsoid GRS80. In addition, a second-order correction was set (atmospheric, topographic, etc.) to generate a second-order Bouguer anomalies map in the study area using Oasis Montaj and jjSpectral software. The resulted map of the Bouguer anomalies of the Gulf of Venezuela is used on the structural framework analysis and the tectonic evolution model.

3.2. Methodology.

Well correlations were constrained using the well tops information provided by PDVSA. Well logs interpretation using the gamma ray and sonic logs to determine the depositional framework and establish the staking patterns for different sequences was developed, in order to understand their depositional environments and associated them with tectonics events. The interpretations and information from reports were used to better constrain the location of acoustic basement, key horizons, and stratigraphy present in the provinces.

Based on the integration of Bouguer anomalies and acoustic basement map (generated from seismic), stratigraphy, regional geology, structural styles, and previous studies, the area was divided into three geological provinces. The division helped to explain the structural setting, stratigraphic framework, and the evolution of the study area.

The synthetic seismograms and seismic well ties were performed for eight (8) wells where seismic, time-depth curve, sonic, and density logs were available (A, D, E, F, G, I, K, and L). Seismic mapping of seven (7) tectonostratigraphic sequences (Cretaceous; Early Paleocene; Late Paleocene-Eocene; Oligocene; Early Miocene; Middle- intra Late Miocene; and Late Miocene-Pliocene) and the acoustic basement were performed, based on these well-seismic ties and the regional correlations.

The structural style was characterized and different faults families were identified which are associated with the main stress-field during the different stages of deformation. The tectonic plate model (Escalona and Norton, 2015) was reviewed in order to update it with new geochronological data that have been published recently.

Structural trends were also considered to estimate the displacement of the Oca fault and evaluated the scenario of a segmented section of the Maracaibo Basin that was moved north-eastwards. Fault patterns and deformation present in the Maracaibo and Falcón Basin, Sierra de Perijá thrust-belt, and the Guajira Peninsula, were analyzed and compared with the structures in the study area in order to gain enough evidences to evaluate the possible extension of the Maracaibo Basin towards the southeastern part of the Gulf of Venezuela.

Furthermore, subsidence plots in three key wells was constrained, using the age information based on biostratigraphy and seismic character to define the periods of erosion, time missing, rates of sedimentation, and thickness of the layer that was eroded. These plots were particularly

useful to understand the relationship between sedimentation and tectonics, given valuable information of the main events, which affect the Gulf of Venezuela.

Finally, paleogeographic maps with an evolution model for the Gulf of Venezuela are proposed from the integration of the observations and results obtained during this study.

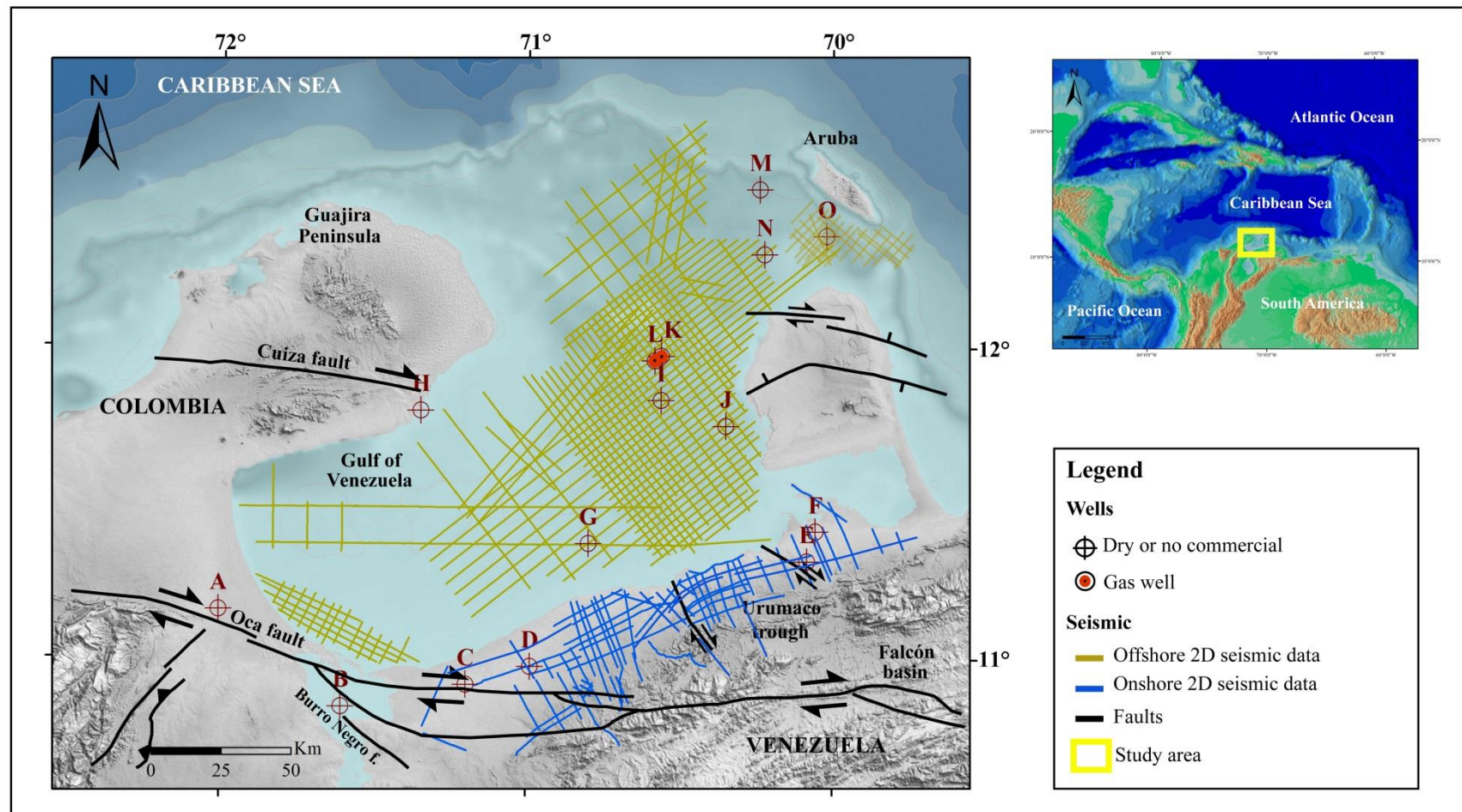


Figure 3.1. Location of the study area and data used for this study. It consists of fifteen (15) wells and an extensive data set of more than 7600 km (4722 mi) of 2D seismic data.

4. SUBSURFACE GEOLOGY OF THE GULF OF THE VENEZUELA.

4.1. Geologic provinces.

The subsurface geology of the study area is divided into three different geological provinces: (1) the Maracaibo (the southernmost province); (2) the Urumaco (covering the area of the Urumaco trough and where the Perla field is located); and (3) the Caribbean province (the northern most province) (Figures 4.1 and 4.2). The provinces were defined based on similar structural styles, stratigraphy, basement character, gravity anomalies, top of acoustic basement map, and previous works (Gorney et al. 2007; Baquero, 2015; Castillo et al. 2017) (Figure 4.2).

4.1.1. The Maracaibo province.

The Maracaibo province is the southernmost province of the study area. It suggested to be a northward continuation of the Maracaibo Block, with an extension of the allochthonous Paleozoic basement with continental-affinity found in the Maracaibo Basin, which contains the Cretaceous oil source rock (La Luna Formation) (Figure 4.2). The stratigraphic framework in the Maracaibo province is well-correlated with previous interpretations of the Maracaibo Basin (Escalona and Mann, 2006c), where Paleogene sequences and Cretaceous sequences overlying the acoustic basement are recognized (Figures 4.1, 4.2, and 4.3).

4.1.2. The Urumaco province.

Urumaco is the central province where a major NW-SE elongated graben is identified on top of the acoustic basement, also recognized on Bouguer anomalies map (Figure 4.2). The boundary between the Maracaibo and Urumaco provinces is characterized by an abrupt change between both structural-stratigraphic distinctive frameworks. It is defined by a major NW-SE-oriented, high-angle fault that segments the depression related to minimum anomalies of the gravity map, creating a triangle shape in the southern segment of this structure (Figure 4.2). This fault separates the Maracaibo Basin typical stratigraphy to the west (Maracaibo province) from a basin filling not older than Eocene to the east (Urumaco province) (Figures 4.1 and 4.3).

Recent studies on age dating identified Pre-Cambrian rocks with continental-affinity in this region, called after as the Falcónia Terrane (Grande, 2013a,b; Baquero, 2015), which is a distinctive characteristic along this province (Figure 2.2).

On the other hand, Cenozoic thermogenic petroleum system was proved in this province (Castillo et al. 2017), in contrast to a Cretaceous source rock defined in the previous Maracaibo province.

4.1.3. The Caribbean province.

The Caribbean province covers the region associated with the Cretaceous Caribbean arc, previously described from age dating, and regional gravimetric and magnetic data (Gorney et al., 2007; Blanco, 2017). The boundary between the Urumaco and the Caribbean province is associated with a regional NW-SE, or roughly E-W strike-slip fault, which separates the continental-affinity, allochthonous fragment associated with Falcónia Terrane in the Urumaco province (Grande, 2013a,b; Baquero, 2015) from the Cretaceous metamorphic rocks of the Caribbean arc towards the north (Figure 4.2). The sedimentary history seems to be related with the stratigraphy observed in the Urumaco province. (Figure 4.1).

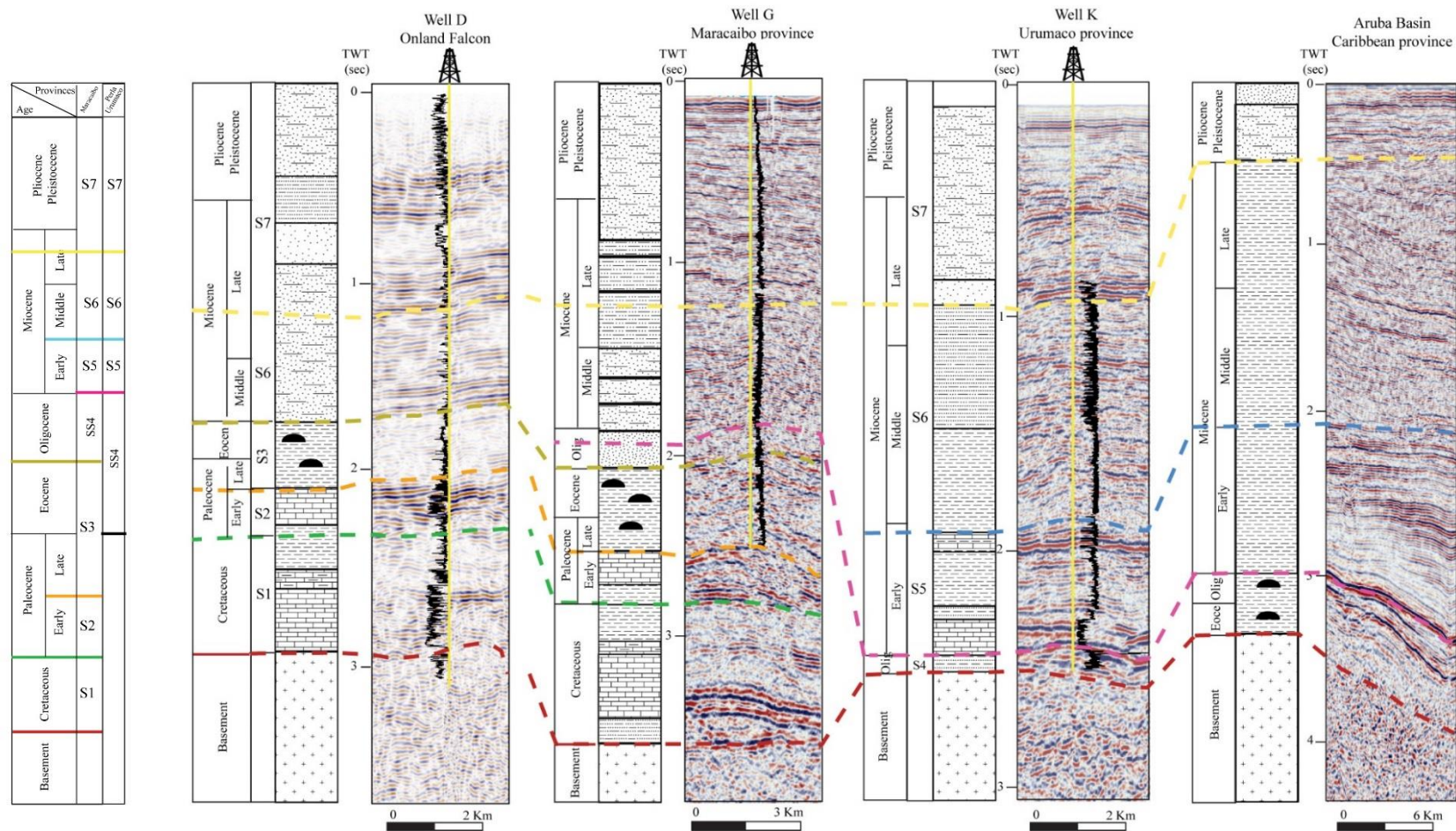
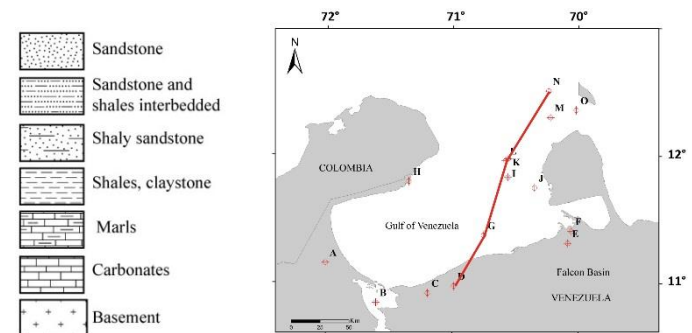


Figure 4.1. The SW-NE-oriented Gulf of Venezuela stratigraphy, showing the correlation between seismic and well data. Seven (7) main sequences were recognized in the region, bounded by unconformities recognized based on lap relationship, seismic character, well log character, and biostratigraphy reports. Sequences from 1 to 3 are not present at neither, the Urumaco and the Caribbean province.



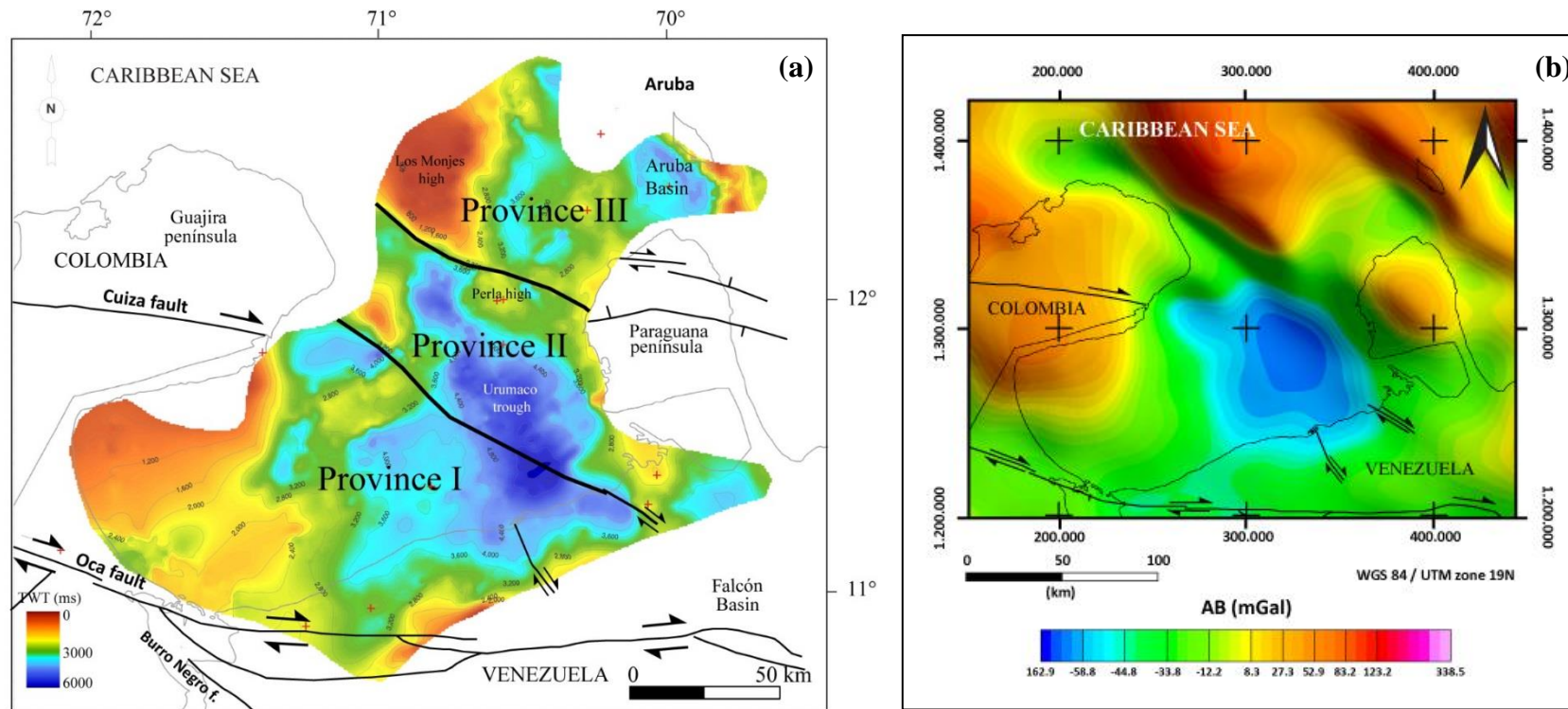


Figure 4.2. Basement provinces defined in the Gulf of Venezuela (northwestern South America). **(a)** Top acoustic basement map showing the depth of the acoustic basement constructed from seismic data (in two-way travel time, TWT). Three basement provinces are constrained; Province I: Maracaibo; Province II: Urumaco; Province III: Caribbean. **(b)** Bouguer anomalies map showing quite similar signatures than the acoustic-basement map.

4.2. Structural and stratigraphic framework of the Gulf of Venezuela.

4.2.1. Fault families.

The structural framework and subsidence control were constrained from the definition of six (6) fault families that widely affect the study area, based on the interpretation of seismic data, grouped on the basis of similar patterns and relative timing that can be associated to specific events (Figures 4.3 and 4.4). These fault families reveal the complexity of the region and the reasons of its actual geometry.

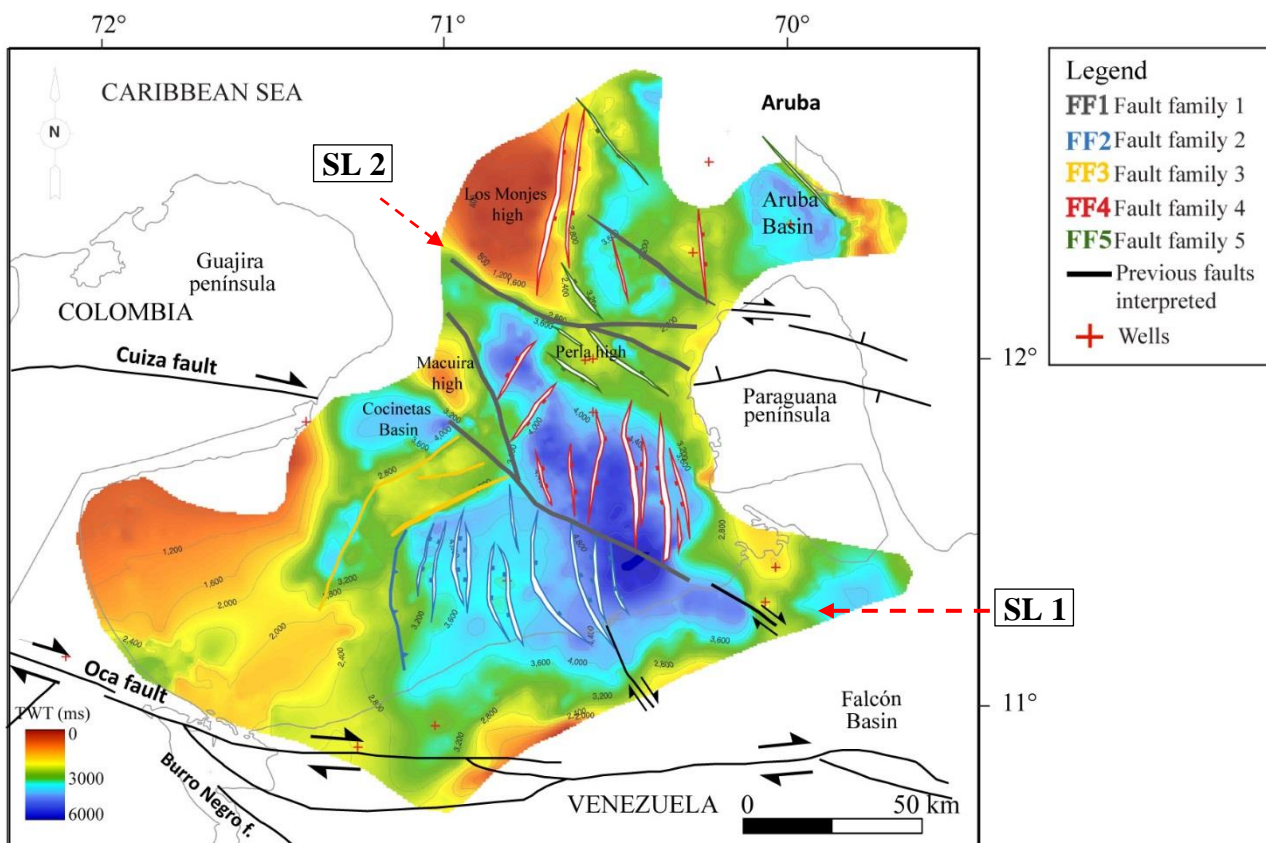


Figure 4.3. Structural map at top of the acoustic basement showing all the fault families recognized on the region. Faults can be grouped in five (5) sets. Major structural trends were compiled from Audemard (1991, 2001) and Blanco et al., 2015.

