

Tectono-stratigraphic Evolution of the Maturin Foreland Basin: Eastern Venezuela

Maria I. Jacome

Universidad Simón Bolívar, Departamento de Ciencias de la Tierra, Baruta, Edo. Miranda, Venezuela

Nick Kuszniir

University of Liverpool, Department of Earth Sciences, Liverpool, U.K.

Felipe Audemard

Petróleos de Venezuela (PDVSA) Exploración y Producción, Caracas, Venezuela

Steve Flint

University of Liverpool, Department of Earth Sciences, Liverpool, U.K.

ABSTRACT

New regional interpretation of approximately 2000 km of seismic profiles constrained with more than 20 wells evenly located in the Maturín Foreland Basin in Eastern Venezuela show an extremely thick foreland sediment accumulation, varying from 7 km in the west to 10 km in the east. The interpretation also demonstrates that the total shortening in the seismically imaged portion of the Monagas Foothills and Foreland Thrust Belt decreases from the west (50 km) to the east (35 km), showing no direct relationship between shortening and sediment accumulation. Depth-converted isopach maps show large thicknesses of middle Miocene, Pliocene, and Pleistocene sediments, which is indicative of different episodes of tectonically controlled subsidence. Maximum tectonic-subsidence rates, calculated from decompacted isopach maps, are higher during the Pleistocene (2875 m/Ma) than during the middle Miocene (1260 m/Ma) and Pliocene (1243 m/Ma). Three large depocenters were identified from west (thinnest) to east (thickest), which migrated from northwest (adjacent to the Serranía Thrust Belt) in the middle Miocene to southeast in the present. The thickest Pliocene and Pleistocene depocenters, located in the eastern part of the basin, are not related to thrust-sheet loading, as evidenced by the lack of major active thrust in this area during this time. This shows that the continental lithosphere has subsided by a greater magnitude in the eastern part of the basin than in adjacent areas. Subduction loading associated with the subduction of the South American Continental Plate under the Caribbean could have generated additional subsidence in the Maturín Basin. This is supported by gravity anomaly

evidence. Free-air gravity anomalies for the southeastern Caribbean offshore and Bouguer anomalies for Eastern Venezuela show a continuous negative-gravity anomaly extending from the Barbados Accretionary Prism to Eastern Venezuela, suggesting that the Lesser Antilles Subduction Zone may extend southwestward and affect the Maturín Basin.

INTRODUCTION

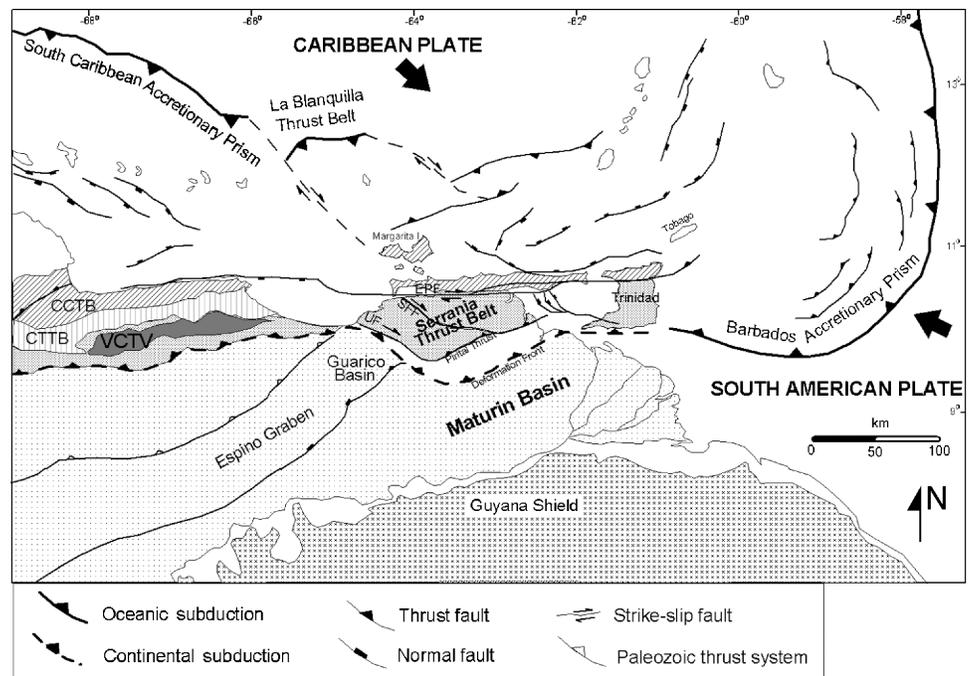
The Maturín Basin in Eastern Venezuela (Figure 1) is located in a compressional tectonic setting that involves the oblique subduction of the South American Plate under the Caribbean Plate. Starting in the uppermost lower Miocene, Eastern Venezuela experienced a major change of subsidence regime. The transpressional front of the Caribbean Plate collided obliquely with the north-facing Cretaceous to Paleogene passive margin of northern South America (Speed, 1985; Lilliu, 1990; Erlich and Barrett, 1990; Roure et al., 1994; Chevalier, 1994; Avé Lallemant, 1997). The Maturín Basin was formed because of the tectonic loading associated with the Serranía del Interior thrust sheets and the pulling down of the South American Plate caused by continental subduction. Four major geodynamic events contributed to the formation of Eastern Venezuela: the Paleozoic orogeny, Jurassic and early Cretaceous rifting associated with the break-up of Pangea, Cretaceous to Paleogene passive-margin development, and the Neogene oblique collision between the Caribbean and South American Plates, generating the Maturín Basin.