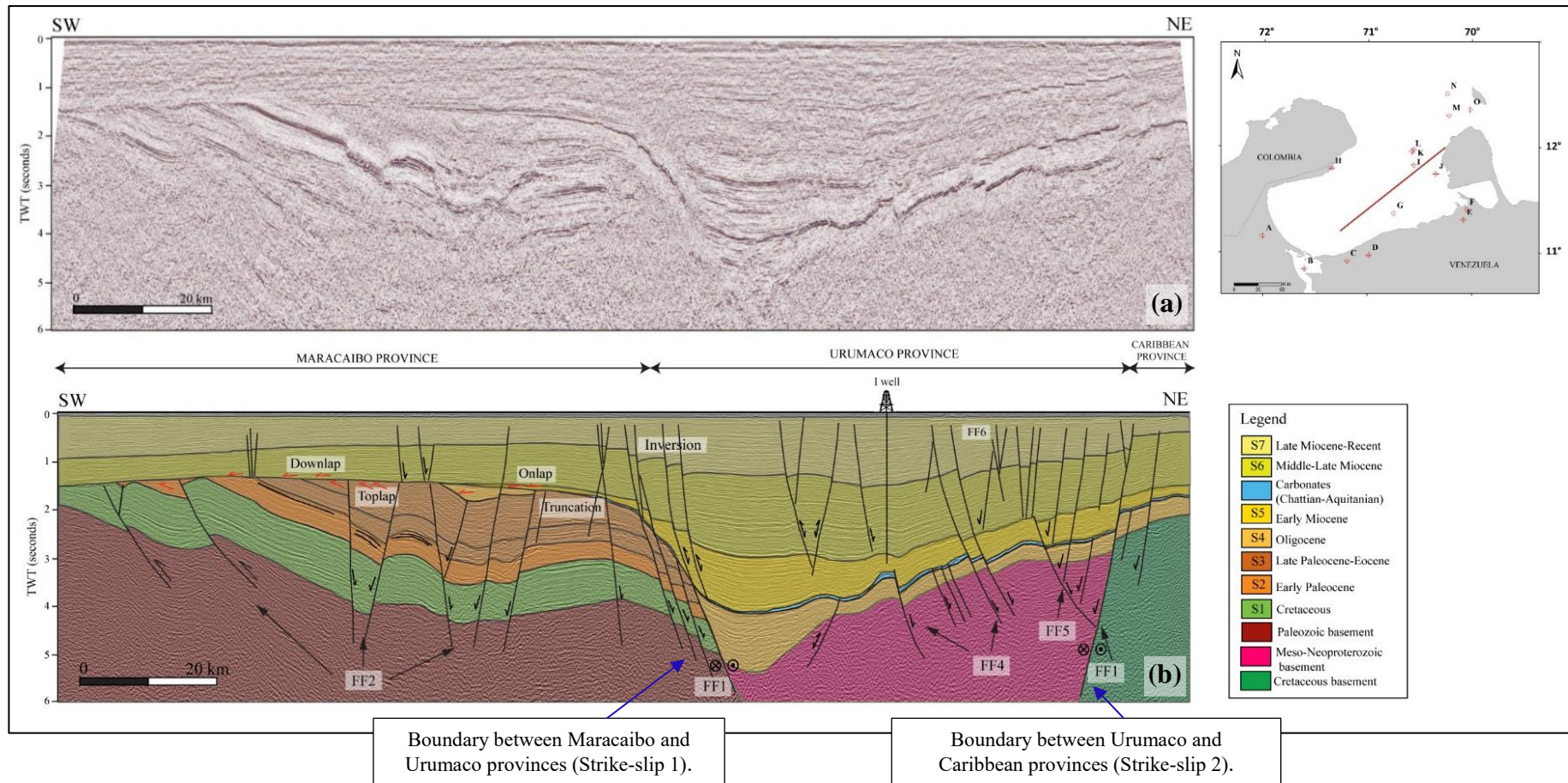


Figure 4.4. Regional seismic line SW-NE. (a) Uninterpreted seismic line. (b) Interpreted seismic line showing the three provinces (Maracaibo, Urumaco, and Caribbean) and its main characteristics. Red arrows indicate lap relationship. To the west, fault family 2 affects sequences from Cretaceous to Paleogene, whereas to the east, fault families 4 and 5 affect sequences from Oligocene to Recent. Three basement provinces are represented: Paleozoic basement (Maracaibo province); Meso-Neoproterozoic (Urumaco province), and Cretaceous basement (Caribbean province). TWT= two way travel time.

4.2.1.1. Fault family 1 (FF1): Paleogene/major east-southeast striking, strike-slip faults.

Faults in this family are suggested to be master-strike-slip faults with normal component striking east-southeast, or roughly E-W (Figure 4.3). They present a regional lateral extension with up to 70 km and variable displacement, with indication of growth strata. The dip of these faults is variable; complex geometry of the fault plane, abrupt changes across the fault and changes from normal to reverse component along the same fault are also recognized (Figures 4.4 and 4.5).

This fault family includes two major distinctive strike-slip fault systems: the strike-slip 1 (SL1) and the strike-slip 2 (SL2) (Figure 4.3). The family named as the strike slip 1, defines an abrupt change between different styles of deformation across the fault. It represents a sharp boundary between the Urumaco trough with Eocene to Recent sequences, and the Maracaibo province, filled with a thick Cretaceous to Recent sequences, as it is visualized on reflection data (Figures 4.3 and 4.4). This major high-angle fault cross the study area, changing its fault plane along the strike (Figures 4.5 and 4.6). A clear high-angle fault plane is observed at its southernmost segment, where the sequences from the Maracaibo provinces are plugging against this fault. The Urumaco trough has a very narrow expression with about 10 km wide (Figure 4.7c).

Moving towards the central segment of the fault, the Urumaco trough is wider (Figures 4.7b and 4.7c). The fault is clearly recognized as a sharp boundary between Maracaibo and Urumaco provinces. However, the fault is segment at the northern part probably associated to synthetic and antithetic shearing of this major fault.

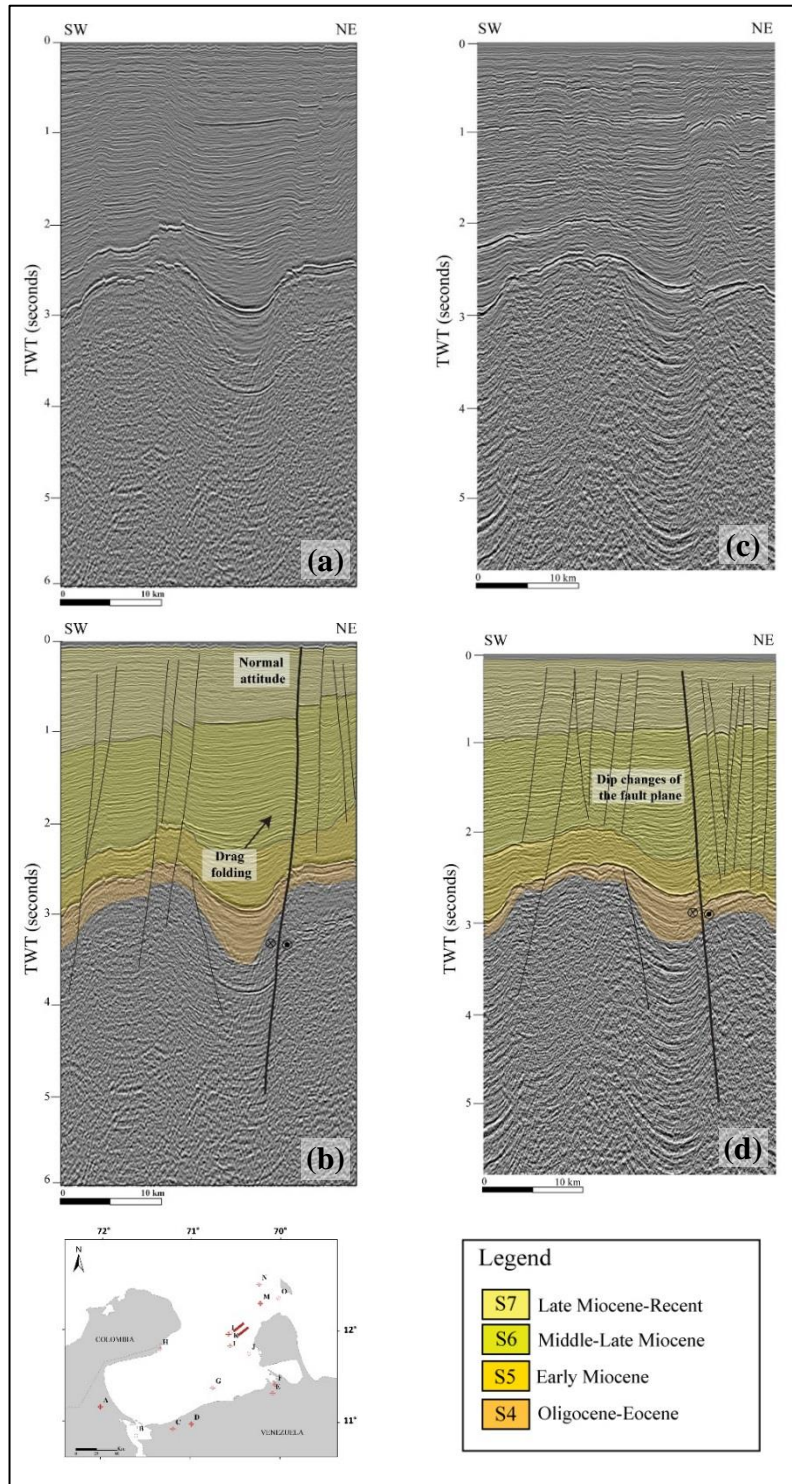


Figure 4.5. Characteristics of the strike-slip 2 faults on different seismic sections, showing changes in the dipping direction of the fault plane. **(a)** Uninterpreted seismic line. **(b)** Interpreted seismic line with a strike-slip fault plane dipping SW. **(c)** Uninterpreted seismic line. **(d)** Interpreted seismic line with a strike-slip fault plane dipping NE.

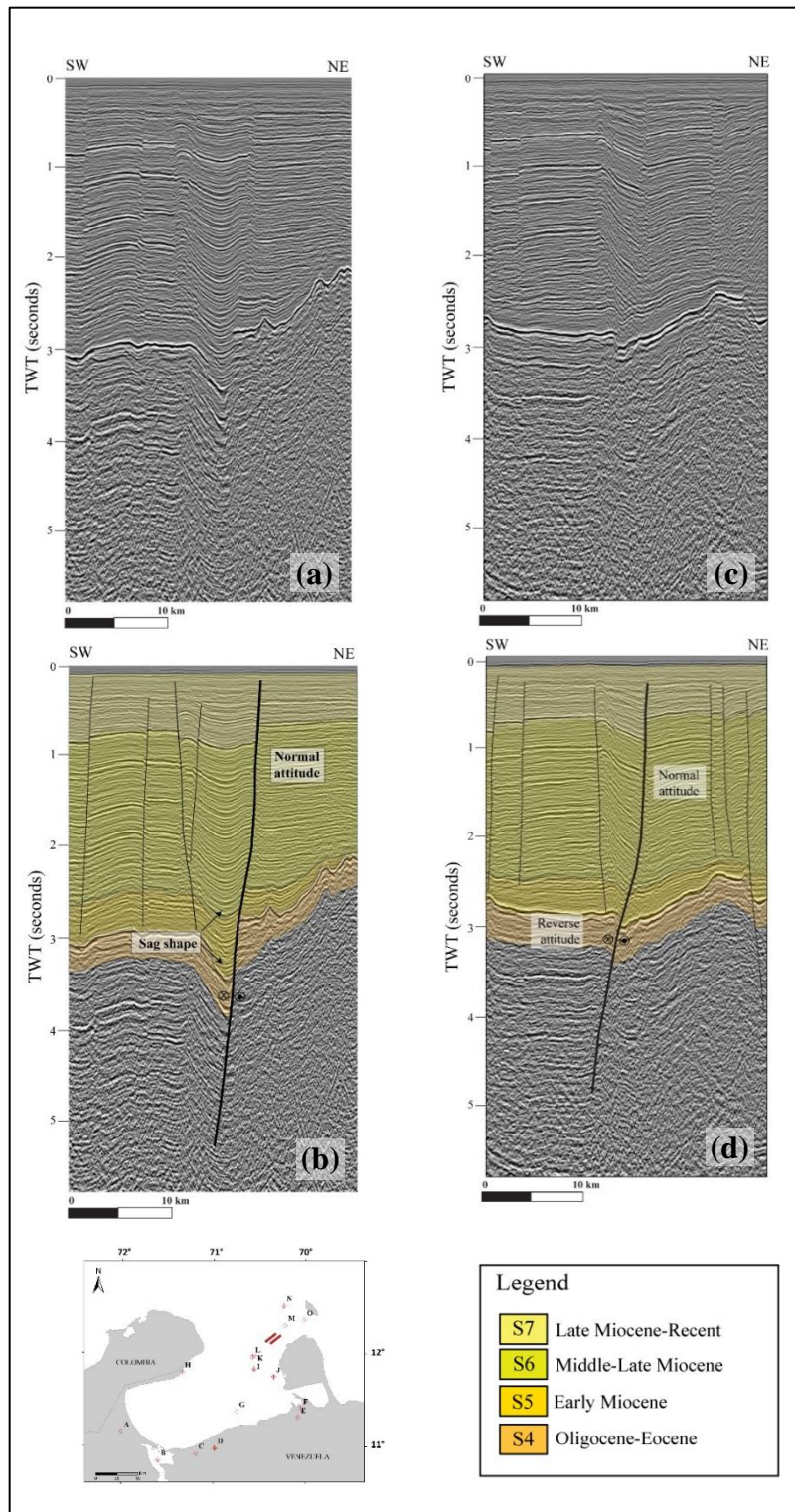


Figure 4.6. Characteristics of the strike-slip 2 faults on different seismic sections, showing changes in the fault plane dipping. **(a)** Uninterpreted seismic line. **(b)** Interpreted seismic line with normal fault attitude. **(c)** Uninterpreted seismic line. **(d)** Interpreted seismic line with reverse and normal fault attitude.

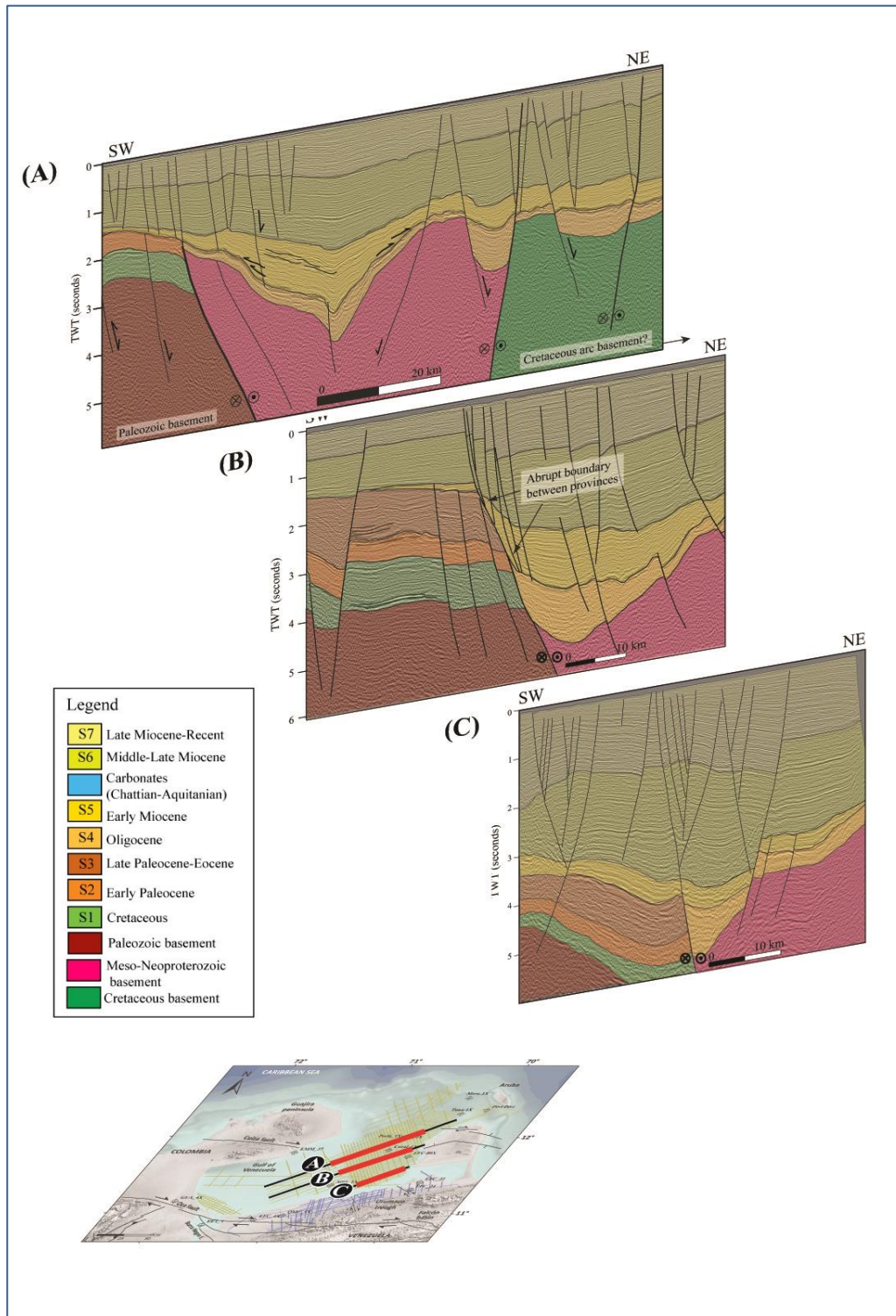


Figure 4.7. Diagram with different sections (red lines on the inset map) along the major strike-slip fault system 1. **(a)** Northwestern segment showing a lower dip angle and diffuse boundary between Maracaibo (Paleozoic basement) and Urumaco provinces (Meso-Neoproterozoic basement). **(b)** Central segment with a high-angle fault representing an abrupt boundary. Urumaco trough offshore is restricted to the Urumaco province. **(c)** Eastern segment, characterized by a high-angle fault. The Urumaco trough is narrower and the Maracaibo province is dipping against this fault.

4.2.1.2. Fault family 2 (FF2): Late Paleocene-Oligocene/northwest-southeast striking normal faults.

This set of faults is affecting the sequences from Cretaceous to Paleogene in the Maracaibo province (Figure 4.3). Large displacements and offsets up to 300 ms in older sequences are recognized. The dip angle of these faults is suggested to be higher than 45° , either dip to the SW or NE. Most of these set of faults are truncated by a regional unconformity (Figures 4.4 and 4.8). However, in some cases, an offset is observed through the younger sequences indicating reactivation after deposition. Different geometries on the seismic sections are related with the deformation of this fault family: grabens and horsts structures (Figure 4.8). Some members of this family located closer to the Urumaco province boundary showed inversion along the Middle Miocene - Late Miocene sequences (?).

On the other hand, some members of the fault family 2 might extend towards the western region of Falcón basin (Figure 4.3). These normal faults probably were formed during the last stages of the Early Paleocene, being active until the Oligocene. Their age might be older in association with Jurassic rifting, however, it is difficult to constrain.

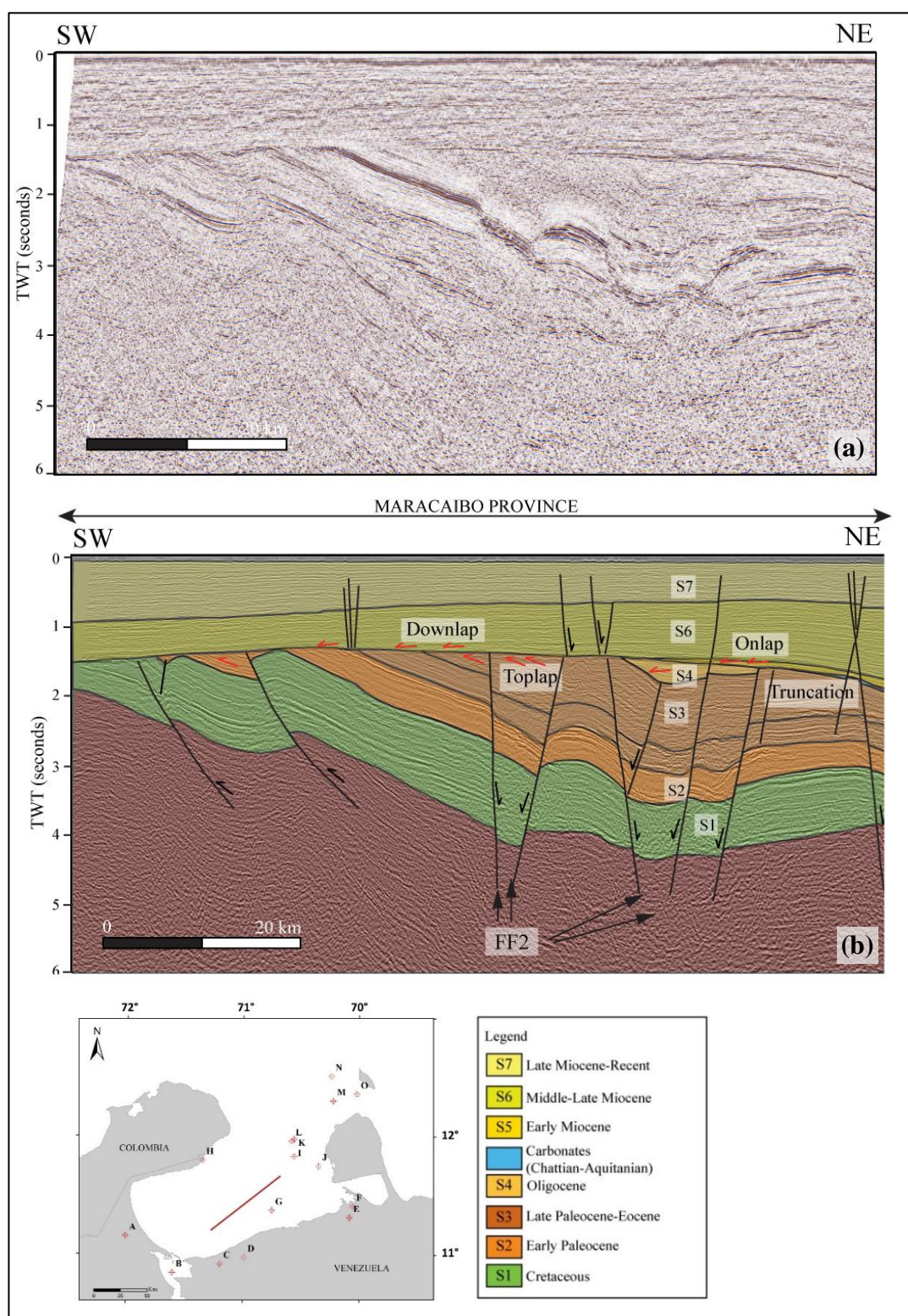


Figure 4.8. (a) Uninterpreted seismic line. (b) Interpreted SW-NE seismic section showing the fault family 2 and structures associated to this system. Red arrows indicate lap relationship. Fault family 2 controls horst and graben structures, and also controlled the deposition of sequences 3 and 4. Chaotic reflectors are identified in S3, more parallel toward the Urumaco trough. S4 sequence is observed, onlapping against S3.

4.2.1.3. Fault family 3 (FF3): Paleogene/east-northeast striking normal faults, reactivated as reverse faults.

Fault family 3 consists of thick-skinned normal faults observed in the Maracaibo province (Figure 4.3). Reflection data shows important displacements and offsets as much as 1000 ms. These faults present large lateral extension; however, one member of fault family 1 seems to be a barrier for this family towards the north.

These faults are responsible of forming a NE-SW structural high restricted to the western area of the Maracaibo province; it might be interpreted as a graben, developing pop-up structures due to a subsequent inversion of these normal faults with a slightly implication of a strike-slip component (Figure 4.9). This north-northeastern striking structure is younger than Oligocene because the Eocene-Oligocene unconformity is not folded, eroding the top of the structure. Nevertheless, the major westernmost boundary fault of the structural high, shows a different timing, linked to Early Miocene reactivation.

The northern segment of this structure is characterized by folded and tilted Cretaceous to Paleocene sequences (Figure 4.9). In contrast, the reflectors at the southern area are observed as sub-horizontal with little evidence of deformation.

A prominent compressional structure is recognized towards the west, associated with this fault family. The Cretaceous sequence and the basement are affected by thrust faults probably associated to a mountain-front deformation. The detachment of this structure seems to be located in the Lower Cretaceous. Triangle zones are suggested as the deformation accommodation mechanism (Figure 4.10).

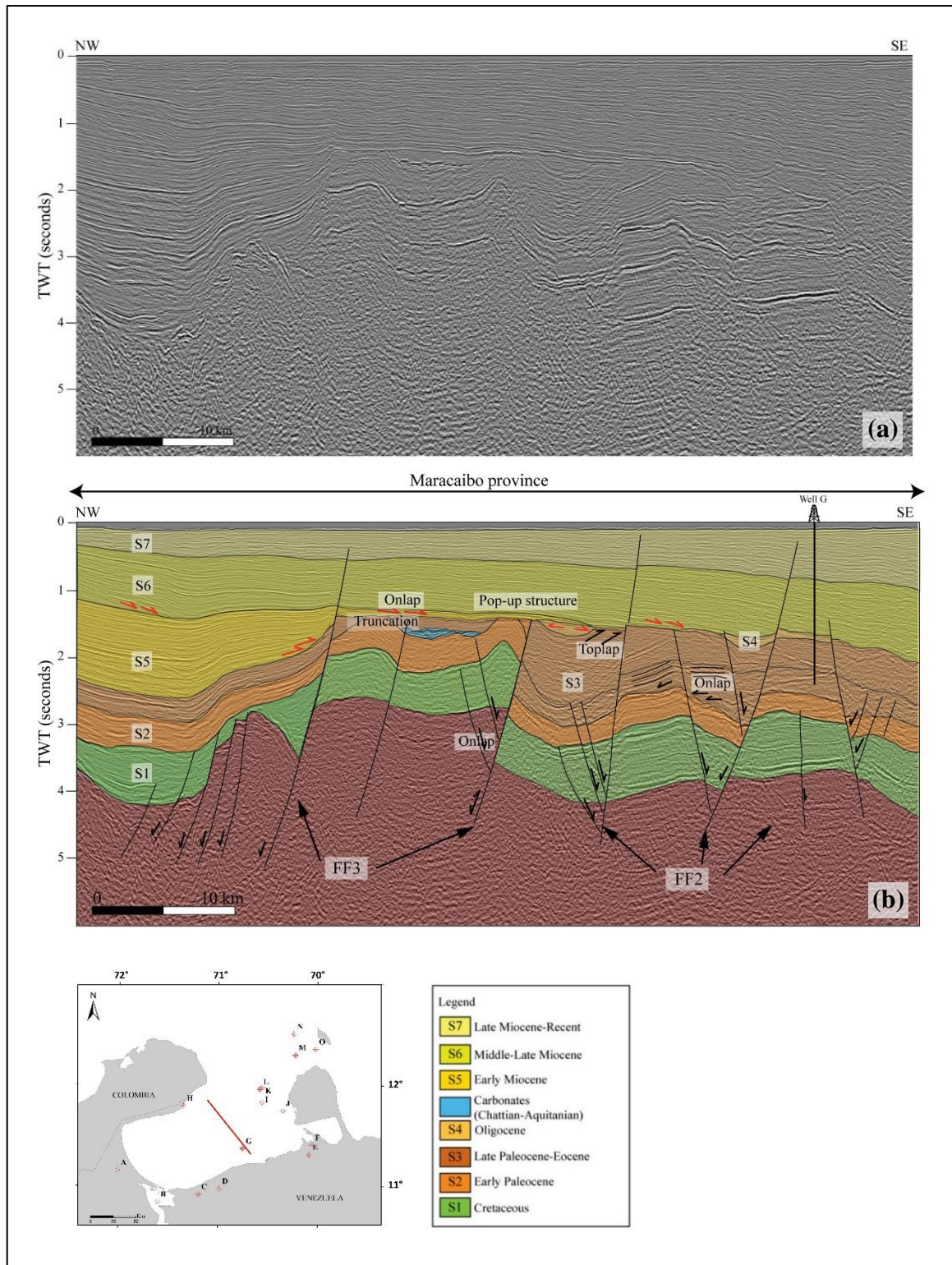


Figure 4.9. (a) Uninterpreted seismic line. **(b)** Interpreted NW-SE seismic section showing the fault family 2 and the fault family 3. Red arrows indicate onlap relationship. SW-NE graben structure inverted as pup-op structure is shown. A carbonate bank developed during the Late Paleocene is also observed. In addition, onlapping reflectors from S3 against S2 are recognized. Parallel reflectors with strong amplitude are interpreted as turbidites deposits.

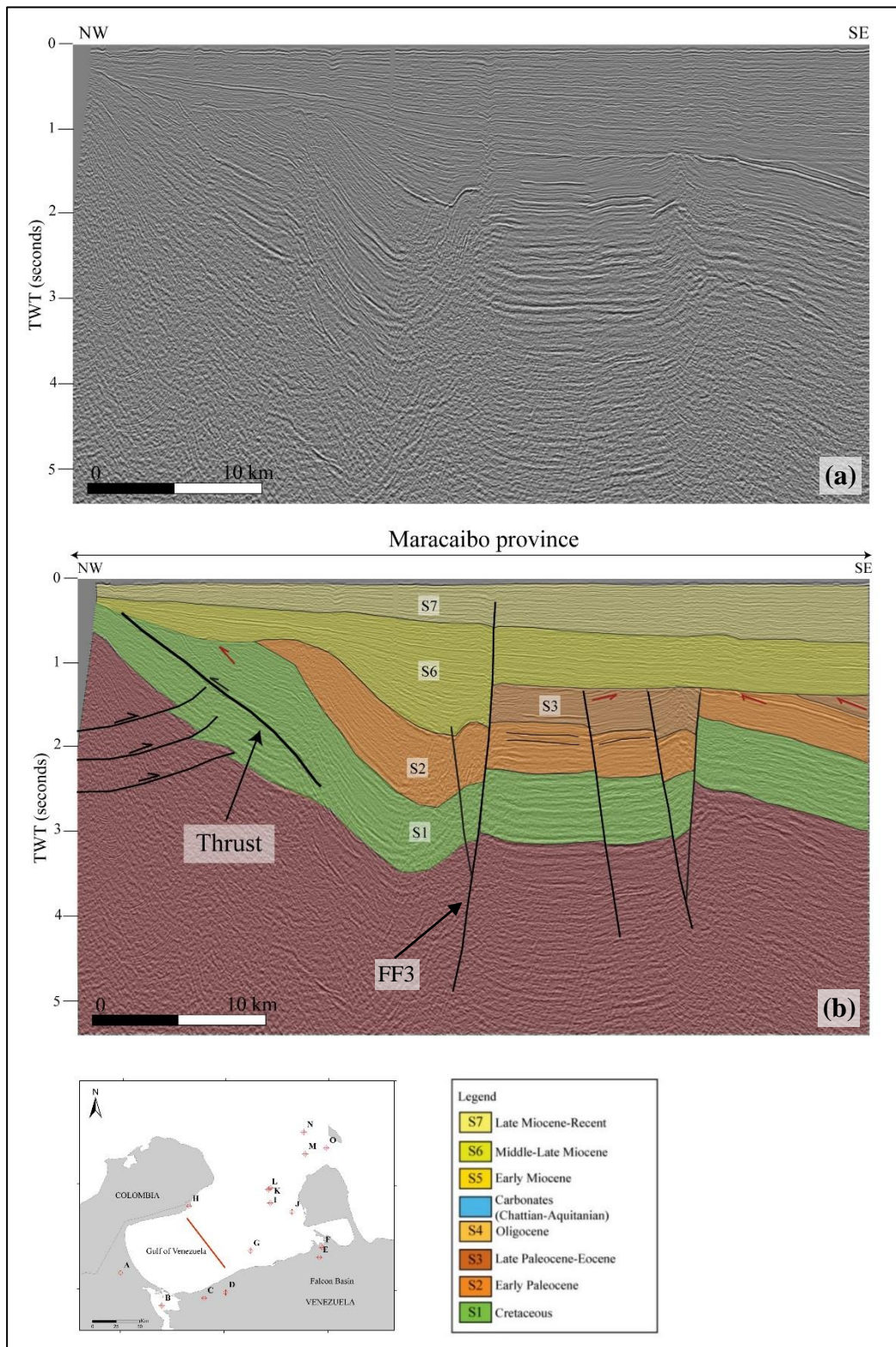


Figure 4.10. (a) Uninterpreted NW-SE seismic line. (b) A thrust fault is identified, affecting the Cretaceous sequence and the basement in the Maracaibo province. The detachment of this structure seems to be located in the Lower Cretaceous. Triangle zones are suggested as the deformation mechanism.

4.2.1.4. Fault family 4 (FF4): Late Oligocene/north-northwest striking normal faults.

Seismic reflection reveals a cluster of relative low-angle faults located in both, the Urumaco and the Caribbean provinces, consisting of subparallel NW-SE striking normal faults, dipping to SW and NE directions (Figure 4.3). Their strike is subparallel to the Late Oligocene fault family 2. These faults involve the acoustic basement, extending across the entire sedimentary section recorded on seismic data, with a maximum vertical offset about 400 ms. Sea-floor offset is indicative of recent fault movement (Figure 4.4).

Their lateral extension is limited into the study area; most of the members of this family are associated with the Urumaco trough development. The growth of sedimentary layers in the hanging-wall suggests syn-tectonic events, or active faulting during the deposition of Early to Middle Miocene sequences. Antithetic faults dipping towards the NE show rotated fault blocks geometry (Figure 4.11). Reactivation as reverse faults is observed during Middle Miocene to Late Miocene, restricted to the center area of the Urumaco province, indicated by anticlines in the hanging-wall. Moreover, fold-bend fault structures are recognized during the Oligocene in the Urumaco and Caribbean provinces, associated with inversion of the fault family 4 (Figure 4.7 and 4.11).

4.2.1.5. Fault family 5 (FF5): Oligocene-Holocene/west-northwest striking normal faults.

Fault family 5 consists of subparallel, high-angle, NW-SE striking normal faults with thick-skinned deformation, present in the Urumaco and Caribbean provinces (Figure 4.3). These faults are dipping towards the north and south, reaching no more than 100 ms of throws. Evidence of growth strata is recognized in the hanging wall on some sections during the Oligocene, indicating fault activity during the deposition. Faults from this family are more common in the Urumaco province bounding the Perla high (Figures 4.3 and 4.4).

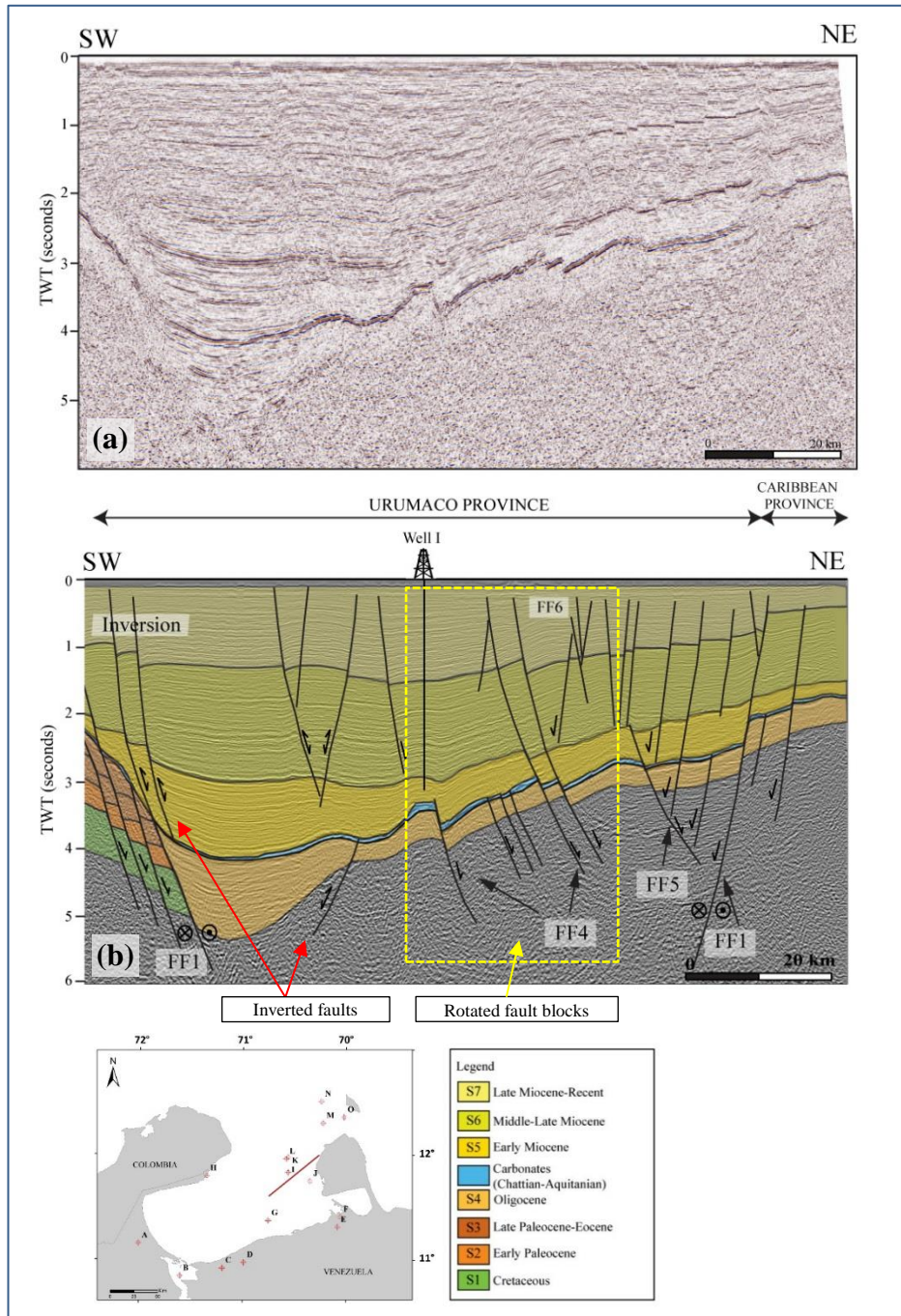


Figure 4.11. (a) Uninterpreted SW-NE seismic line. **(b)** Interpreted seismic section, with small black arrows indicating fault motions. Red arrows indicate inverted normal faults related with fault family 4. Yellow square highlights rotated fault blocks associated with fault family 4.

4.2.1.6. Fault family 6 (FF6): Early Miocene-Holocene/normal faults.

This set of faults is mainly present in the Caribbean province. Members of this family are thin-skinned deformation, affecting younger sequences over the Oligocene unconformity (Figure 4.4). The dip is towards the northeast and southwest. Minor displacements are observed, and throws along this faults are up to 300 ms. Evidence of grow strata is not recognized. Therefore, these faults were not active during the deposition of these sequences.

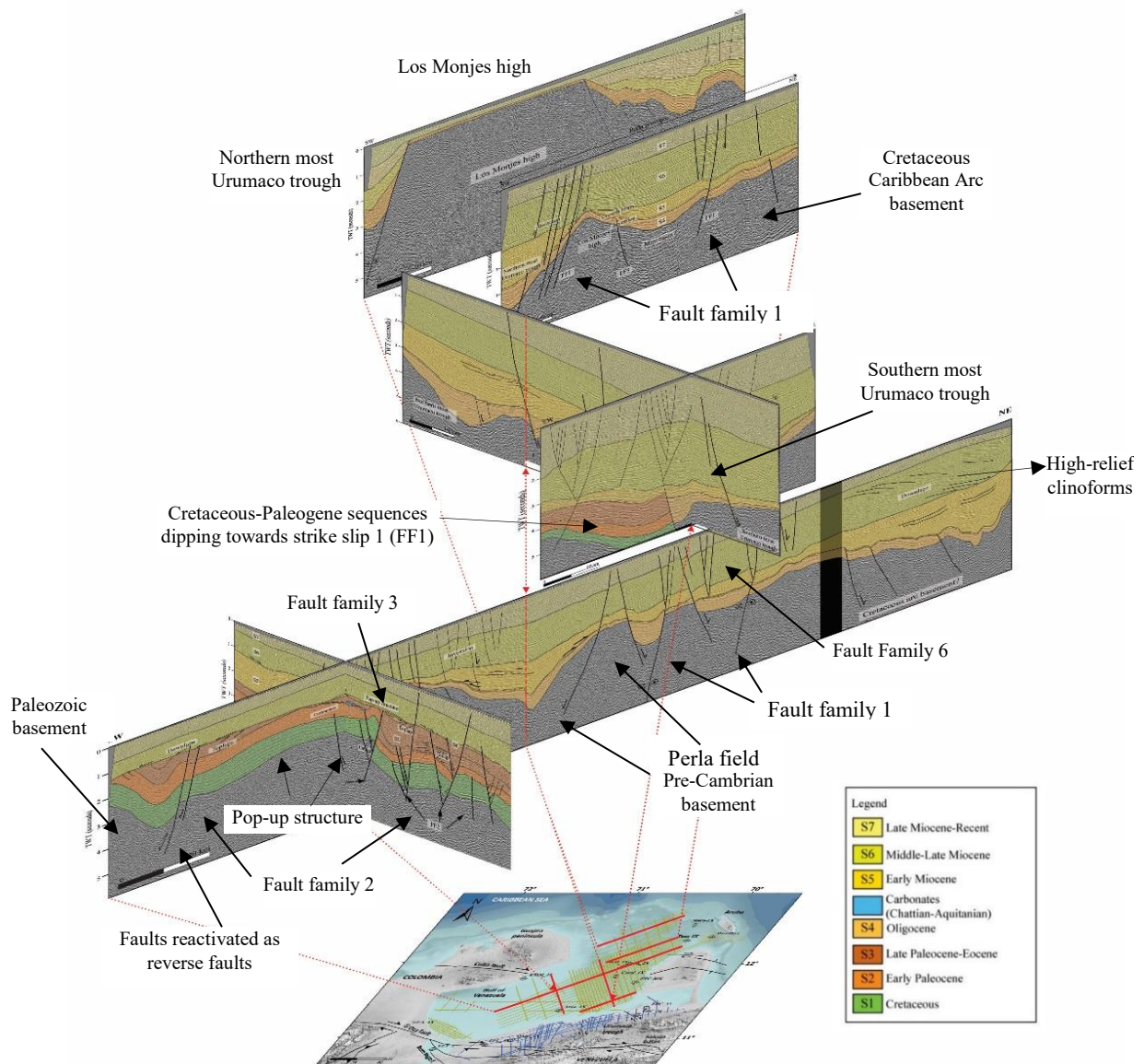


Figure 4.12. Fence diagram constructed from 2D seismic lines in different locations in the basin. The figure is showing main characteristic identified at the Gulf of Venezuela.

4.2.2. Focal mechanisms and its relationship with the interpreted faults.

Focal mechanism solutions suggest different earthquake-related movements along the faults interpreted in the study area. In the case of the major strike-slip 1 (family 1) (Figures 4.3), focal mechanisms with mainly normal component are observed (No. 8, 9, and 11: Figure 4.13), indicating a possible behavior as a normal fault in this region at the present. On the other hand, in the western segment, a focal mechanism is located over the strike of this fault (No. 4), reporting an almost pure strike-slip component, which is in agreement with the interpretations on seismic reflection data. Furthermore, the reported depth for the epicenters are in a range from 10 to 28 km, which might suggest a crustal influence for this fault.

In the case of the strike-slip 2 (a fault family 1 member), focal mechanism solutions have not been calculated. Nevertheless, three different solutions are observed at the Paraguaná Peninsula (No. 12, 13, and 14). The ones closer to the offshore region of the Gulf of Venezuela (No. 12 and 13) present strike-slip component associated with the previous interpreted Punta Macolla fault onland (Audemard, 2001).

On the other hand, the fault family 3 might be still active with an important strike-slip movement, represented by a focal mechanism in the southern part (No. 6: Figure 4.13). Moreover, a focal mechanism in the Urumaco province shows a normal solution related with the fault family 2 (No. 7). Reverse fault displacement is not reported by these calculated focal mechanism.

The table 4.1 shows a summary of all the focal mechanism compiled for the study area.

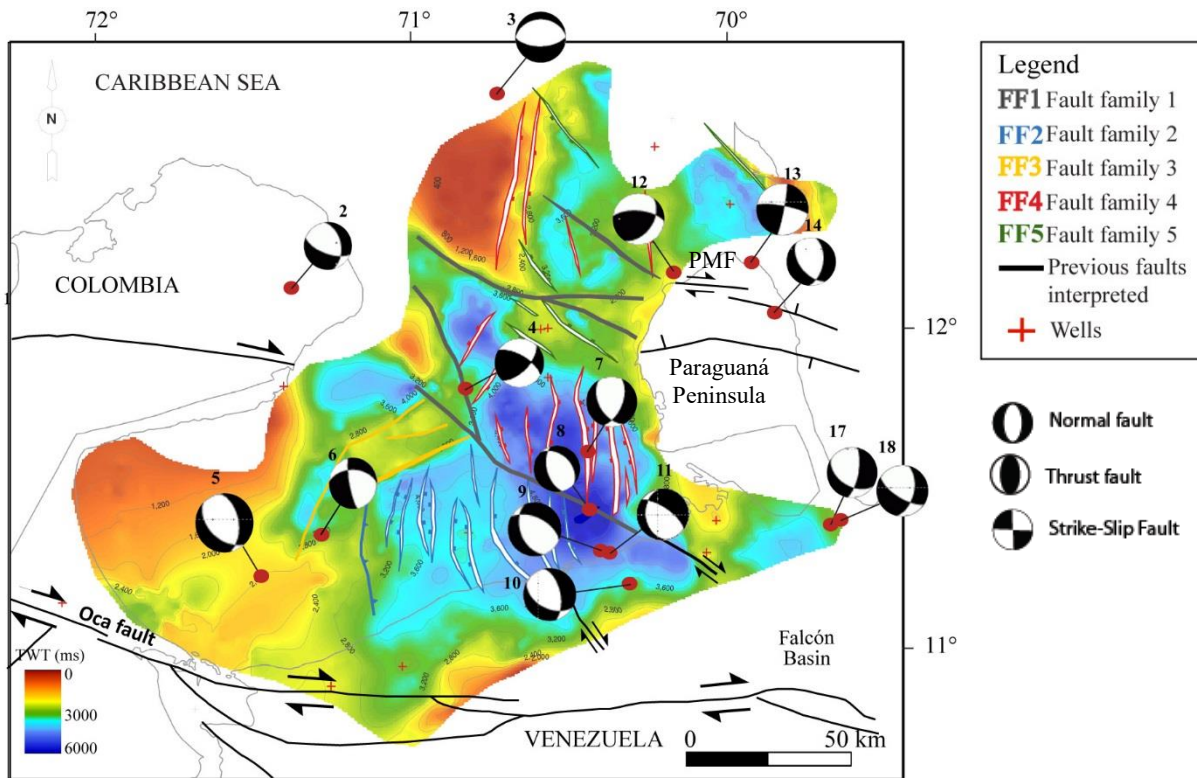


Figure 4.13. Focal mechanism solutions for the study area (compiled from the FUNVISIS catalog: www.funvisis.gob.ve). Focal mechanism No.4 is showing a strike slip displacement where a major strike-slip fault was recognized on seismic sections, with a epicenter depth at 28.6 km. Solutions labeled are described in the appendix. Abbreviations: PMF: Punta Macolla fault.

Tabla 4.1. Summary of focal mechanisms compiled for the area.