The Maturín Basin is an important oil-producing basin in Venezuela with a large amount of well-log and seismic data. Previous structural interpretations of the Maturín Basin involved balanced cross sections of single seismic profiles in the western area (Roure et al., 1994; Chevalier et al., 1995; Passalacqua et al., 1995; Hung, 1997). These cross sections proposed different décollement levels (16 km, 20 km, 25 km, or 32 km), different amounts of shortening (from 16 to 115 km.) and different Neogene foreland sediment thicknesses (from 7 km to 12 km). Before this study, there were no depth-converted and balanced cross sections for the central and eastern parts of the basin. Consequently, a new regional seismic interpretation of the Monagas Foreland Thrust Belt and Maturín Basin is presented here.

Regional interpretation of approximately 2000 km of seismic profiles constrained by well data has been used to generate three regional northwest-southeast depth-converted cross sections across the Maturín Basin. A sequence stratigraphic correlation of well logs has been used to investigate the paleobathymetry and distribution of facies related to tectonism. The absence of cores precluded detailed facies analysis. Depth-converted isopach maps of relevant tectonostratigraphic sequences have been generated from

Regional interpretation of approximately 2000 km of seismic profiles constrained by well data has been used to generate three regional northwest-southeast depth-converted cross sections across the Maturín Basin. A sequence stratigraphic correlation of well logs has been used to investigate the paleobathymetry and distribution of facies related to tectonism. The absence of cores precluded detailed facies analysis. Depth-converted isopach maps of relevant tectonostratigraphic sequences have been generated from

Figure 1. Tectonic map of northeastern Venezuela, showing the interaction between the oceanic Caribbean Plate and the continental South American Plate. Abbreviations: EPF = El Pilar Fault, SFF = San Francisco Fault, UF = Urica Fault, CCTB = Cordillera de la Costa Thrust Belt, CTTB = Cauagua-El Tinaco Thrust Belt, VCTB = Villa de Cura Thrust Belt. Simplified after Ysaccis and Aude-mard, 2000.