Focal Mechanism	Depth (km)	Magnitude	Coordinates		Date
			North	West	
No. 1	15.0	4.9	11.734	72.236	09.06.2017
No. 2	92.5	5.0	12.090	71.330	01.01.2006
No. 3	20.7	4.9	12.620	70.720	21.02.2014
No. 4	28.6	3.9	11.786	70.806	20.10.2017
No. 5	25.6	4.2	11.240	71.400	01.12.2011
No. 6	136.4	3.8	11.330	71.240	22.10.2005
No. 7	30.9	4.6	11.580	70.740	23.07.2009
No. 8	25.2	4.4	11.420	70.420	28.08.2005
No. 9	11,6	4,1	11.300	70.380	17.10.2010
No. 10	15.9	3.8	11.220	70.300	19.02.2012
No. 11	25.6	4.0	11.292	70.367	22.10.2016
No. 12	14.0	4.7	12.150	70.180	22.03.2017
No. 13	23.8	3.7	12.150	69.930	08.04.2015
No. 14	16,1	4,2	12.030	69.860	12.03.2011
No. 15	14.1	4.1	12.033	69.680	09.03.2017
No. 16	12.8	4.9	12.096	69.651	10.03.2017
No. 17	20.6	4.0	11.360	69.680	30.09.2009
No. 18	25.1	4.3	11.380	69.670	27.09.2009
No. 19	5.0	4.7	10.870	69.620	04.01.2013
No. 20	5.4	4.7	10.830	69.600	02.09.2014

4.2.3. Sequences.

Seven (7) main sequences were recognized bounded by unconformities, on the basis of lap relationship, seismic character, well log character, and biostratigraphy reports (Figure 4.1). Sequences from S1 to S3 are absent in the Caribbean and Urumaco provinces. S4 in the Maracaibo province correspond to Oligocene; in the Urumaco and Caribbean provinces is defined by Oligocene-Eocene, due to genetically relation. Above the regional unconformity, the sequences: S5, S6, and S7 can be correlated (Figures 4.14 and 4.15). Through the study area, different characteristics and changes are observed in the sequences as follows.

4.2.3.1. Sequence 1 (S1): Cretaceous (Maracaibo province).

(a) Well character:

Sequence 1 (S1) is not penetrated by wells in the Gulf of Venezuela (offshore). However, it has been reported in several wells on-land in the vicinities areas: northern Falcón, Guajira Peninsula, and the northernmost region of Maracaibo Basin (wells: A, B, D, and H). Thicknesses reported are about 600 up to 1000 m (Figures 4.14 and 4.15).

Early Cretaceous gamma-ray response is defined by a blocky package of carbonates. Then, a heterogeneous gamma-ray curve with high and low values is observed, generally coarsening upwards. Thickness up to 90 m, decreasing towards the east is recognized. The upper and last unit is the Late Cretaceous, and is defined by a strong increase in gamma- ray values, associated with silts and shales. Thinning towards the east is recognized (Figure 4.14).

(b) Seismic character:

This sequence unconformable overlies the acoustic basement. It is inferred to be Early to Late Cretaceous, using well tie information from well G, which reached Late Paleocene in the Maracaibo province, and comparing seismic character and well information onland. Internally, it is characterized by semi-continuous reflectors with medium to high amplitude in the lower part, associated with carbonate platform deposition (recognized in all the seismic lines). The upper part of the sequence consists of low to variable amplitude reflectors whose continuity is from intermediate to poor. In general, the reflectors are more continuous in the northern most part of the province (Figure 4.8).

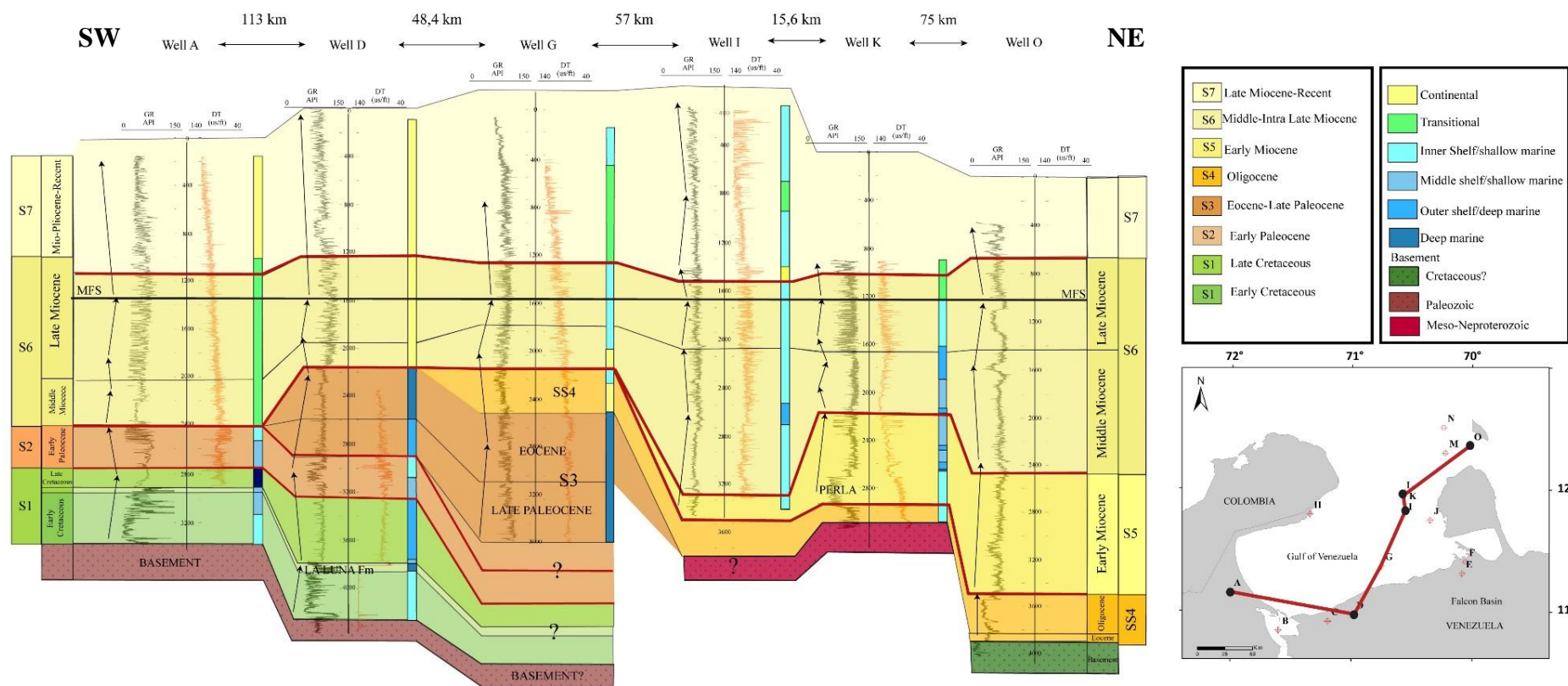


Figure 4.14. Regional correlation SW-NE. Different stratigraphy framework between the provinces is recognized. Seven main sequences bounded by unconformities are also showing.

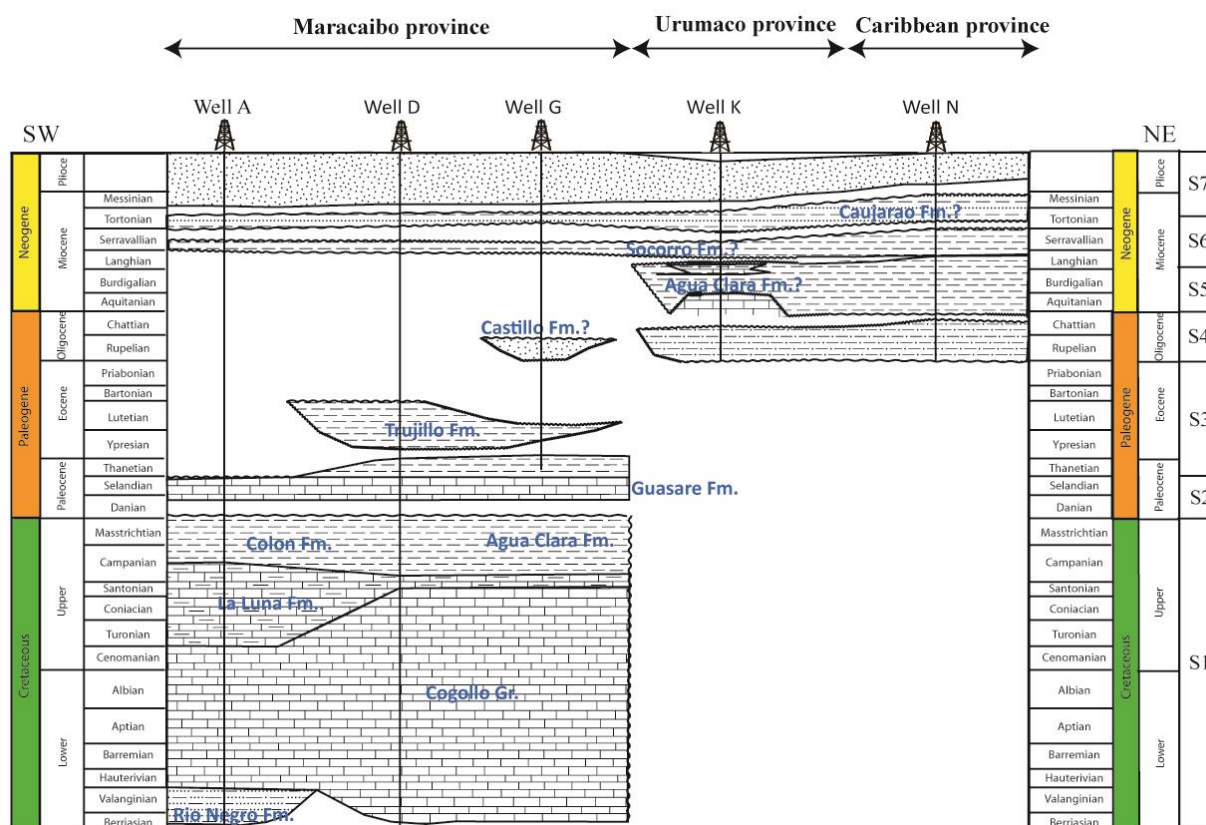


Figure 4.15. Chronostratigraphic chart from key wells. Time missing for the regional unconformity increased southwards. Maximum time gap is 42.7 Ma reported in well A overlying Paleocene rocks, in contrast to 14.7 Ma in well G and 2 Ma in well K, overlying Oligocene rocks (Urumaco province).

(c) Top time structural and thickness maps:

In general, the sequence is dipping north-eastward plugging into the boundary between the Maracaibo and Urumaco province, ranging from 0 up to 5800 ms depth (TWT). It has been under deformation towards the east, related with the fault family 2. A monocline structure led to erosion as is indicate in Figure 4.4. Moreover, the SW-NE elongated structural high recognized on seismic is observed (associated with fault family 3), which led to deformation and uplifted of this sequence (Figure 4.16a). Thickness map shows a decrease in values towards the east and southwest. The main depocenter observed is associated with a thrust, which caused sequence repetition in the southwestern area, interpreted on a seismic line, with approximately 1000 ms of thickness (Figure 4.16b). In addition, another SW-NE elongated depocenter is recognized probably associated with previous activity of the fault family 2.

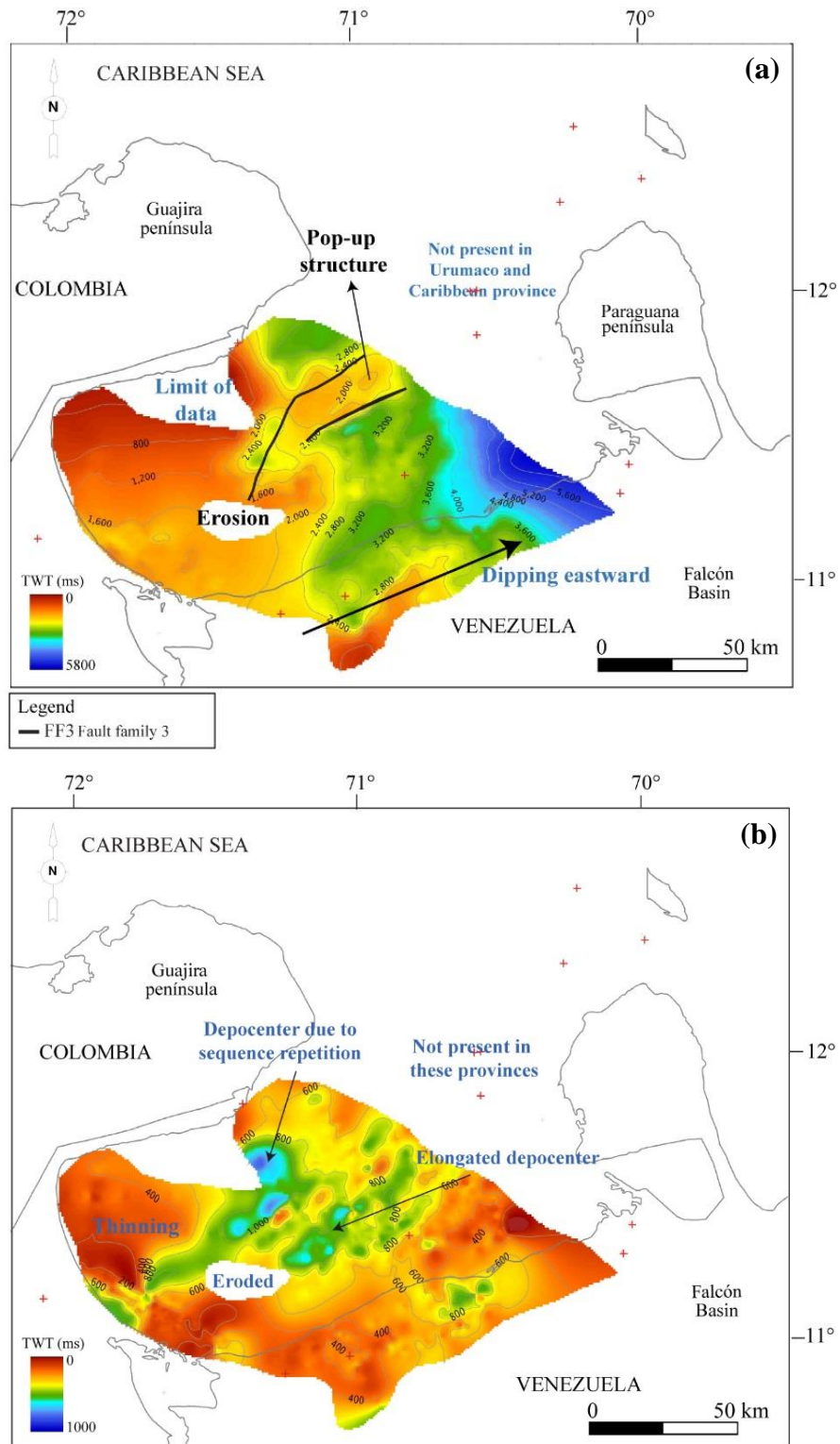


Figure 4.16. Maps showing the main characteristic of Cretaceous sequence (S1). **(a)** Top structural map. **(b)** Thickness map.

(d) Interpretation:

The log character shows in general the same patterns in the region, representative of sequences deposited in deltaic or shallow marine conditions. First, a sequence of marls associated with La Luna Formation was deposited in shelf anoxic conditions during the Turonian-Campanian (PDVSA internal reports) (Renz, 1959; Bralower and Lorente, 2003). The upper unit consists of a major marine shales and silts deposition, also interpreted as Late Cretaceous in the Maracaibo Basin (Lugo and Mann, 1995; Parnaud et al., 1995), where a maximum flooding surface took place. In general, this sequence is characterized by inner to outer shelf environments formed during a marine transgression (Figure 4.14). A regression is recognized at the last stages of Late Cretaceous where the Colon Formation is deposited (Figure 4.15). Furthermore, this seismic character correlates with previous interpretations in the Maracaibo Basin, as a carbonate platform formed where thermal subsidence led to sediment accumulations (Lugo and Mann, 1995).

In addition, an important depocenter is observed where a thrust fault is interpreted (Figures 4.10 and 4.16b). This structure has been previously reported as the main thrust detachment in western Venezuela since the upper marine unit of the Colon Formation has been involved along this detachment surface creating these thicker depocenters (Audemard, 1991; Mann et al.; 2006).

Overall, the Cretaceous sequence (S1) is interpreted as a passive margin where a relevant active deformation during this period is not observed. Nevertheless, the sequence is notably thinner towards SW probably affected by the ongoing terranes uplift associated to the collision of the Great Arc of the Caribbean against NW South America (Pindell et al., 1998) by Late Cretaceous.

4.2.3.2. Sequence 2 (S2): Early Paleocene (Maracaibo province).

(a) Well character:

This sequence is not penetrated by wells offshore. It lies unconformable on top of the sequence 1, reported on wells onland with a range of 65 up to 300 m thick. Two lithological units are recognized using the gamma-ray log. First, a lower unit with high gamma-ray values and some lower peaks, related with marine shales, silts, and some interbedded sandstones. Second, the

upper unit shows a different pattern, with low gamma-ray values in a blocky shape and shales interbedded, linked to inner neritic conditions associated with carbonates deposits (Figure 4.14).

(b) Seismic character:

A series of strong reflectors defined the upper part of the sequence with higher frequencies and intermediate amplitudes than the underlying unit. The contact between these two quite different units shows a strong impedance response. An unconformity caps this sequence, which in some sections appear as angular, showing onlapping reflectors from the overlying sequence against this sequence (Figure 4.9).

(c) Top time structural and thickness maps:

The surface is variable, up to 5600 ms. The boundary between the Maracaibo and the Urumaco provinces, represents an abrupt increase in depth northeastward, as is also observed in the S1 (Figure 4.17a). This unit shows strong erosion or not deposition in the southwestern parts. In general, the sequence is thinning toward the north with transitional changes from south to north. The main depocenter is observed at a high uncertainty area due to data grid coverage (Figure 4.17b).

(d) Interpretation:

This sequence gradually changes from outer shelf to shallower deposits during a marine regression (SW-NE). Shallow marine condition allowed the deposition of the Guasare Formation (carbonates at the top of the sequence) (Figure 4.17). Fault family 2 seems to be inactive at this time.

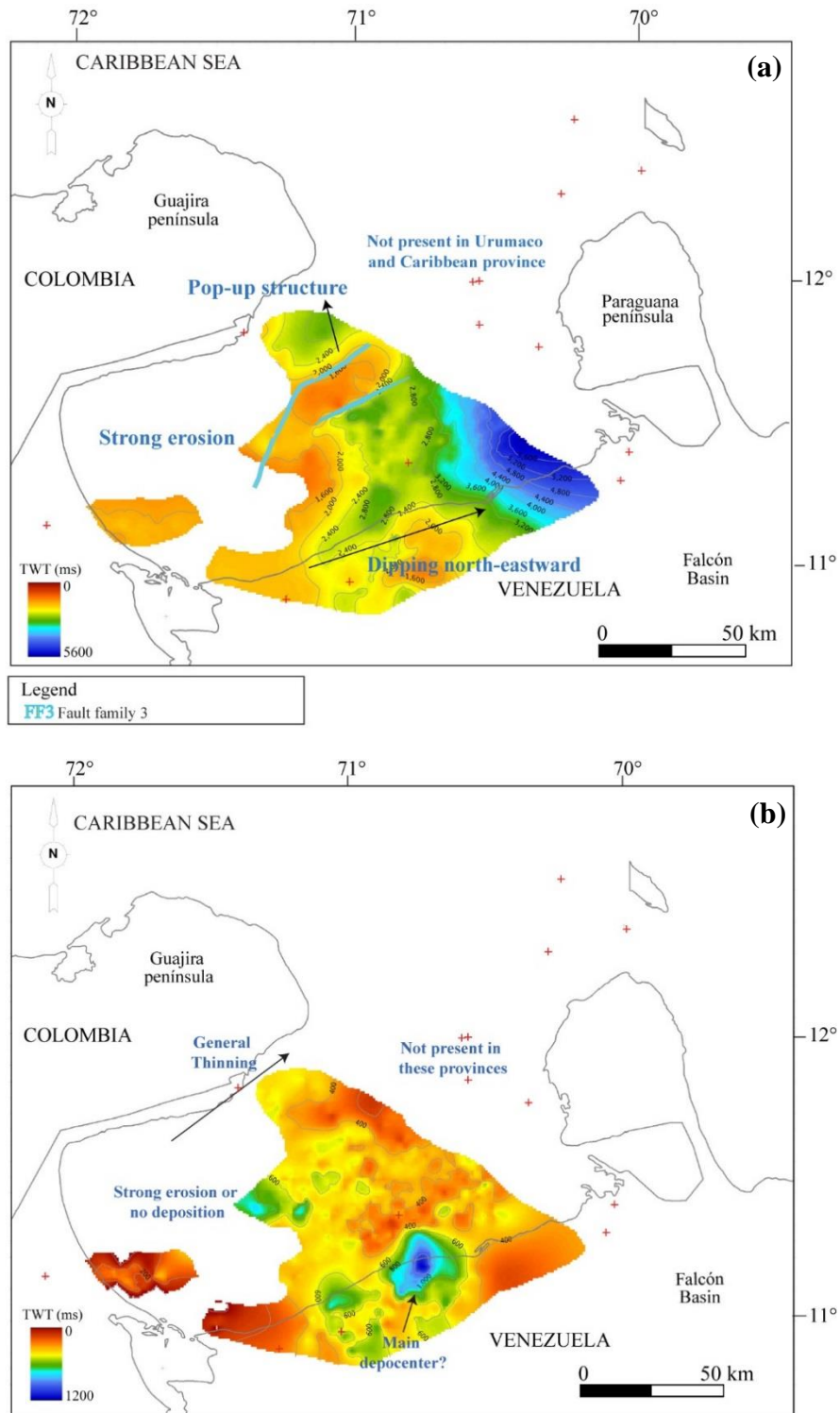


Figure 4.17. Maps showing the main characteristic of Early Paleocene sequence (S2). (a) Top structural map. (b) Thickness map.

4.2.3.3. Sequence 3 (S3): Late Paleocene-Eocene (Maracaibo province).

(a) Well character:

This is the older sequence that has been penetrated offshore in the Maracaibo province, located about 2000-2600 m depth. It was not reported by the well located in the southwestern area of the Maracaibo province (well A) (Figure 4.14). Thickness is variable due to erosion or not deposition of the Eocene unit, ranging from 100 to 1000 m. Maximum time gap is 42.7 Ma reported in well A overlying Paleocene rocks (Figure 4.15), contrary to 14.7 Ma in well G and 2 Ma in well K, overlying Oligocene rocks (Urumaco province); ages are taken from PDVSA internal biostratigraphy.

The contact between S2 and S3 is unconformable with an abrupt lithology change. Furthermore, this boundary is defined by an increase in gamma-ray log values linked to shale deposits. However, some packages of sandstones are observed. In general, a coarsening upwards trend is recognized. Moreover, biostratigraphy reports indicate marine to outer shelf environment for this sequence (Figure 4.14).

(b) Seismic character:

Chaotic, wavy, and discontinuous reflectors composed this sequence. However, this seismic behavior is variable since the reflectors show high amplitudes and continuity towards the boundary with the Urumaco province (Figure 4.8). Parallel high amplitude reflectors are recognized in some lines, interpreted as deep marine deposits (Figure 4.9). Evidence of growth strata is not recognized.

Moreover, this sequence is capped by a regional angular unconformity, which is easier to identify on reflection data with erosional truncations and toplaps as its main signature. The sequences are more affected for this unconformity in the southern areas. Therefore, time missing increase southwards, capping different sequences through the study area (Figures 4.9 and 4.15).

Mounded configurations with high amplitude and wavy reflectors, related to high-contrast impedance and vertical-growth, are recognized in a mini-basin at the northwestern area of the Maracaibo province, within a Paleogene deformation-related high.

(c) Top time structural and thickness maps:

The time structural map shows contours between 800 and 4000 ms (TWT). The surface plunges towards the east as S1 and S2, being intersected by fault families 2 and 3 (Figure 4.18a). Thinning and erosion towards the basement highs is characteristic of this sequence. Furthermore, two major NE-SW elongated depocenters are observed, controlled by the fault families FF3 and FF2 (Figure 4.18b).

(d) Interpretation:

The sequence S3 marked the end of the passive margin and the beginning of an active compressional margin. This sequence is interpreted as deep marine shales, during a marine transgression with some intervals where the gamma-ray values decrease, associated with turbidites deposits. Chaotic-discontinuous reflectors and considerable thickness changes through the sequence suggest syn-tectonic sedimentation, where normal faults of the fault families 2 and 3 are active (Figure 4.18b). Truncations and toplap suggest previous deformation and uplifted of the SW structural high before the regional unconformity (Figure 4.9). Atop this high, there are some deposits associated with carbonate banks buildup that generates an internal local unconformity and shows more than 5 km width (Figure 4.9).

The prominent unconformity correlates with the regional Eocene unconformity recognized in the Maracaibo Basin, where a younging of this unconformity is also observed with a major gap along the forebulge (Figure 4.15) (Escalona and Mann, 2006c). The marine deposits recognized along the area are probably associated with sedimentation that comes from the Proto-Maracaibo River (Escalona and Mann, 2006c). Thinning towards NW is associated with deformation and uplifted of the referred structural high, which creates the shallower conditions to develop the carbonate banks (associated with the reactivation of fault family 3) (Figure 4.9).

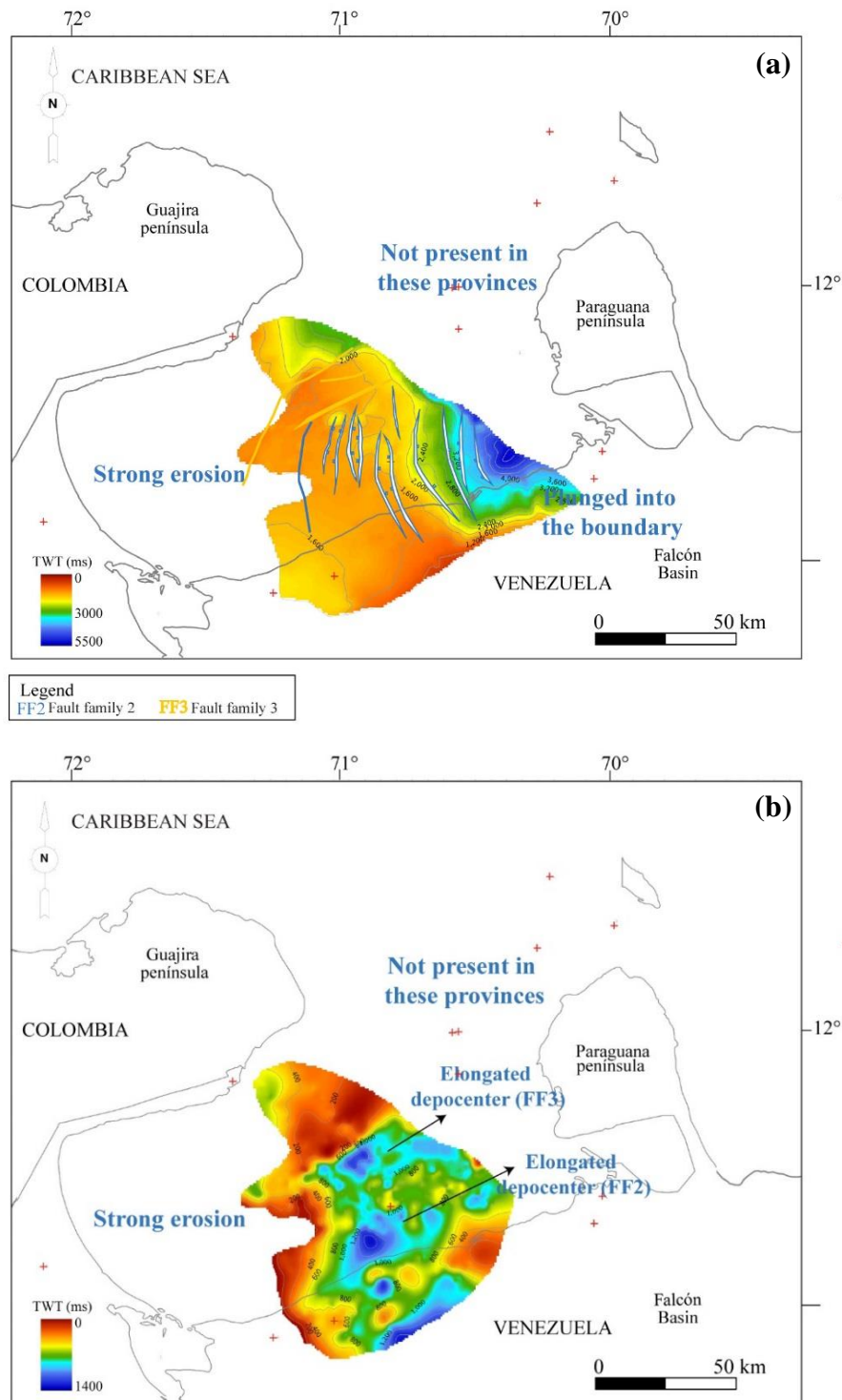


Figure 4.18. Maps showing the main characteristic of Late Paleocene-Eocene sequence (S3).
(a) Top structural map. **(b)** Thickness map.

4.2.3.4. Sequence 4 (S4):

- Sub-sequence 4-1 (S4-1): Oligocene (Maracaibo province).

(a) Well character:

The well G reported the S4 sequence, located at 2300 m depth and thickness about 400 m (Figure 4.14). This sequence is defined by a coarsening upward gamma-ray curve. This sequence is dominated by sandstones with shale interbedded and a few amounts of coal associated with continental facies (PDVSA biostratigraphy reports).

(b) Seismic character:

This subsequence is difficult to map and recognize on the seismic sections since it is mostly eroded in the area. Nevertheless, in some sections an unconformity is observed where S4 is onlapping against S3 (Figure 4.8). Reflectors are relative continuous with moderate amplitude. The top of this sequence is defined by the regional unconformity, which also capped sequences from S1-S3 (Figures 4.8, 4.9, and 4.15).

(c) Interpretation:

The S4 represents an important environmental change from marine deposits (S3) to continental conditions for this sequence. The observations are according with the events recognized in the Maracaibo Basin, with uplifted of the Paleogene sequence, generating continental conditions (Escalona and Mann, 2006a).

- Sub-sequence 4-2 (S4-2): Eocene-Oligocene (Urumaco and Caribbean provinces).

(a) Well character:

This sequence has been reported in wells K, L, M, and O. The Eocene was penetrated in well O. Therefore, the Eocene unit is considered as part of S4, due to genetics relationship (Figure 4.14). The thickness range from 80 to 350 m, located at approximately 2900 m. In addition, lithology identified on the logs indicates lateral facies variability. Based on previous reports, the wells K and L consist of shales and thin layers of calcareous sandstones. Moreover, the Perla carbonates started to develop at the last stage of this sequence. In contrast, a deep marine claystone and shales deposits are recognized in the Aruba basin (well O).

(b) Seismic character:

The sequence S4-2 overlies unconformably the Cretaceous(?) acoustic basement (Figure 4.14). Low-amplitude and poor-continuity reflectors with chaotic facies are observed. However, a more continuous and higher-amplitude reflection character is recognized in depressions along the study area, specifically in the Urumaco trough and the Bonaire Basin. The unconformity capped this sequence, and it is the top of sequences S1-S3, as it was mentioned before (Figures 4.8 and 4.9).

(c) Top time structural and thickness maps:

The top surface of this sequence is characterized by abrupt changes. Reaching 4400 ms depth on the structural map, an NW-SE elongated depression is recognized, associated with the Urumaco trough. Furthermore, a depression related with the Aruba Basin is also observed as well as a prominent structural high related with Los Monjes (Figure 19a). Main depocenters are recognized in the southern most edge of the sequence, developed along a member of fault family 1 (strike-slip 1). Other depocenters are observed towards the north. A thinning of this sequence is developed linked with high structures (Figure 19b).

(d) Interpretation:

Inner shelf to deep marine conditions are interpreted in this sequence. This is in agreement with Gorney et al (2007), where a comparison of this sequence in Bonaire Basin with previous works (Curet, 1992) is performed. This sequence is associated with deep marine depositional setting, that support the observations made in the northernmost region of the study area. Uplift of Perla high might be present at the last stage of this sequence due to a carbonate platform developing during Late Oligocene.

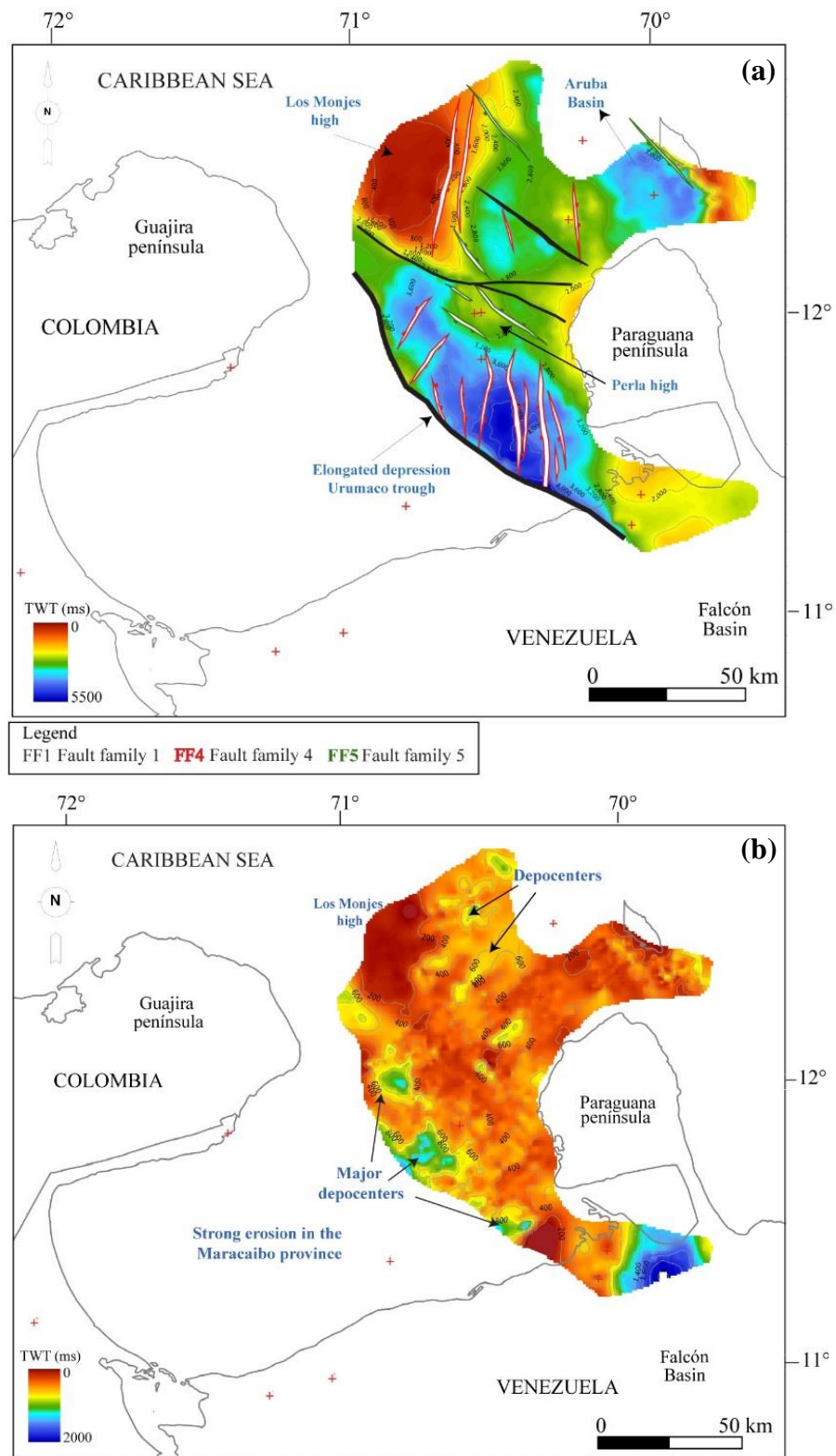


Figure 4.19. Maps showing the main characteristic of the Oligocene sequence (S4-2) (Urumaco and Caribbean provinces). **(a)** Top structural map. **(b)** Thickness map.

4.2.3.5. Sequence 5 (S5): Early Miocene (Maracaibo-Urumaco-Caribbean provinces).

(a) Well character:

This sequence has not been penetrated in the Maracaibo province. Thickness between 200 to 600 m is observed. In the wells K and L, the gamma-ray log reveals two main units: a generally blocky, high-values unit, associated with carbonates deposits in shallow marine conditions; and a thick unit with overall low-values indicative of shales and claystones deposits with interbedded sandstones. Moreover, a thick marine shale unit with some thinner sandstones layers are observed in wells O and N, towards the northern region (Figures 4.14 and 4.15).

(b) Seismic character:

The S5 is filling the Urumaco trough in a divergent-filled context that is internally characterized by poor-continuity wavy reflectors. These reflectors have higher amplitude and better continuity into the top of the sequence.

A chaotic wavy reflectors section between 2200 and 2400 ms is recognized within the Urumaco trough infilled (Figure 4.11). In contrast, some sections at the northern part of the study area are characterized by reflections with good continuity, exhibiting moderate to high amplitudes. Furthermore, pinch-out towards the south is characteristic of this sequence with onlap terminations over the regional unconformity (Figure 4.20a). Grow strata is recognized in the hanging wall of the fault families 1 and 4 (Figure 4.21).

This sequence is significant thicker towards the southwest of the Monjes high, suggesting active deformation of the fault family 1 during its development. On the other hand, a mini basin controlled by Los Monjes uplift is defined by divergent, discontinuous, and chaotic reflectors (Figure 4.21).

In addition, high-amplitude reflectors at the base of this sequence are observed, and could be mapped in some sections (Figure 4.11).

(c) Top time structural and thickness maps:

The surface ranges from 800 ms to 4000 ms (TWT). It exhibits an irregular pattern due to the fault activity, flatting towards southwest and dipping southeastern (Figure 20a). The thickness map reveals large fault activity (from the fault families 1 and 4) with deformation associated during deposition, showing values from 200 to 1200 ms (TWT). Four (4) major depocenters are developed: three (3) NW-SE-oriented depocenters associated with the Aruba Basin, Urumaco trough, and Cocinetas Basin, respectively, and one (1) NE-SW-oriented depocenter related with Los Monjes high deformation. The largest depocenter (Urumaco trough) seems to be only restricted to the offshore area, with a major depozone in the northern segment of this structure. In addition, the S5 pinch-outs to the south, and onto structural highs to the northwest (Los Monjes) (Figure 20b).

(d) Interpretation:

In general, this sequence is interpreted as inner shelf to deep marine environments. Thickness changes by infilled of mini-basins and troughs indicate deposition of this sequence during active tectonism related with the fault families 1, 3, and 4 (associated with an increase in subsidence). In addition, the thinning-trend over structural highs indicates erosion with subsequent re-deposition within main depocenters (Figure 20b).

On the other hand, a Lower- to Middle-Miocene unconformity is reported in the Paraguaná Peninsula and west Curaçao basins (Gorney et al., 2017) that can be correlated with the top unconformity of this sequence.

During the Early Miocene, highs are developed in the Urumaco and Caribbean provinces, which allowed carbonates deposition such as the Perla bank, predominantly composed of larger benthic foraminifera and red algae, and minor components of green algae and corals (Pomar et al., 2015). The Urumaco trough still constitutes the most relevant elongated depocenter in the study area.

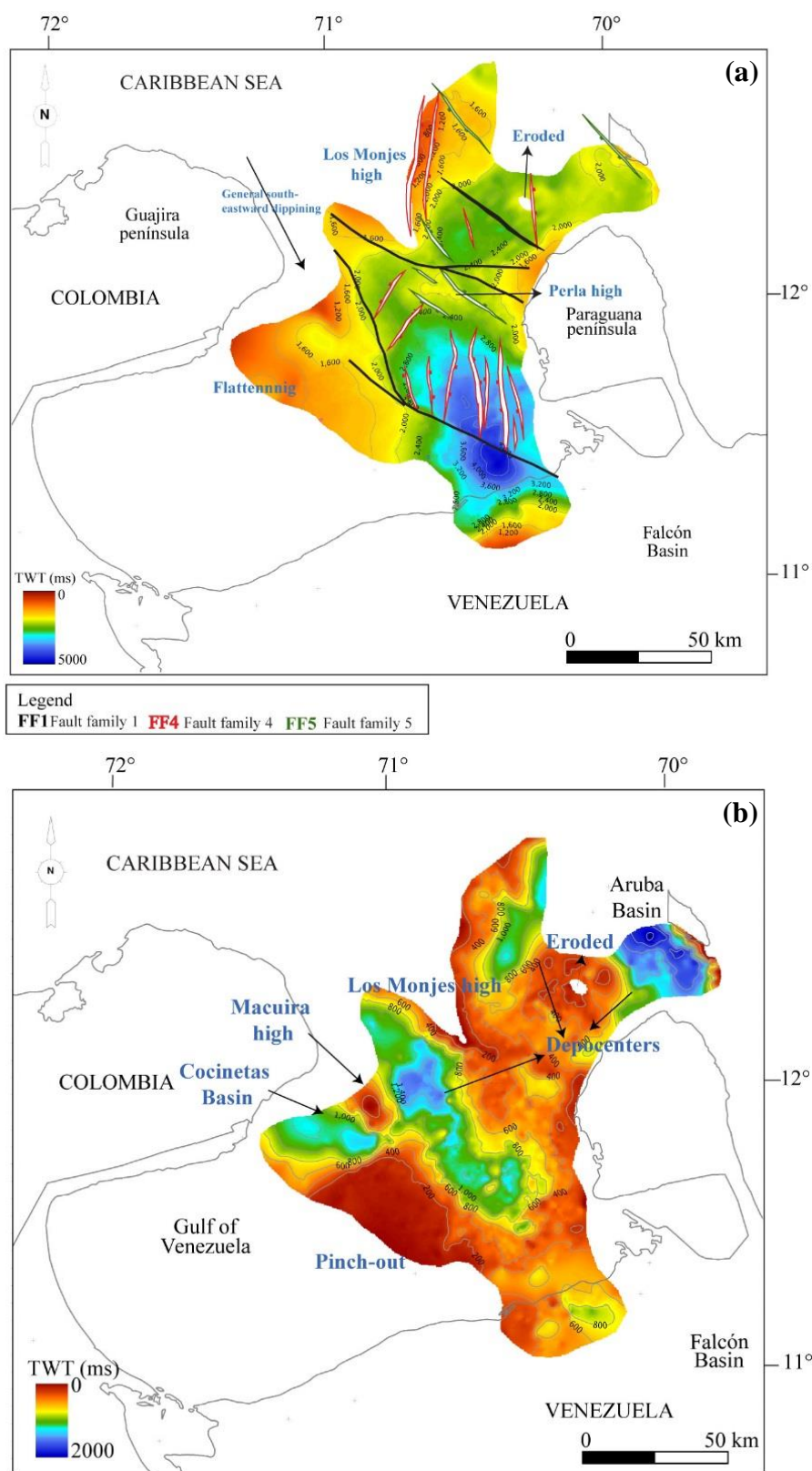


Figure 4.20. Maps showing the main characteristic in the Early Miocene sequence (S5) (Urumaco and Caribbean provinces). **(a)** Top structural map. **(b)** Thickness map.

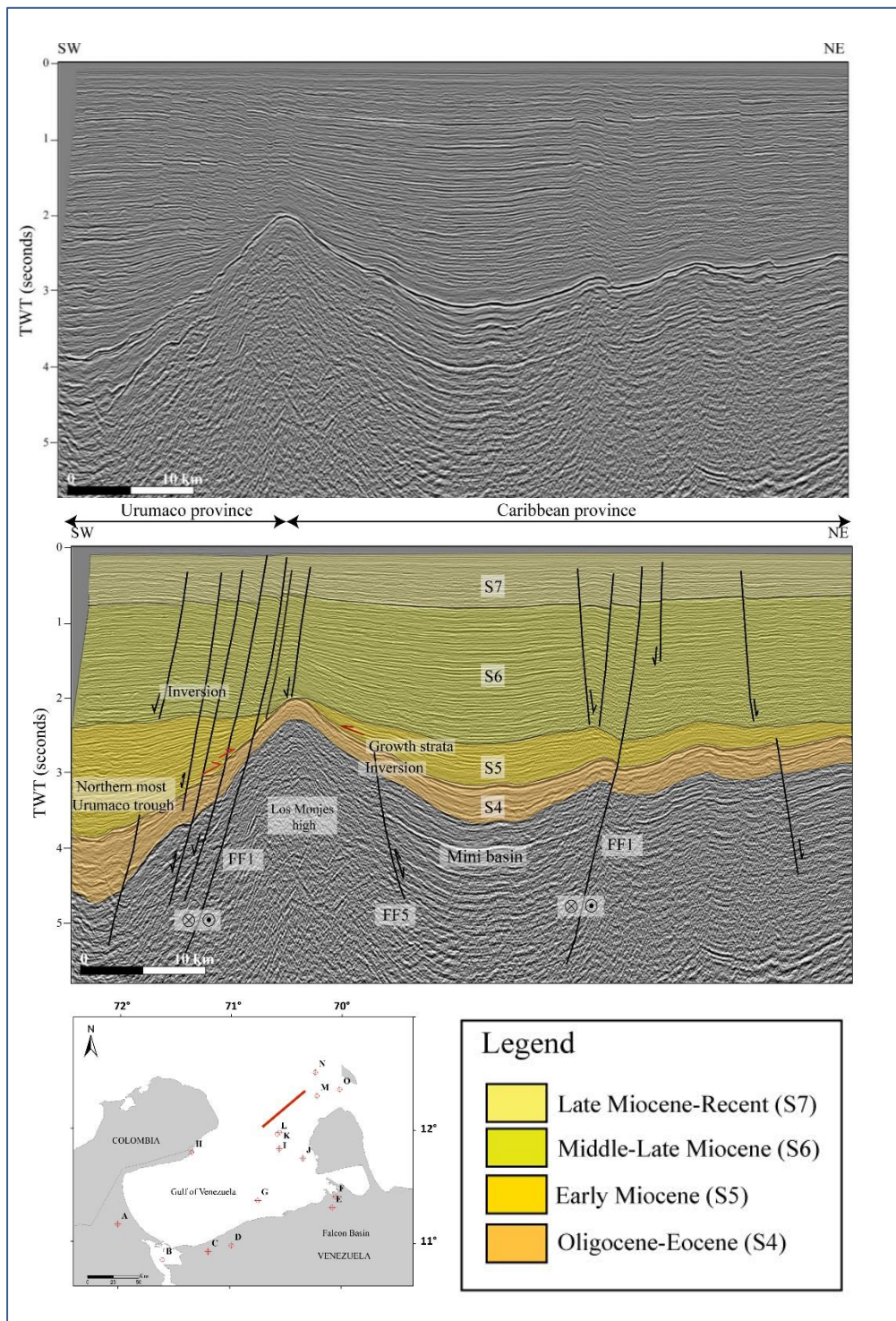


Figure 4.21. Seismic section showing the southernmost structure of Los Monjes high.