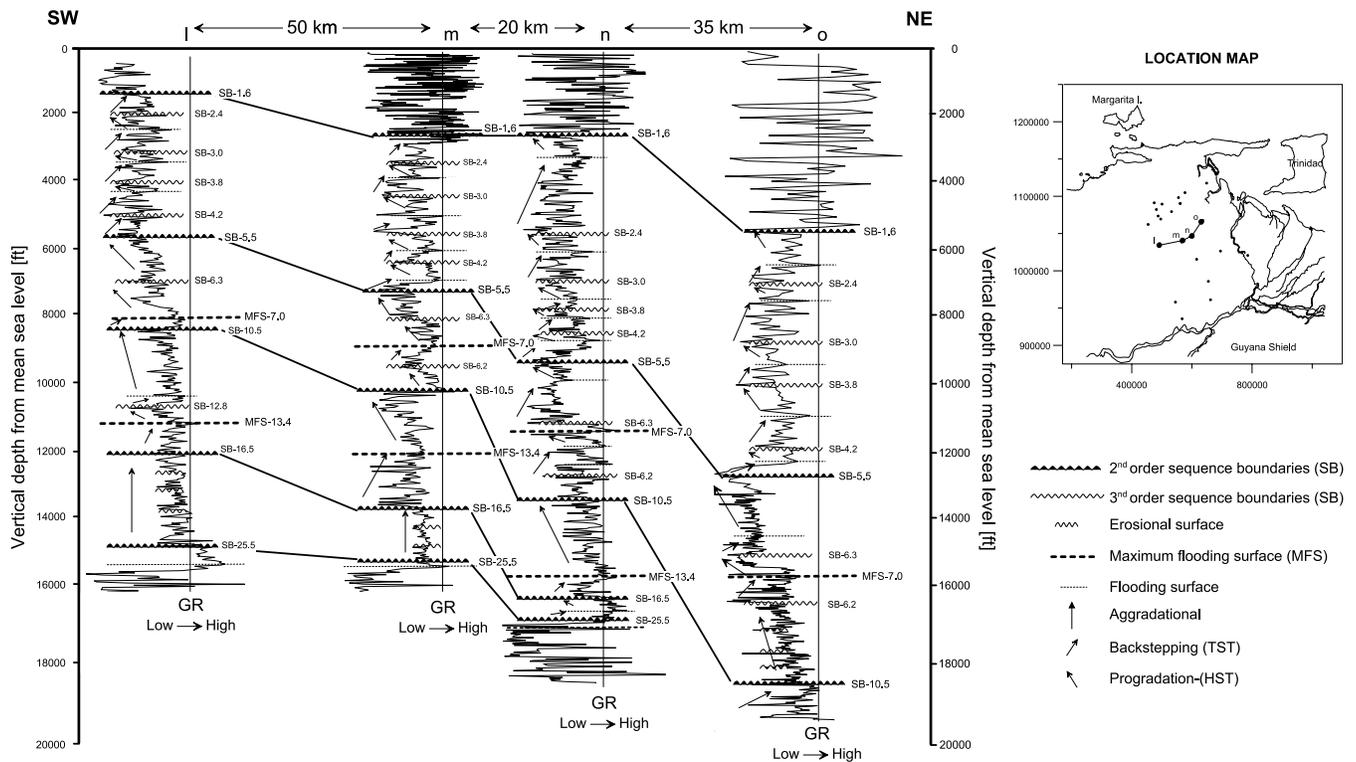


Figure 2. East-west well-log correlation for wells located in the sedimentary axis of the Maturín Basin. Note that Pliocene-Pleistocene sediments thicken to the east. SB-25.5 is the “foredeep unconformity” that divides the passive-margin sequence from the foreland sediments. The maximum deepening of the Maturín Foreland Basin, caused by its flexural response to the emplacement of the Serranía Thrust Belt during the middle Miocene, is marked by MFS-13.4. The upper Miocene (between SB-10.5 and SB- 5.5) and Pliocene-Pleistocene (SB-5.5 to Present) are characterized by a regional prograding system, with lower gamma-ray (GR) values.

the seismic interpretations in order to understand the subsidence history of the basin, and the evolution of depocenters and their relationship to geodynamic processes. The main aim of this work has been to understand the origin of the Neogene Maturín Foreland Basin.