4.2.3.6. Sequence 6 (S6): Middle to Intra Late Miocene.

(a) Well character:

This sequence was penetrated by all available wells in the study area. A range between 800 to 1400 m of sand with shale interbedded is recognized in well logs, showing an irregular gamma-ray curve at the upper part, characteristic of heterolithic deposits (Figure 4.14). In addition, coal is reported in the well G based on core reports.

(b) Seismic character:

This sequence also represents part of the infilled of the Urumaco trough. Internally, S6 presents variable amplitudes and moderate-to-good continuity of the reflectors. Divergent and semi-parallel are the most representative reflectors (Figure 4.11). In the Maracaibo province, different patterns could be observed: at the lower unit, the reflectors are more continuous than in the upper unit, where their character is wavy and chaotic. In addition, several intra-unconformities are observed that affect this sequence (Figure 4.8).

Normal prograding, high relief clinoforms geometries are recognized at the northern most areas (Caribbean province) (Figure 4.12). In addition, downlap reflection terminations against the regional unconformity is recognized in the Maracaibo province, suggesting a local southwards progradational filled (Figure 4.8). Evidences of inversion are observed in this sequence, associated with the fault family 4 (Figure 4.4).

(c) Top time structural and thickness maps:

Sequence 6 comprises one of the thicker units interpreted covering the study area. The Urumaco trough is still recognized at the top of the structural map (Figure 4.22a). The S6 is characterized in the Maracaibo province by an undeformed wedge-shape geometry dipping and thinning southwest from 1200 ms to 200 ms (TWT) (Figure 4.4 and 4.22a). Significant thickness variation is observed in both, the Urumaco and Caribbean provinces, recognized by main depocenters, controlled by fault activity (Figure 4.22b). In these two provinces, this surface is steeper, plunging into the Urumaco trough, which continues to the northern most area of the Falcón Basin.

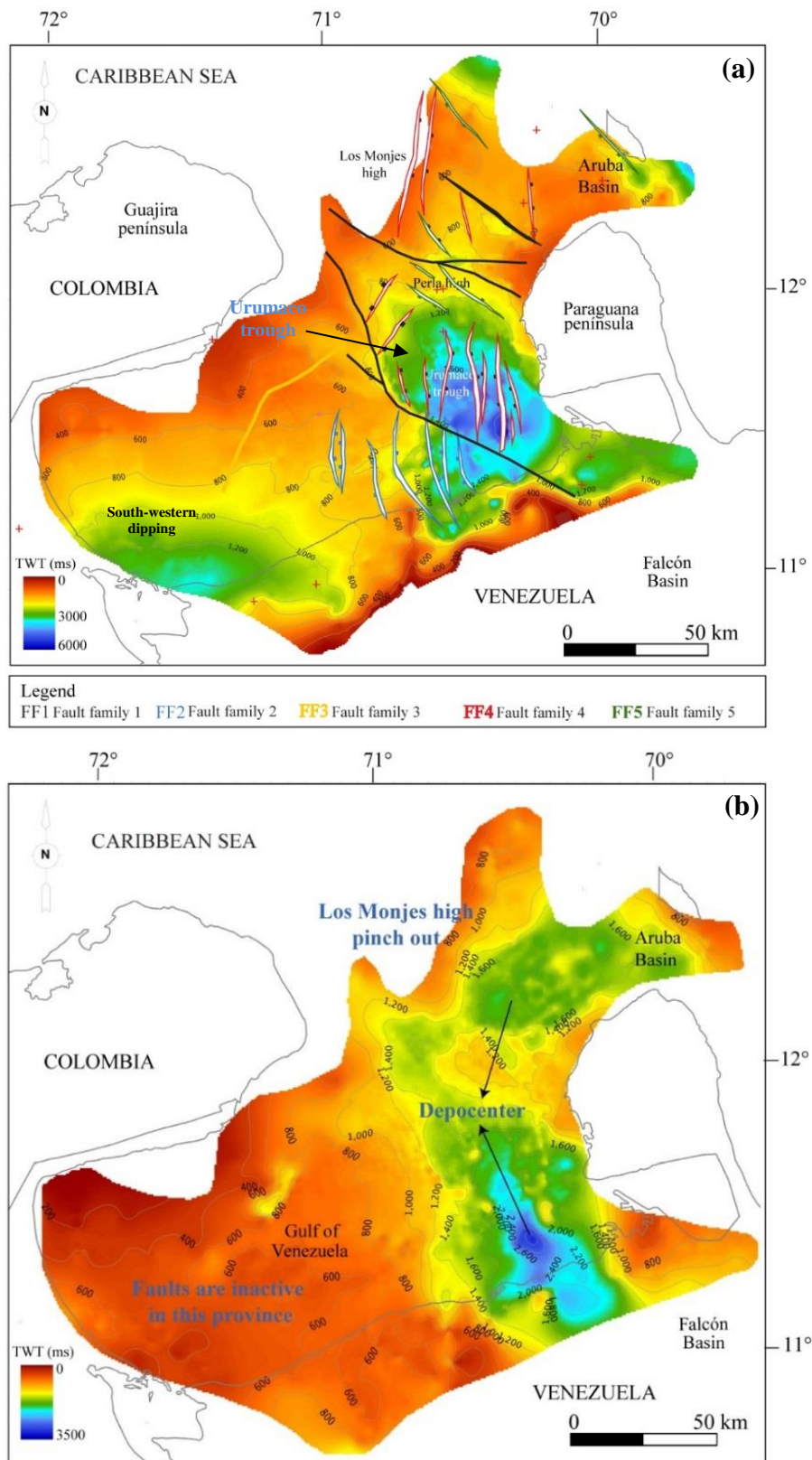


Figure 4.22. Maps showing the major features of the Middle to Intra Late Miocene sequence (S6). (a) Top structural map. (b) Thickness map.

(d) Interpretation:

The features observed along this sequence suggest an inner shelf to transitional environment at the southern areas. Towards the north, the conditions are associated with a deep marine-outer shelf. However, the regional trend indicates marine regression. Different intra-unconformities recognized in the S6 might be associated to several periods of subsidence and uplifted during the deposition of this sequence (typically of strain-partitioning deformation). On the other hand, no deformation is affecting this sequence in the Maracaibo province (Figure 4.22a), on the contrary to the Urumaco and Perla provinces, where fault families 1 and 3 are active. The S6 assemblage suggests a syn-tectonic unit ranging to a wedge-shape in the southern region (Figure 4.22b).

4.2.3.7. Sequence 7 (S7): Late Miocene to Recent.

(a) Well character:

Overall, the gamma-ray curve defines a coarsening upwards sequence (Figure 4.14). Inner neritic to continental deposits are recognized. The southernmost part of the study area reflects blocky sandstone units, related with a continental setting. Based on biostratigraphy reports (PDVSA), the sequence is deposited in continental conditions towards the southern region that changes to a transitional and shallower marine environment northwards.

(b) Seismic character:

Variations between high-amplitude and chaotic reflectors is very common for this sequence, as well as moderate- to poorly-continuity of these reflectors (Figures 4.4 and 4.8). Evidence of progradation is not recognized as in S6. Moreover, downlap reflections are observed against the lower unconformity. Minor internal unconformities are also recognized.

(c) Thickness map:

In general, the sequence S7 shows a range between 400 to 600 ms. Similar characteristics than S6 are observed in the S7 thickness map. However, at the northern most region depocenters are not observed. The main depocenter associated with the Urumaco trough is still controlled by the fault families 1 and 4, showing continuation towards the Falcón Basin and restricted to

the southeast part in the Urumaco province. Furthermore, gradual thickening towards the southern region is recognized (Figure 4.23).

(d) Interpretation:

The tectonic loading that characterizes the Maracaibo province since the Early Miocene has influenced on the gradual thickening towards the southwestern most region of the sequence S7 (Figure 4.23), creating accommodation space (depocenter). Overall, the depositional conditions are transitional since heterolithic sequences are observed along the area.

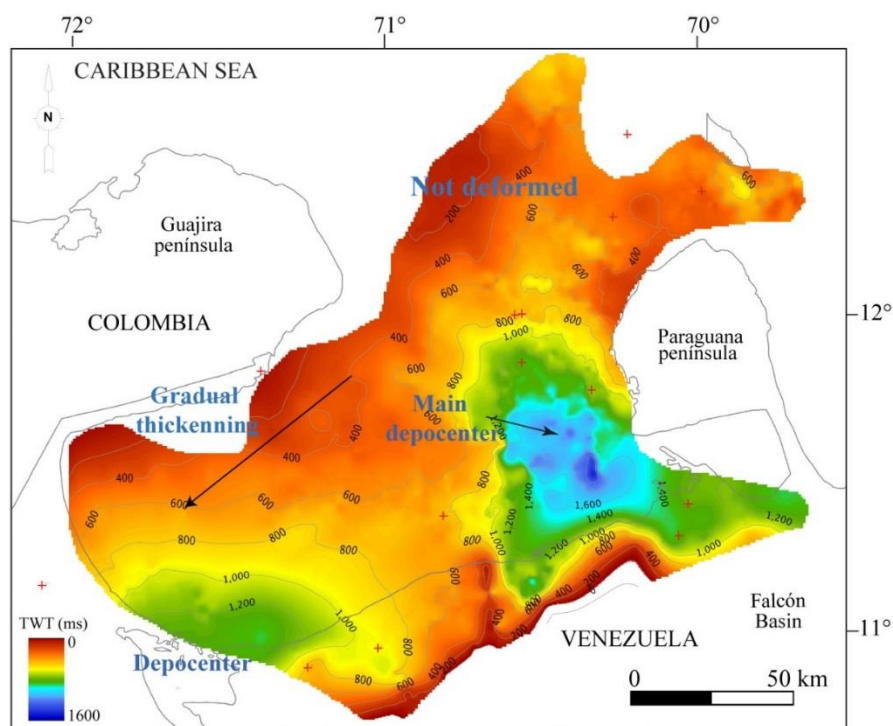


Figure 4.23. Thickness map showing the major features of the Late Miocene-Recent sequence (S7).

4.3. Subsidence patterns in the Gulf of Venezuela.

Subsidence plots reflect a relationship between sedimentation, tectonics, and subsidence. Therefore, the curve patterns and behaviors on the plots are associated with the main geologic events that affected the study area. Three different burial histories are shown, displaying total subsidence from key wells in the basin.

4.3.1. Maracaibo province.

The well A located onland in northwestern region of the Maracaibo Basin, shows a steady subsidence pattern from Early to Late Cretaceous. Spanning from Paleocene to Early Miocene, the subsidence curve shows a steeply subsidence pattern. Moreover, during the Late Paleocene-Eocene, an abrupt tectonic uplift interrupted the subsidence phase. Finally, an increase in subsidence rates occurs in the Early Miocene (Figure 4.24a).

On the other hand, the well G located offshore in the Maracaibo province, displays a similar trend such as the well A. However, the subsidence rates show different patterns from the Oligocene to Recent, occurring small periods of subsidence rates. (Figure 4.24b).

4.3.2. Urumaco province.

The well K, located in the Caribbean province, shows a subsidence curve that is different from the Maracaibo province. An initial period of subsidence is recognized, and then an inversion during the Late Oligocene occurred. The last phase of deformation is characterized by fast subsidence rate with small periods of inversion. This last stage shows similar patterns to those observed since the Oligocene in the well G (Figure 4.24c).

4.3.3. Interpretation.

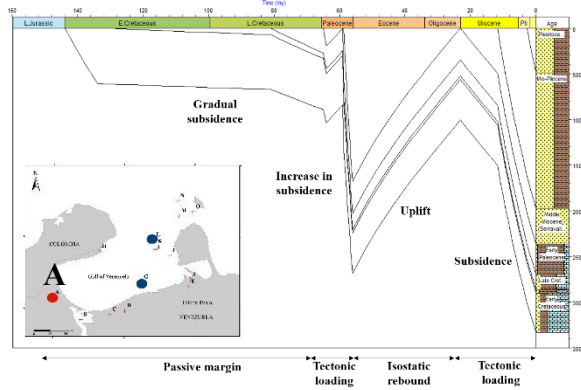
Subsidence rates display by the well A (Figure 4.24a) seem to display similar patterns and timing than the Maracaibo foreland basin. The different phases observed on the subsidence plots (well A) is the response to major geological events: (1) An initial passive margin (Late Cretaceous-Paleocene); (2) A burial foreland phase, associated with the oblique collision between the Caribbean and South American plates (Paleocene-Early Eocene); (3) Isostatic rebound (Oligocene) triggered by the Maracaibo Basin uplift; and (4) Tectonic loading related to the uplift of the Sierra de Perijá and Mérida Andes mountains. These observations are in accordance with previous works (Escalona and Mann, 2011) (Figures 4.24a and 4.24d).

In the case of well K, this geological trend resembles the Caribbean tectonic phases described by previous authors (Escalona and Mann, 2011). During the Oligocene, the subsidence phase is associated with phase 1, where the sedimentation starts in this province. Following by an abrupt inversion around approximately 26 Ma, which corresponds in timing with the phase II previous described (~23 Ma). This period of uplifting, coincides with one major unconformity

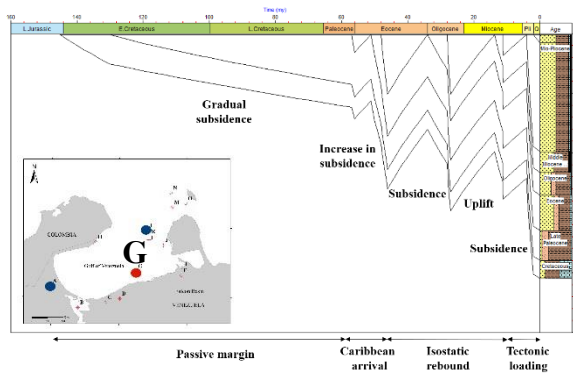
interpreted in the basin. The last tectonic phase is associated with a segmentation tectonics phase III, associated with strain-partitioning due to oblique compression (Figures 4.24c and 4.24e).

On the other hand, tectonic phases in the well G are associated with the Maracaibo Basin until the Oligocene period. Then, the Urumaco province seems to be affected by the Caribbean deformation, displaying different periods of fast subsidence, and small periods of inversion. This assumption, suggests that the location of this well is closer to a major boundary between quite-different terranes (Maracaibo and Caribbean) (Figures 4.24b, 4.24d, and 4.24e).

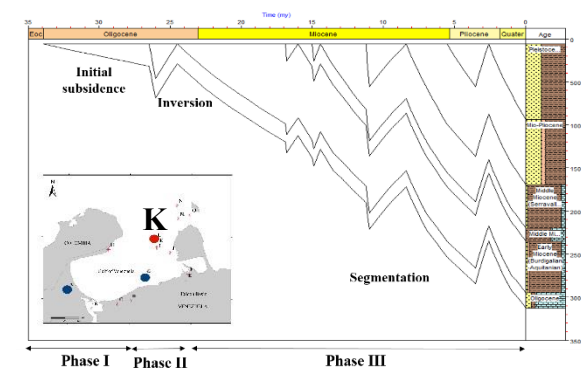
(a) WELL A (Maracaibo province)



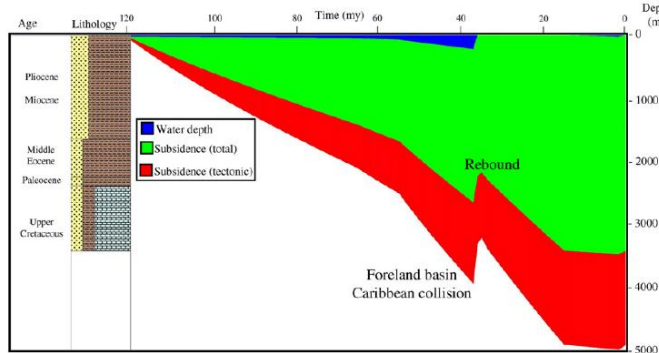
(b) WELL G (Maracaibo province)



(c) WELL K (Urumaco province)



(d) WELL 1 (Maracaibo province)



(e) WELL 2 (Caribbean province)

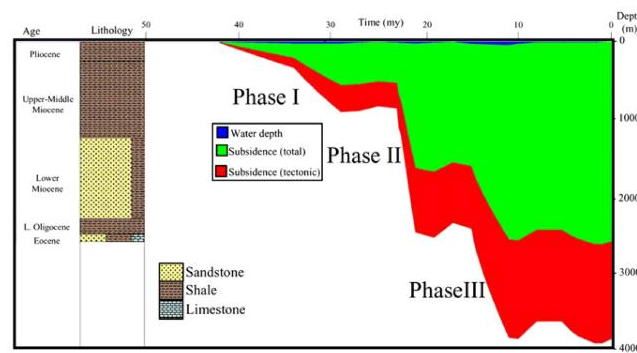


Figure 4.24. Subsidence plots from key wells in the study area. **(a)** Well A shows a subsidence curve with geologic events associated to the Maracaibo Basin: gradual subsidence, increase in subsidence, uplift, and steeply subsidence. **(b)** Well G is associated with the Maracaibo Basin events until the Oligocene period. Then, the Urumaco province seems to be affected by the Caribbean deformation. **(c)** Well K resembles the Caribbean tectonic phases. **(d)** and **(e)** are subsidence plots calculated for the Maracaibo Basin and Caribbean terranes, respectively (Escalona and Mann, 2011). Well location maps are shown (inset).

5. DISCUSSION.

5.1. Strike-slip configuration and implications.

A strike-slip system is present in the Gulf of Venezuela, as a kinematic consequence of an oblique convergence of the Caribbean oceanic plate and the northwestern most corner of the South American continental plate. These series of roughly east-west oriented strike-slip faults along the southern edge of the Caribbean accommodate the eastward displacement of the allochthonous terranes and the Caribbean plate itself. However, this is not a simple east-west strike-slip plate boundary, since evidence on seismic data and previous GPS studies have indicated active displacements at different times (Trenkamp et al. 2002; Perez et al., 2001).

5.1.1. The major strike-slip system recognized in the Gulf of Venezuela.

5.1.1.1. Cuiza- Río Seco fault (strike-slip 1 system).

A 200 km long, WNW-ESE strike-slip 1 fault system is interpreted as a lateral ramp that represents the suture between the South American stable continental plate (Maracaibo autochthonous province) and the allochthonous terranes (Urumaco province) in northwestern South America (Figure 5.1). Based on the important seismic characters differences observed on the seismic interpretation (Figure 4.4), a hard boundary between both provinces is proposed in central Gulf of Venezuela. In addition, a focal mechanism solution also reveals a strike-slip component along this fault plane (hypocenter=28.6 km depth) which support an entire crustal influence of this fault (Figure 4.13). It affects the entire sedimentary record with activity since no later than Oligocene to Present. Major activity with a large vertical component is recognized during the Oligocene to Early Miocene.

On the other hand, this fault is suggested to be the offshore northwestward continuation of the WNW-ESE striking Río Seco fault (also named as Sabaneta fault), interpreted onland of northwestern Falcón Basin (Audemard, 1997, 2001). The Río Seco fault is characterized as a right-lateral strike-slip with over 20 km of extension.

The westernmost extension of the strike-slip 1 system is suggested to be as far as the Cuiza fault, located onland in the Guajira Peninsula (Figure 5.1). The Cuiza fault has been previously proposed as an active structure during the Early Oligocene with its major strike-slip activity during this time (Gomez, 2001). By Miocene, the Cuiza fault has been active as a dominant normal fault.

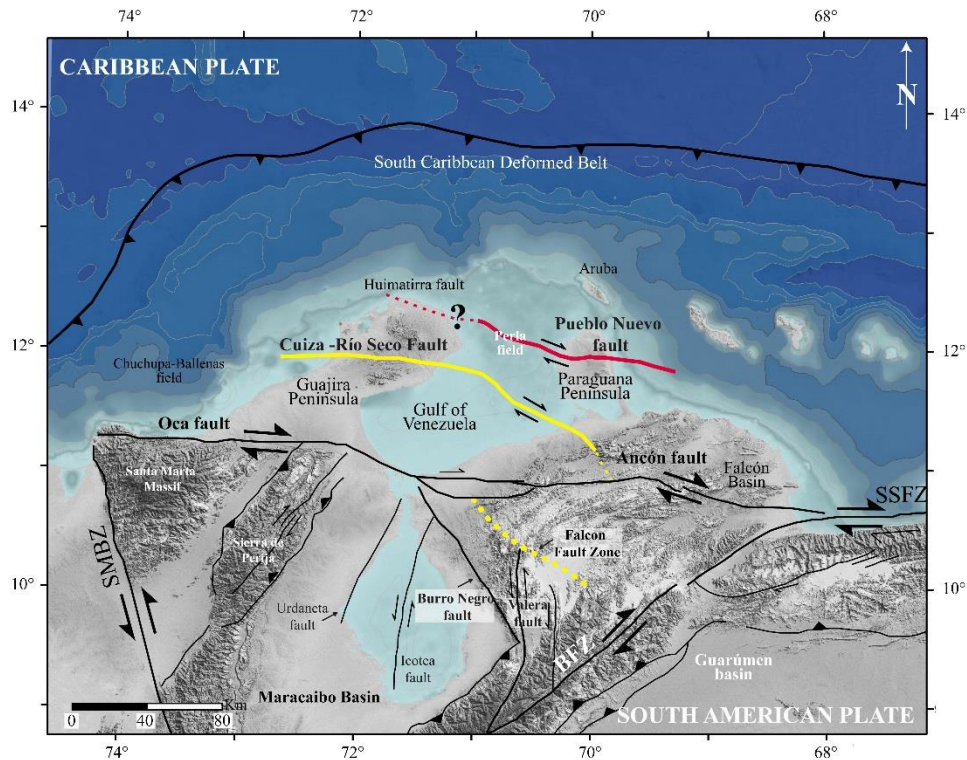


Figure 5.1. The major strike-slip fault systems recognized in the Gulf of Venezuela: the Cuiza- Río Seco fault system (solid yellow line); the Pueblo Nuevo fault (solid red line), and the Falcón Fault Zone (dotted yellow line).

- **Role of the Falcón Fault Zone.**

It is considered the possibility of a further southern extension of the Cuiza- Río Seco fault system, beyond the Oca- Ancón fault system southwards (Figure 5.1). Two major faults have been described in this area as lateral ramps related to this northern most Cuiza- Río Seco system: the Burro Negro Fault and the Falcón Fault Zone.

First, the Burro Negro fault has been proposed as a major Paleogene right-lateral strike-slip, or lateral ramp fault, which separates an underthrust Maracaibo platform to the south, from the edge of the southeastward moving fold and thrust system of Early to Middle Eocene age (Escalona and Mann, 2006c). In contrast, it is suggested that the Burro Negro fault zone does not represent the easternmost limit of the Maracaibo autochthonous block. Therefore, this terrane might be extended across the Burro Negro deformation zone (Contreras, 2008).

A second southeastward-striking lateral ramp fault, which is located 40-45 km to the northeast of the Burro Negro fault has been proposed, named as the Falcón Fault Zone (Figure 5.1). This

lateral ramp represents a boundary formed during southeastward thrusting of the Lara Nappes (Hervouet et al., 2005; Contreras, 2008).

Therefore, taking in consideration the horizontal right-lateral displacement estimated on the Oca- Ancón fault (70-80 km) since the Middle-Late Oligocene (Kellogg, 1984), the restoring of the Cuiza- Río Seco fault system might be aligned with the Falcón Fault Zone with a possible extension along this lateral ramp. On the other hand, since the left-lateral strike-slip Valera fault is considered as one of the most prominent tectonic feature in northwestern Venezuela, it might be major crustal fault extending northward into the Oca- Ancón fault system, and it also has to be considered as a possible continuation of the Cuiza- Río Seco fault (?).

5.1.1.2. Pueblo Nuevo fault (strike-slip 2 system).

A second 160 km long, WNW-ESE strike-slip fault 2 system is interpreted at the northernmost region of the study area, associated with the boundary between both, the allochthonous terranes in the Gulf of Venezuela and the Great Arc of the Caribbean (Figure 5.1).

The eastward continuation of this fault into the onland Paraguaná Peninsula is associated with the Pueblo Nuevo fault, which coincides with the suture zone previously defined on this region (Blanco et al., 2015) based on the integration of gravity and magnetic data, radiometric dating, and geologic information (Figure 2.3). Moreover, this boundary also coincides with the suture zone between the Mesozoic Caribbean terrane and the South America crust proposed by Baquero (2015).

The strike-slip fault 2 system was previously identified on 3D-time-slices seismic data (Benkovics and Asensio, 2015). This strike-slip 2 system is proposed to be the offshore westernmost continuation of the E-W-trending Punta Macolla-Las Cumaraguas strike-slip fault across the northern Paraguaná Peninsula (Figures 2.4 and 4.3). Nevertheless, the continuation of the strike-slip 2 towards the northern Paraguaná is not clear. The strike-slip interpreted on this region is considered as a minor fault linked to the Pueblo Nuevo fault.

This suture can be continuously trace further northwest into the northern part of the Guajira Peninsula, where the Chimare suture is proposed to be the main boundary between the continental South American province and the Caribbean terrane (Figure 2.3) (Londoño and

Schiek, 2015), associated with the Huimatirra fault (Figure 5.1). Nevertheless, the data grid does not allow to define properly this continuation.

5.1.1.3. Role of the Oca- Ancón right-lateral strike-slip fault system.

The Oca-Ancón fault system is the most important strike-slip system in northwestern South America, responsible of the eastward migration of the Caribbean plate, affecting significantly the Gulf of Venezuela region. The main activity of this fault has been restricted to Middle-Late Oligocene (Kellogg, 1984) and no later than Eocene (Feo-Codecido, 1971).

Considering an important right-lateral displacement of the Oca- Ancón fault calculated by different authors (Pindell et al., 1998; Escalona and Norton, 2015; Blanco, 2017), it is suggested that the northernmost Sierra de Perijá structure might be present in the Gulf of Venezuela (Figure 5.2). Therefore, the recognized pop-up structure restricted to the Maracaibo province might be associated with an incipient deformation of the Sierra the Perijá located towards the southwestern Gulf of Venezuela, as a branch of the main thrust fault system (Figures 4.10 and 5.2a,b). This NE-SW branch system used to be associated to a Jurassic-rift-related normal faults complex inverted later as reverse faults during a Neogene shortening phase (Duerto et al., 2006). In contrast, the origin of the thrust system interpreted at SW Gulf of Venezuela seems to be no older than Oligocene. In addition, no evidences of Jurassic filled are recognized in the study area.

Furthermore, the thrust fault observed in the Maracaibo province associated with this pop-up structure could be part of this deformation. Major thrust faults and triangle zones have been described previously as the main deformation-related accommodation structures in the southern-central region of the Sierra de Perijá mountain front (Duerto et al., 2006) using a detachment Cretaceous surface (Colon Formation). This is in agreement with the observations made on the seismic data at the southwestern region of Gulf of Venezuela (Figure 5.2d).

A similar structure associated with the southern foothills of Sierra de Perijá was also observed (Mann et al., 2006), showing similar patterns and configuration to those described at SW Gulf of Venezuela (Figure 5.2c). Based on this assumption, a 70-80 km displacement of the Oca fault is proposed on this work, which is in agreement to previous calculations (Table 1.1).

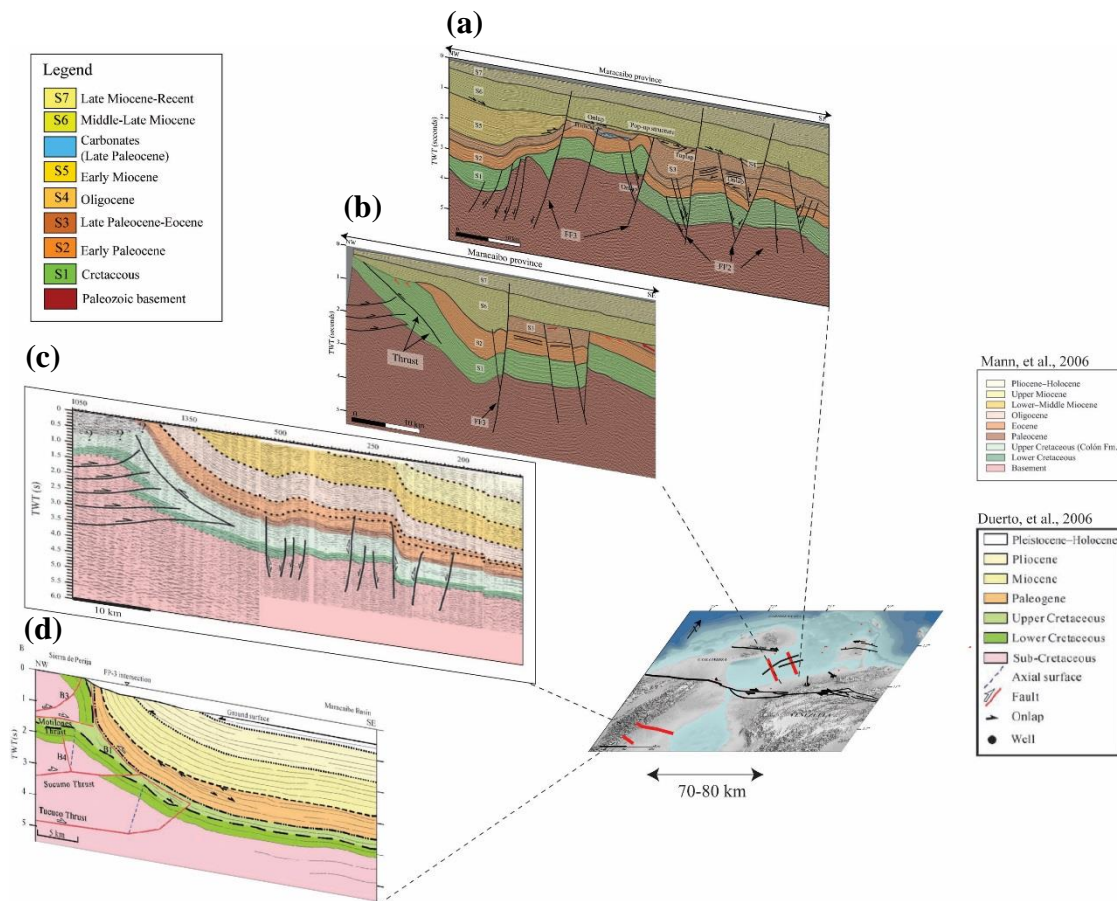


Figure 5.2. Diagram showing the Sierra de Perijá deformation recognized in the Gulf of Venezuela. (a) Pop-up structure recognized in the Gulf of Venezuela. (b) Thrust fault using Cretaceous rocks as detachment in the Gulf of Venezuela. (c) Previous seismic interpretation of the Sierra de Perijá showing a pop-up structure and thrusting-related deformation (Mann et al., 2006). (d) Seismic interpretation of the Sierra de Perijá mountain front showing the thrust fault associated as well as the triangle zones (Duerto et al., 2006).

5.2. Basement distribution in the Gulf of Venezuela.

The modern architecture of the basements in the region shows a discontinuous arrangement as a result of a high deformation zone, related to the dynamic Cenozoic convergence between the autochthonous South American plate and the Caribbean oceanic plate. Therefore, different basement provinces are identified in the Gulf of Venezuela: (a) Autochthonous block defined by Paleozoic rocks (Maracaibo province); (b) Allochthonous block with Meso-Neoproterozoic metamorphic rocks (Urumaco province); and (c) Allochthonous block defined by Cretaceous arc metamorphic rocks (Figure 5.3).

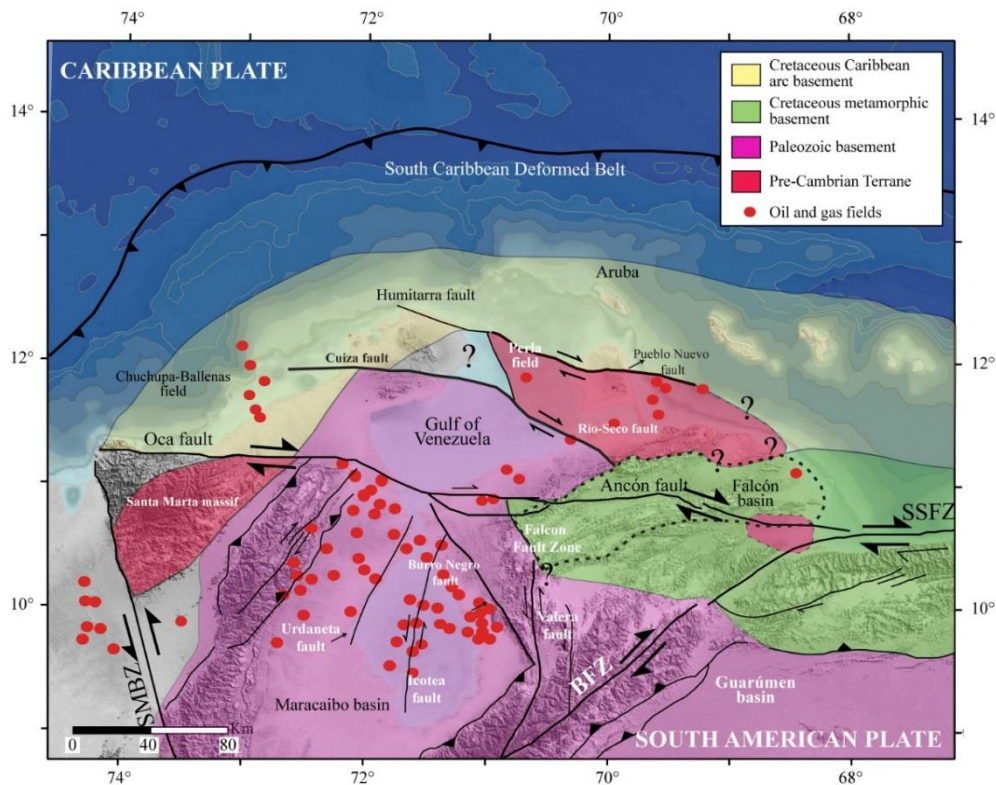


Figure 5.3. Map showing the three different basement provinces proposed in the Gulf of Venezuela, related to the regional-scale provinces defined for northwestern South America.

5.2.1. The autochthonous block - Paleozoic rocks (Maracaibo province).

Based on the stratigraphy framework, structural styles, and gravity data, the Maracaibo province in the Gulf of Venezuela constitutes an extension of the Paleozoic autochthonous basement that previous authors have identified in northwestern South America (Feo-Codecido et al., 1984; Baquero, 2015). This province contains Paleozoic metamorphic rocks found in the Maracaibo Basin, Guajira Peninsula, and in the northwestern region of the Falcón Basin (Feo-Codecido, 1984) and recently confirmed by U-Pb zircon dating (Baquero et al, 2015) (Figures 2.2 and 5.3).

This autochthonous basement has not been penetrated in the Maracaibo province. However, the well G reached the Late Paleocene sequences, and seismic interpretation reveals a stratigraphy framework that correlates with the well-known stratigraphy in the Maracaibo Basin, suggesting the extension of this block towards the Gulf of Venezuela (Figure 5.3). Therefore, the Upper Cretaceous La Luna Formation source rock should be present in this

Maracaibo province (SW Gulf of Venezuela). This assumption is in agreement with the basement provinces distribution proposed by Gorney et al. (2007) (Figures 2.2 and 5.3).

5.2.2. The allochthonous block – Meso-Neoproterozoic metamorphic rocks (Urumaco province).

Recent geochronology studies using zircon dating, confirm Meso-Neoproterozoic ages with continental-affinity in a terrane located near to La Vela Bay and Falcón Basin (Baquero, 2015), which previous authors have called the Falcónia terrane (Grande, 2013a,b) (Figure 2.2). Therefore, the Urumaco central province is interpreted as an allochthonous Meso-Neoproterozoic block with continental-affinity and it is not related either with the Cretaceous oceanic Caribbean terranes or the Paleozoic autochthonous basement (Figure 5.3).

The boundary between the Paleozoic and Pre-Cambrian basements is set in the sharp boundary described as the Cuiza- Río Seco fault system (Figures 4.3, 4.4, and 5.3). In addition, the larger Bouguer anomalies contrast along this major fault also reveals a hard boundary between these two provinces (Figure 4.2).

On the other hand, this allochthonous block is suggested to be a fragment that was transported during the Caribbean eastwards displacement and accreted in its actual position in the Gulf of Venezuela. This block is proposed to be originally placed in the northern region of Santa Marta Massif, assumption that is in agreement with some works that have proposed that these Meso-Neoproterozoic rocks can be correlated with rocks with same age located in the Santa Marta Massif (Van Der Lelij, 2013; Baquero, 2015) (Figure 5.3 and 5.4).

Some rocks with the same Meso-Neoproterozoic ages have been found in other localities in NW Venezuela (Guajira, Yumare-El Guayabo complex) nevertheless, they are considered detached fragments from this main block.

5.2.3. The Cretaceous Caribbean arc basement (Caribbean province).

Based only on the seismic characters is difficult to define lateral differences between the Urumaco and Caribbean provinces. Nevertheless, the Pueblo Nuevo fault (strike-slip 2 system) is suggested to be the boundary between the continental allochthonous Pre-Cambrian rocks (Urumaco central province) and the Cretaceous Caribbean arc (Caribbean northern province)

(Figures 4.7, 5.1, and 5.3). This fault coincides with the suture zone proposed by previous authors (Baquero, 2015; Blanco, 2017) (Figures 2.3, 5.1, and 5.3).

Wells drilled in the Aruba Basin (northernmost region of the study area) have identified a typical basement of the Cretaceous Caribbean arc (Curet, 1992). It consists of Tholeiitic basalts and andesitic volcanic rocks with oceanic-affinity. This arc is also recognized on the gravity anomalies map (Figure 4.2b).

5.3. Evolution of the Gulf of Venezuela.

Based on the stratigraphy and structural interpretation, different tectonic phases have been identified for each province in the Gulf of Venezuela. In addition, the subsidence plots also reveal that these provinces were affected by different events related with major tectonic regimens.

5.3.1. The Maracaibo province.

5.3.1.1. Phase 1: Cretaceous-Early Paleocene (Passive margin).

During this time, a passive margin covers the Gulf of Venezuela in a quiescence period with gradual subsidence rates (Figure 4.24a,b). This sequence widely correlates with the interpretations for the Maracaibo Basin at this time, with the deposition of La Luna formation as one of the most important events. This phase is characterized by a carbonate-platform, within inner to outer shelf environment, during a marine transgression. Increase in subsidence at the end of Late Cretaceous results in deep marine shales deposits (Figure 4.15). A subsequent uplift event caused erosion in the southern areas that is supported by the different toplaps and truncations observed on the seismic data.

5.3.1.2. Phase 2: Paleocene-Eocene (Foreland basin).

Overall, the eastward trajectory of the Caribbean plate during the Late Paleocene-Eocene made a 250 km-long, southeastwardly deviation over the northern continental margin of South America (Pindell and Erickson, 1994; Colleta et al., 1997).

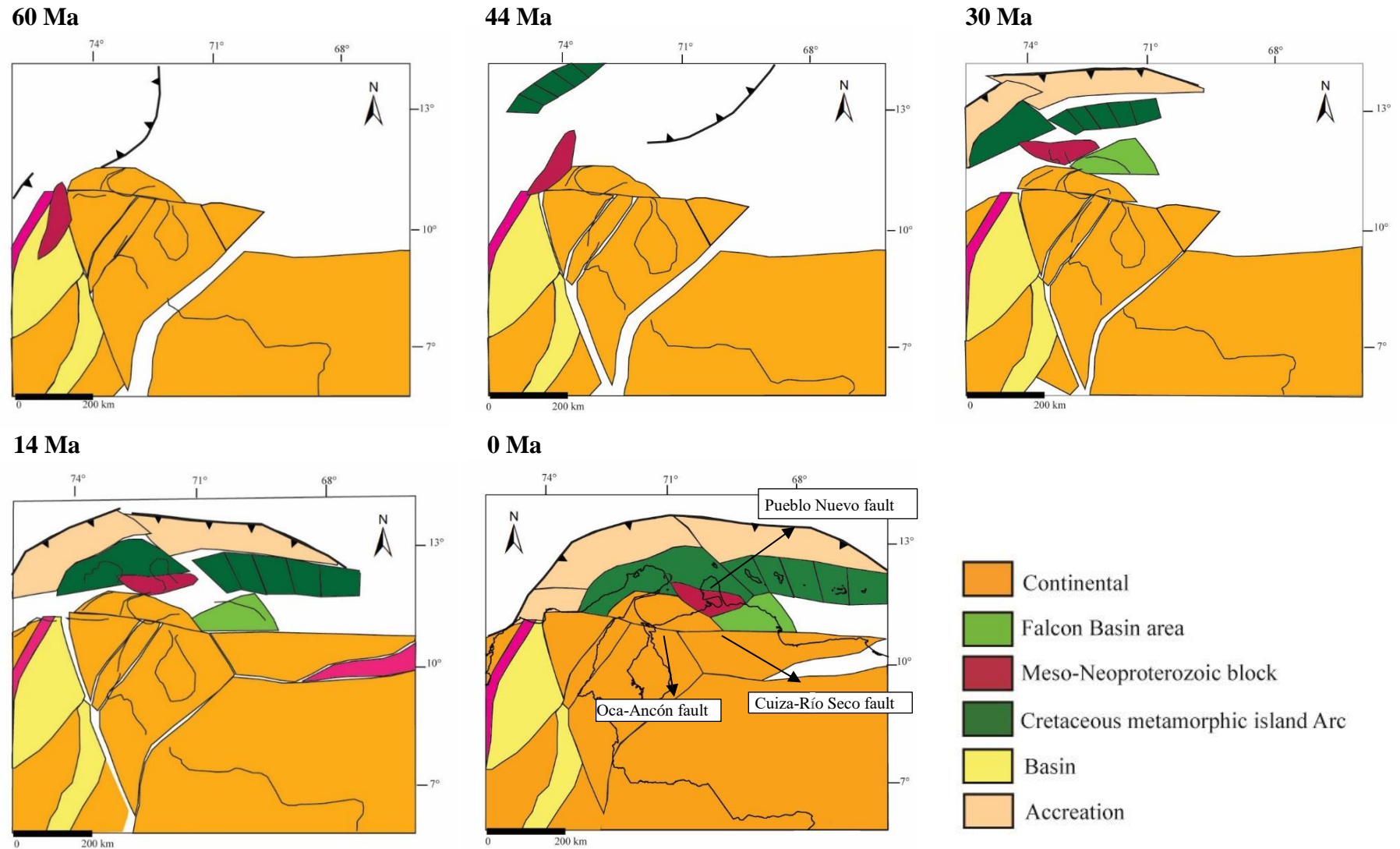


Figure 5.4. Plate tectonic model update. The diagram is showing a plate tectonics reconstruction updated with the Meso-Neoproterozoic block in the Gulf of Venezuela, at different ages: 60 Ma, 44 Ma, 30 Ma, 14 Ma, and present (modified from Escalona and Norton, 2015).

This bend resulting from an oblique collisional margin, which conduces to the development of the Cuiza-Rio Seco as a lateral ramp, forming a sharp structural and stratigraphic boundary contact between the autochthonous block of the Maracaibo foreland basin and the allochthonous block from the Pre-Cambrian terranes (Figure 5.4).

Subsidence plots indicate that the southern region of the Gulf of Venezuela (Maracaibo province) is also affected by the same event that is recognized in the Maracaibo Basin. Subsidence rates increased due tectonic loading generating space of accommodation in the foreland basin. Therefore, this second phase is characterized by syn-tectonic sedimentation related with the activity of fault family 2.

However, the Caribbean-South America oblique collision affects the deposition of areas nearby to the Cuiza-Río Seco suture zone. Therefore, the distribution of the Early Paleogene facies seems to change from well-studied fluvial and deltaic facies, with tidal influence in a tectonically stable Maracaibo Basin, to deep marine conditions with floor fans deposits (Trujillo Formation) that were deposited during the emplacement of the allochthonous block and thrusting of the Lara Nappes (Figure 5.5).

It is also recognized along the Burro Negro fault, separating undeformed outer Maracaibo Basin (northeastern) and the intensely deformed inner Maracaibo Basin and Lara Nappes (Escalona and Mann, 2006c; Contreras, 2008). Furthermore, the Proto-Maracaibo River is suggested to be the clastic source for deep water turbidite deposition in the eastern side of the province (Figure 5.5).

Finally, a NW-SE pop-up structure is developed during this phase, associated with the Sierra de Perijá, which allowed the deposition of carbonates banks at the top of this structure (Figure 4.9). Two major faults were interpreted from the fault family 3, associated with this uplifted structure. The activity of these faults is recognized not younger than Late Paleocene, however, they also can be interpreted as older normal faults from the passive margin that were reactivated during the deposition of this sequence.