SEISMIC INTERPRETATION

Two northwest-southeast and east-west regional well-log correlations (Figures 2 and 3) were carried out using gamma-ray (GR) and spontaneous-potential (SP) logs for eight wells provided by PDVSA (Petróleos de Venezuela, S.A.). The biostratigraphic framework used here has been published previously (Audemard et al., 1994; Di Croce, 1995; Bejarano et al., 1996; Crux et al., 1996; Funes et al., 1997; Di Croce et al., 1999) and consists of well-log data from wells distributed regionally in Eastern Venezuela. Many wells in this area do not have adequate paleontological control, so the ages for sequence boundaries (SB) and maximum flooding surfaces (MFS) are tentative. The SBs and MFSs were named based on their approximate

age. For example, SB-5.5 is a sequence boundary occurring at approximately 5.5 Ma. Ten northwest-southeast and southwest-northeast regional 2-D seismic lines have been interpreted and tied to available well data. These have been used to construct three regional transects across the Maturín Basin. Transects 1, 3, and 5 are northwest-southeast regional seismic interpretations of the western, central, and eastern parts of the basin (Figure 4). The main objectives of the seismic interpretation and the well-log correlation are to understand the regional distribution of sedimentary facies and their association with subsidence and tectonism, and to identify the first synorogenic deposition.

Monagas Foothills and Foreland Thrust Belt

This province forms the transition from the uplifted and strongly shortened Serranía del Interior Thrust Belt to the foreland basin. The limits are the Serranía foothills to the north and the deformation front to the south (Figure 1). The Monagas Foreland Thrust Belt contains pre-Cretaceous, Cretaceous, and Tertiary rocks that have been thrust and folded