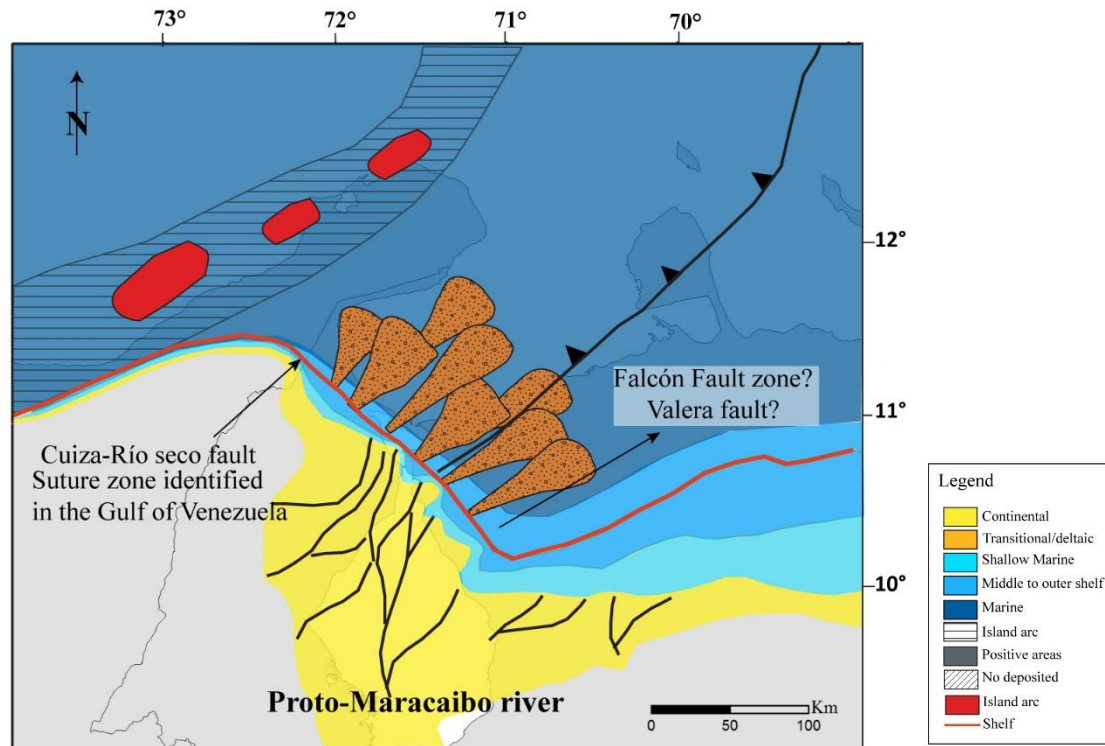


Figure 5.5. Middle Eocene paleogeographic reconstruction. The Cuiza-Río Seco fault is formed as a lateral ramp. The map is showing the continuation southward of this fault through the Falcon Fault Zone. Two major geologic provinces are recognized. Notice that the coastline is at Present time (modified from Escalona and Mann, 2011).

5.3.1.3. Phase 3: Oligocene (Tectonic uplift).

Subsidence plots indicate uplift during Late Oligocene in the Maracaibo province, supported also by the continental facies interpreted in well G. The tectonic loading process associated with the Caribbean collision ceases, therefore, an uplifted due to isostatic rebound is produced, in association with the reactivation of the family fault 2 (Escalona and Mann, 2006c).

During this phase, a regional unconformity is developed due to subaerial exposed of the Paleogene and even Cretaceous sequences, which can be correlated with the large Eocene unconformity in the Maracaibo Basin. Time missing increase dramatically southwards, reporting up to 40 Ma comparing to the northern regions where is only about 2 Ma.

The uplifted of this Maracaibo block produced a regional paleo-drainages change, creating a barrier for the proto-Maracaibo river, moving towards the east, developing the proto-Orinoco river (Escalona and Mann, 2011).

5.3.2. The Urumaco province.

5.3.2.1. Phase 1: Late Oligocene-Early Miocene (Transtension).

By the end of the Oligocene, the Caribbean-South America plate boundary in western Venezuela changed from a convergent boundary to a transtensional one with a right-lateral strike-slip fault system established along the margin (Gorney et al., 2007). In the Urumaco province, two fault families (families 1 and 4) were active at this time leading an increase in the subsidence rate for the region, which is supported by a steeply curve pattern in the well K (Figure 4.24c)

On the other hand, a significant increase in sedimentation and infilling of the basins is developed during the Early Miocene. Moreover, major right-lateral strike-slip faults create a deformation zone that lead the opening of the Urumaco trough as a transtensional basin during the Oligocene (Figure 5.6). This transtensional setting is associate with a realeased bend recognized along the Cuiza-Pueblo Nuevo fault system (central segment), generating a deeper water environment. This phase marks a period of strain-partioning in the area, where the deformation is accommodated by right-lateral displacements of Oca- Ancón and Cuiza-Río Seco faults.

In addition, some transpresional-related structural highs are developed during this time, allowing the deposition of carbonate banks such as Perla. Furthermore, a couple of remarkable highs associated with the seawards extension of Macuira range and Los Monjes are developed (Figure 4.3).

In the Caribbean province, this transtensional setting generated rifting structures that segmented the Leeward Antilles ridge in several elongated northwest-oriented basins with marine conditions: Aruba, West Curazao, and East Curazao (Gorney et al., 2007). This interpretation is supported by observations where a deep NW-SE depocenter is developed in association with the Aruba basin (Figure 4.3).

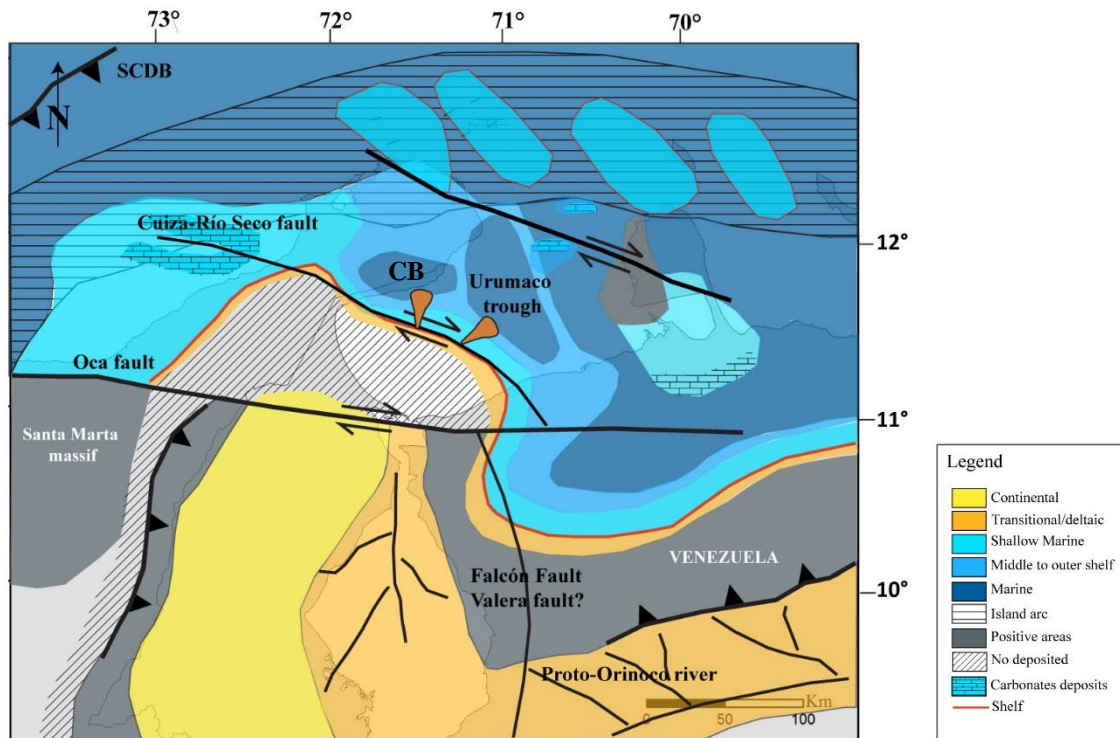


Figure 5.6. Late Oligocene-Early Miocene paleogeographic reconstruction. The map is showing the opening of the Urumaco trough and Cocinetas basin (CB). Carbonate banks deposits are developed in the Urumaco and Caribbean provinces. The Oligocene is scattered present in the Maracaibo Basin due to strong erosion. Early Miocene pinches-out towards the south. Notice that the coastline is at Present time (modified from Maceralli, 1995; Vence, 2008; Escalona and Mann, 2011).

5.3.2.2. Phase 2: Middle Miocene-Present (Caribbean and Urumaco: segmentation) (Maracaibo: tectonic loading).

During this time, small periods of subsidence and inversion are the main characteristics of this phase (segmentation), supported by several minor unconformities observed on seismic sections, as well as the subsidence rates recognized on the plot (Figure 4.24c). The segmentation period starts around 7 Ma, similar to that constrained in previous studies (Escalona and Mann, 2011)

The Urumaco basin continues its opening but the activity is concentrated on the southernmost region of this structure. The Late Miocene unconformity might be associated with the same event, causing the inversion of the Falcon Basin, which is slightly younger towards northeastern of the study area. This characteristic is also recognized in the Middle Miocene unconformity interpreted in the Falcon Basin (Gorney et al., 2007).

Inversion during Middle and Late Miocene is related with short periods of inversion and subsidence that described this sequence, supportive by the subsidence plots, due to the oblique convergence of the Caribbean and the South American plate. The strain is partitioned into different strike slip faults, recognized in the Gulf of Venezuela (Cuiza- Río Seco and Pueblo Nuevo fault) that accommodate the eastwards displacement at different times, considering the activity of these faults (Figure 5.7 and 5.4).

In general, transitional to deltaic environment is interpreted in the Maracaibo province moving to marine condition in the north, main clastic sediments source is located in the south (Figure 5.7).

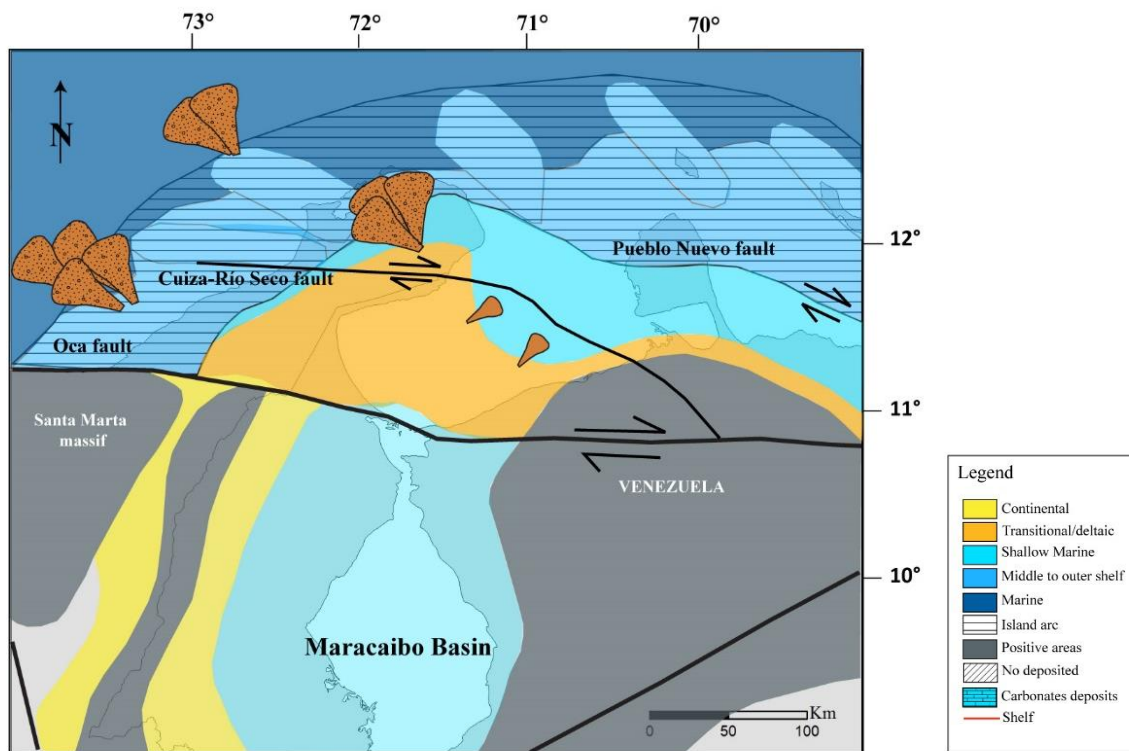


Figure 5.7. Middle Miocene-to-Present paleogeographic reconstruction. The figure showing the clastic sediments source from the south and the variability from transitional to marine facies. Two regional strike slip faults are recognized in the Gulf of Venezuela, representing the partitioned deformation (modified from Maceralli, 1995; Vence, 2008; Escalona and Mann, 2011).

5.4. Petroleum systems overview.

There are two well-differentiated petroleum systems associated with the discontinuous arrangements of basements in the study area. First, the Maracaibo province is suggested as the northward continuation of the Maracaibo Basin, with a petroleum system that includes the well-

known Later Cretaceous source rock (La Luna Formation). In contrast, a Cenozoic source rock has been proved in the Urumaco and Caribbean provinces with the Perla field discovery (Castillo et al., 2017) and Chuchupa-Ballena fields, respectively.

5.4.1. Source rock.

5.4.1.1. Maracaibo province.

La Luna Formation has been widely studied in the Maracaibo Basin. In the Gulf of Venezuela, it is located about 4500 m depth based on seismic interpretation, and 3800 m depth onland in the northern region of Maracaibo Basin (well A). This source rock was deposited in the range from Upper Cenomanian to Upper Campanian. The thickness is variable, thinning towards the east with ~30-90 m reported at onland wells (well D). La Luna was deposited in an oxygen-depleted bottom-water conditions in a shelf-to-slope marine environment (Perez-Infante et al., 1996).

Two main episodes of rapid tectonic subsidence affect the Maracaibo province: the Paleogene Caribbean-South American plate oblique collision and the Neogene uplift of the Sierra de Perijá- Mérida Andes. These two events created the proper conditions for hydrocarbons generation. This source rock reaches larger depths towards the northeast of the Maracaibo province due to emplacement-related deformation of the Lara Nappes and Falconia terrane, causing over-maturation.

5.4.1.2. Urumaco and Caribbean provinces.

These two provinces are defined by different basement terranes. However, they might probably have the same petroleum system due to coupling by the time of source rock deposition. Therefore, the basement configuration is not playing an important role for the Cenozoic basins located in this region.

The Caribbean region contains Eocene-Oligocene terrigenous organic-rich shale source rocks (gas-prone type III kerogen) (Curet, 1992; Gorney et al., 2007). Paleogene source rock reached maturity in the Leeward Antilles region. However, the Caribbean slab seems to play an important role reducing heat flow into the basins (Escalona and Yang, 2013). Therefore, basins located in the eastern region are more prone to reached maturity than the western regions due to diachronous subduction of the Caribbean oceanic crust beneath NW South America.

The kitchen for the source rock is suggested to be located in the Urumaco trough where a strong period of subsidence during the Oligocene-Early Miocene was identified. This assumption is in agreement with geochemical data (Castillo et al., 2017).

5.4.2. Reservoir.

5.4.2.1. Maracaibo province.

The most prolific reservoir rock in the Maracaibo Basin are the Eocene and Miocene reservoirs associated with a foreland wedge filled by clastic sediments (Lugo and Mann, 1995). However, the northern areas of the Maracaibo province are placed in a marine setting where different targets have to be considered. Potential reservoirs in the northwestern region of Maracaibo province are fractured basement metamorphic rocks, carbonate rocks from the Cogollo group, and Miocene stratigraphic wedges. In addition, the Late Paleocene-Eocene turbidites-related sediments transported by the Proto-Maracaibo River, and Late Paleocene carbonates deposits related with pop-up structures are also established as a good exploration target.

5.4.2.2. Urumaco and Caribbean provinces.

Along these provinces, the main reservoir is a Late Oligocene-Early Miocene carbonates succession recognized in the Perla field, deposited in shallower waters at the top of a basement high, built in the middle-outer ramp environment (Castillo, et al. 2017). Shows a thickness about 300 m, and consists of larger benthic foraminifera and red algae (oligophotic) with a minor contribution from shallow water (euphotic) carbonate components (green algae and corals) (Pinto et al., 2011; Borrromeo et al., 2011, Benkovics et al., 2012).

5.4.3. Traps.

5.4.3.1. Maracaibo province.

Several traps with different characteristics and trapping mechanisms were identified. The risk is very high due to limited wells information (Figure 5.8).

- (1) Stratigraphic traps related to carbonate banks deposits atop of pop-up structures associated with the inversion of normal faults (e.g. uplifting of the Sierra de Perijá).
- (2) Structural traps related with inversion of normal faults during the Oligocene uplift, associated with isostatic rebound (e.g. central areas of the Maracaibo province).

- (3) Structural and stratigraphic traps at the truncated Cretaceous sequences, with high-angle NE-dipping. This deformation is also related to the Oligocene uplift.
- (4) Late Paleocene-Eocene turbidites (e.g. sediments from the Proto-Maracaibo River).

Similar to the Maracaibo Basin southwards, the regional NE-dipping of the basin might contribute to the southern up-dip migration of hydrocarbons.

5.4.3.2. Urumaco and Caribbean provinces.

The possible traps identified are:

- (1) Pinch outs of the Miocene sequence against Los Monjes high.
- (2) Stratigraphic traps in Late Oligocene-Miocene carbonate banks.

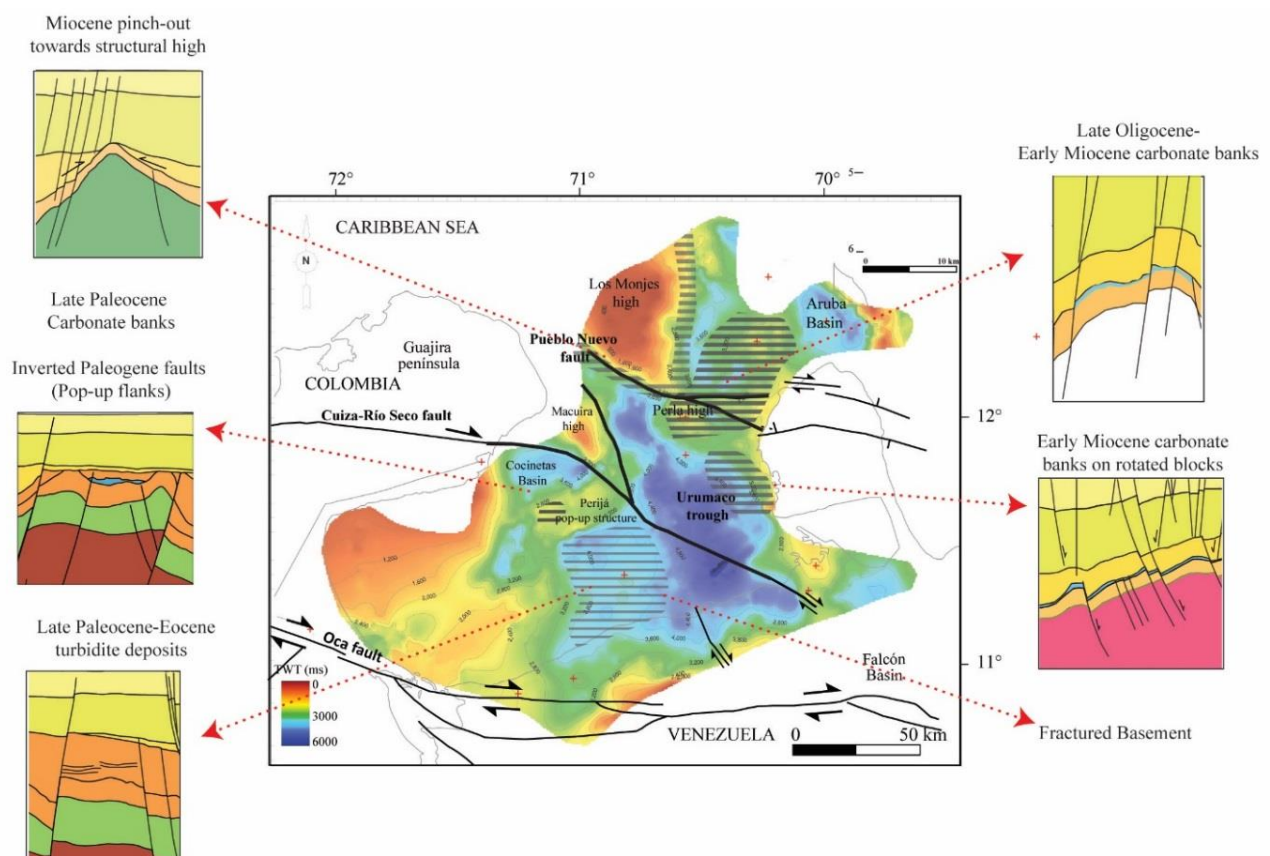


Figure 5.8. Top acoustic basement map showing locations of possible hydrocarbon traps in the Gulf of Venezuela, based on 2D seismic interpretation.

CONCLUSIONS

- Integration of 2D seismic reflection data, subsidence rates analysis, well data, and paleogeographic reconstructions reveal different deformation stages and six fault families associated with the oblique collision between the Caribbean and the South American plates.
- The Gulf of Venezuela comprises three major basement terranes: Paleozoic autochthonous basement (Maracaibo province), Meso-Neoproterozoic allochthonous basement with continental-affinity (Urumaco province), and Cretaceous metamorphic arc (Caribbean terranes). This configuration controls the petroleum systems present in the region.
- The Cuiza-Río Seco fault is a high-angle fault interpreted as a lateral ramp, which is proposed as the boundary between both, the autochthonous and the allochthonous terranes. This fault separates two well-differentiated petroleum systems: (1) Cretaceous source rock with structural and stratigraphy traps to the south, and (2) Cenozoic source rock with mainly stratigraphy traps to the north.
- The Cuiza-Río Seco fault also separates two areas of deformation: (1) foreland basin with posterior uplifted to the south (Maracaibo province), and 2) elongated transtensional basin and back-arc system to the north (Urumaco and Caribbean provinces).
- Evidences of the three phases of the arc-continental deformation were recognized in Urumaco and Caribbean provinces: (1) subsidence, (2) inversion, and (3) segmentation.
- Four tectonic phases were recognized in the Maracaibo province associated with fault families 2 and 3, and subsidence rates: (1) initial passive margin, (2) a burial foreland phase, (3) isostatic rebound (Oligocene), and (4) tectonic loading. Nevertheless, the Gulf of Venezuela is also affected by the Caribbean deformation since Middle Miocene, revealed by subsidence plots, where the segmentation phase is recognized.
- The Maracaibo petroleum system should be present in the western region of the Gulf of Venezuela, opening promising exploration opportunities similar to those plays found in the northwestern corner of the Maracaibo Basin.
- The NE-SW-oriented, pop-up structure restricted to the Maracaibo Province is interpreted to be the incipient continuation of a deformation associated with the Sierra de Perijá. Nevertheless, the uplifted of this structure is considered to be Paleogene

whereas the inversion in the Sierra de Perijá has been constrained to be no early than Neogene. These features are presently located towards the east due to Cenozoic right-lateral strike-slip along the Oca-Ancón fault, which has segmented the northern part of the Maracaibo Basin. Based on this assumption, 70-80 km of displacement was constrained along the Oca fault.

- One major strike-slip fault recognized in the Gulf of Venezuela is suggested to be the offshore continuation of the Pueblo Nuevo fault. This fault is proposed to be a boundary between the continental-affinity terranes (Urumaco province) and the allochthonous oceanic-affinity terranes (Caribbean province).
- The Meso-Neoproterozoic rocks are not part either of the Caribbean arc terranes or Paleozoic terranes, therefore, it is suggested as a fragment that was detached and transported from the Santa Marta Massif, due to the Caribbean eastward deformation to later be accreted into the Gulf of Venezuela.
- The Cuiza-Río Seco and Pueblo Nuevo faults accommodate strain partitioning as well as the Oca- Ancón fault, due to oblique compression of the Caribbean plate against South American plate. However, they seem to have different timing activity. The Cuiza-Río Seco fault is interpreted as a lateral ramp during the Paleogene. Nevertheless, this fault is more active during Late Oligocene and Early Miocene. In contrast, the Oca-Ancón fault system is active as a strike-slip fault during Middle to Late Oligocene. The Pueblo Nuevo fault might have activity that is more recent.

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