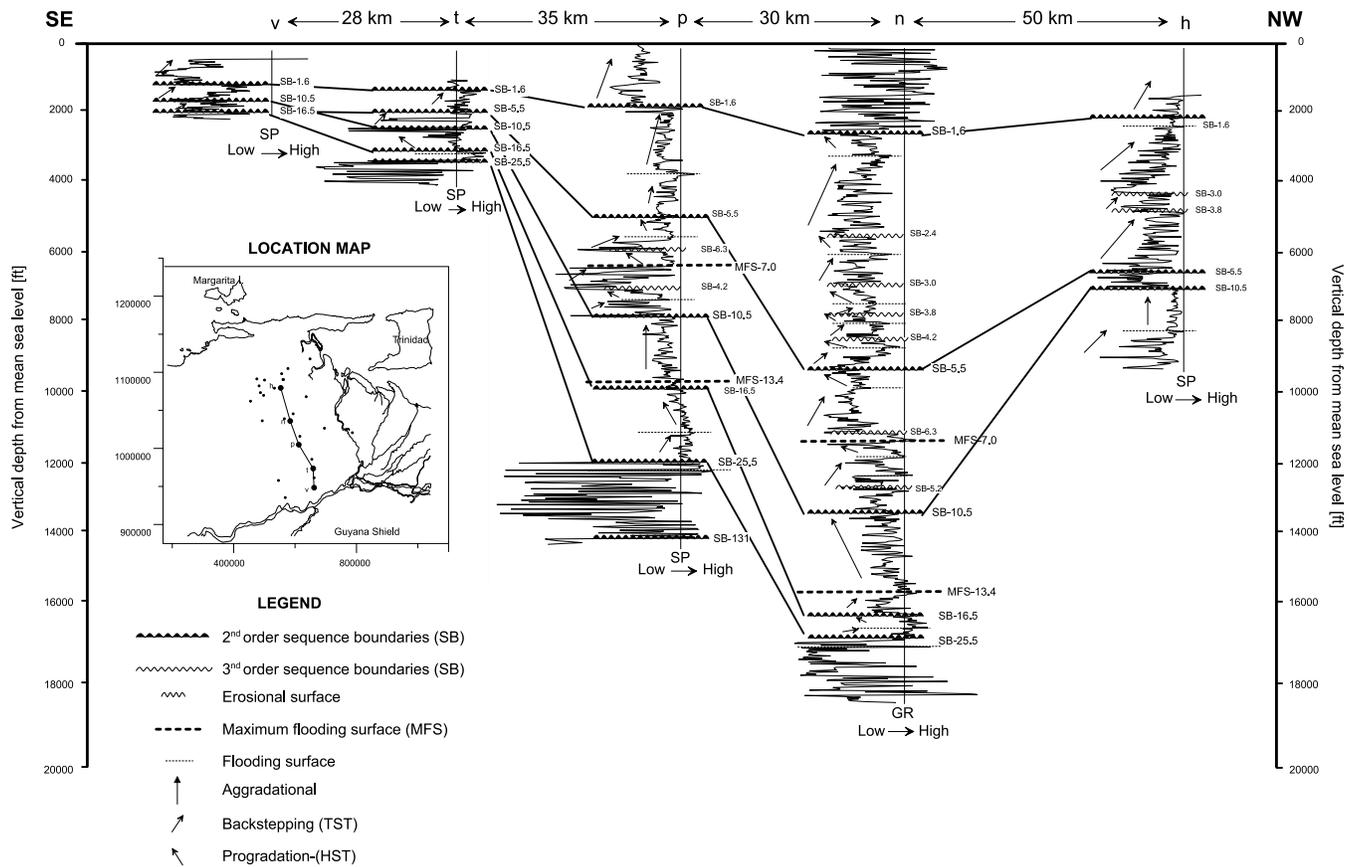


Figure 3. North-south well-log correlation for wells located in the center of the Maturín Basin. Pliocene reaches its maximum thickness in well n (i.e., center of the basin or depositional axis). Toward the south, the units thin and get sandier. Two MFSs are identified: MFS 7.0 and MFS 13.4 (the maximum deepening of the basin). These two maximum flooding surfaces are difficult to identify in the south of the basin. SB-10.5 marks the beginning of a regional coarsening-upward regressive period. GM = gamma-ray log, SP = self-potential log.

(Potié, 1989). The lower to middle Miocene is an accretionary wedge laying over the thrust passive margin succession. The upper Miocene to Pliocene-Pleistocene sequence onlaps onto the emerging fold belt (Figure 4).

Five major thrusts have been identified in the seismic lines. The Pirital Thrust (highlighted in Figure 4) is responsible for the largest amount of deformation and shortening. This fault has been active recently and may connect and reactivate older pre-Cretaceous structures (Lilliu, 1990; Roure et al., 1994). The timing of thrust emplacement can be constrained to be between the last Pliocene-Pleistocene synflexural deposits and the lower to middle Miocene basal unconformity of the piggyback basins formed in the post-fold thrust belt (Roure et al., 1994). There are two phases of deformation, with distinct décollement levels activated successively, associated with the Serranía del Interior emplacement. The first stage involved shallow intra-Cretaceous to Tertiary and deep

pre-Cretaceous décollements, and the second phase reactivated deeper pre-Cretaceous to older structures. The total shortening in the seismically imaged portion of the Monagas Foreland Thrust Belt has been estimated from seismic interpretation at 50 km in the west and 35 km in the east (Figure 4). Mud diapirism has been reported previously (Mariño and Zannin, 1985; Lilliu, 1990; Hung, 1997) and is observed in the south of the fold belt (Figure 4). These diapirs have a southwest-northeast trend and are arranged parallel to the deformation front, with a décollement in intra-Neogene sediments (Ysaccis and Audemard, 2000).

Maturín Foreland Basin

The Maturín Foreland Basin extends from the deformation front in the north to the Orinoco River in the south. The basin is bounded to the west by the Guárico Subbasin and to the east by the Atlantic Ocean (Figure 1). The foreland basin is filled with

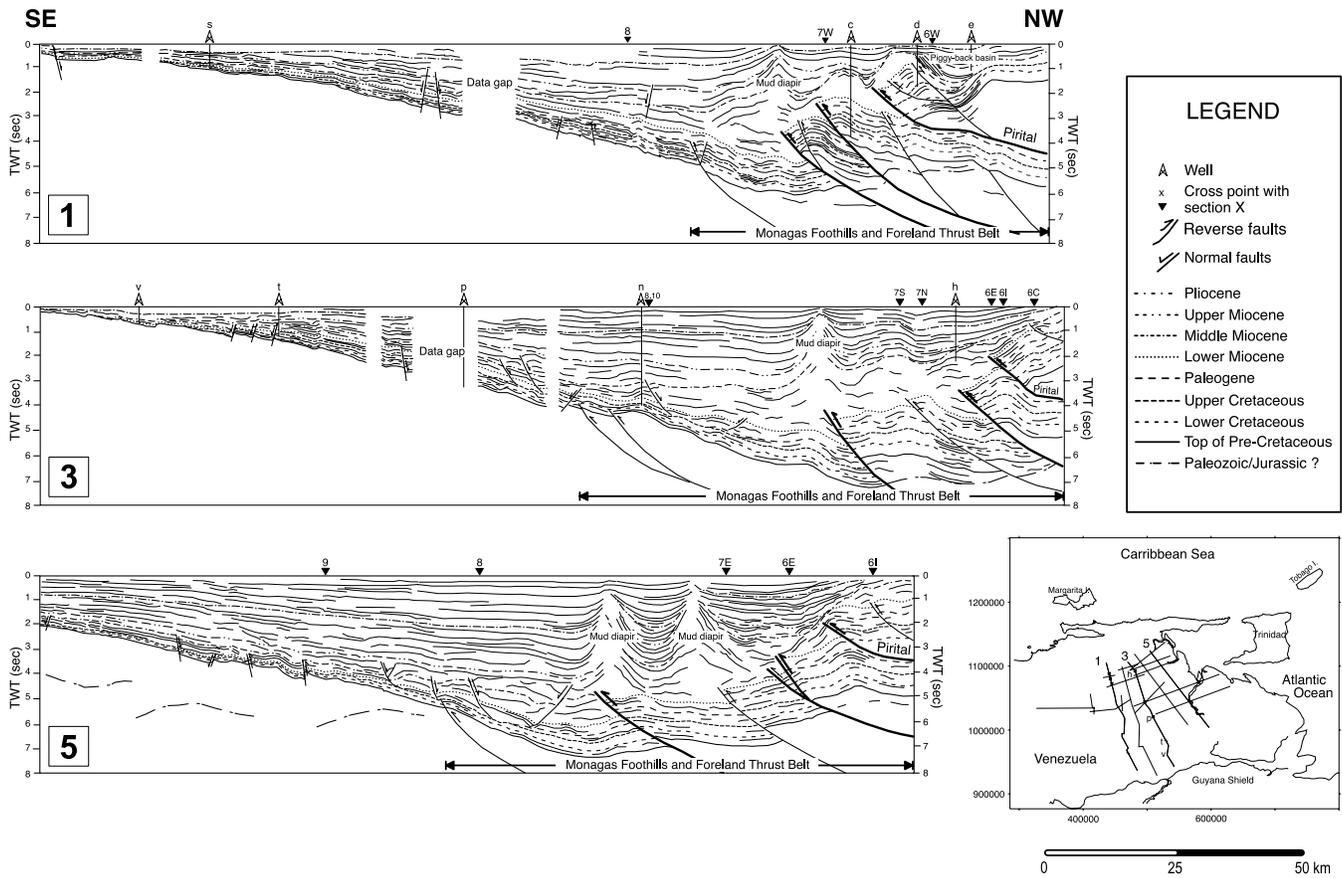


Figure 4. Seismic line drawings for transects 1, 3, and 5. The Pirital Thrust is highlighted.

6–10 km of Neogene sediments, accommodated as the result of thrust-sheet loading that forced the American continental lithosphere to flex downward between the Guyana Shield and the El Pilar Fault (Roure et al., 1994). Sediment sources are from the south (Guyana Shield), the north (the rising Serranía del Interior Thrust Belt), and the west (El Baul Arch) (Lilliu, 1990; Di Croce, 1995). Well logs and seismic information have permitted subdivision of the pre-Cretaceous to Recent stratigraphy of the basin into five tectono-stratigraphic units: pre-Cretaceous, Cretaceous to Paleogene, lower Miocene, middle Miocene, upper Miocene and Pliocene-Pleistocene.

Pre-Cretaceous

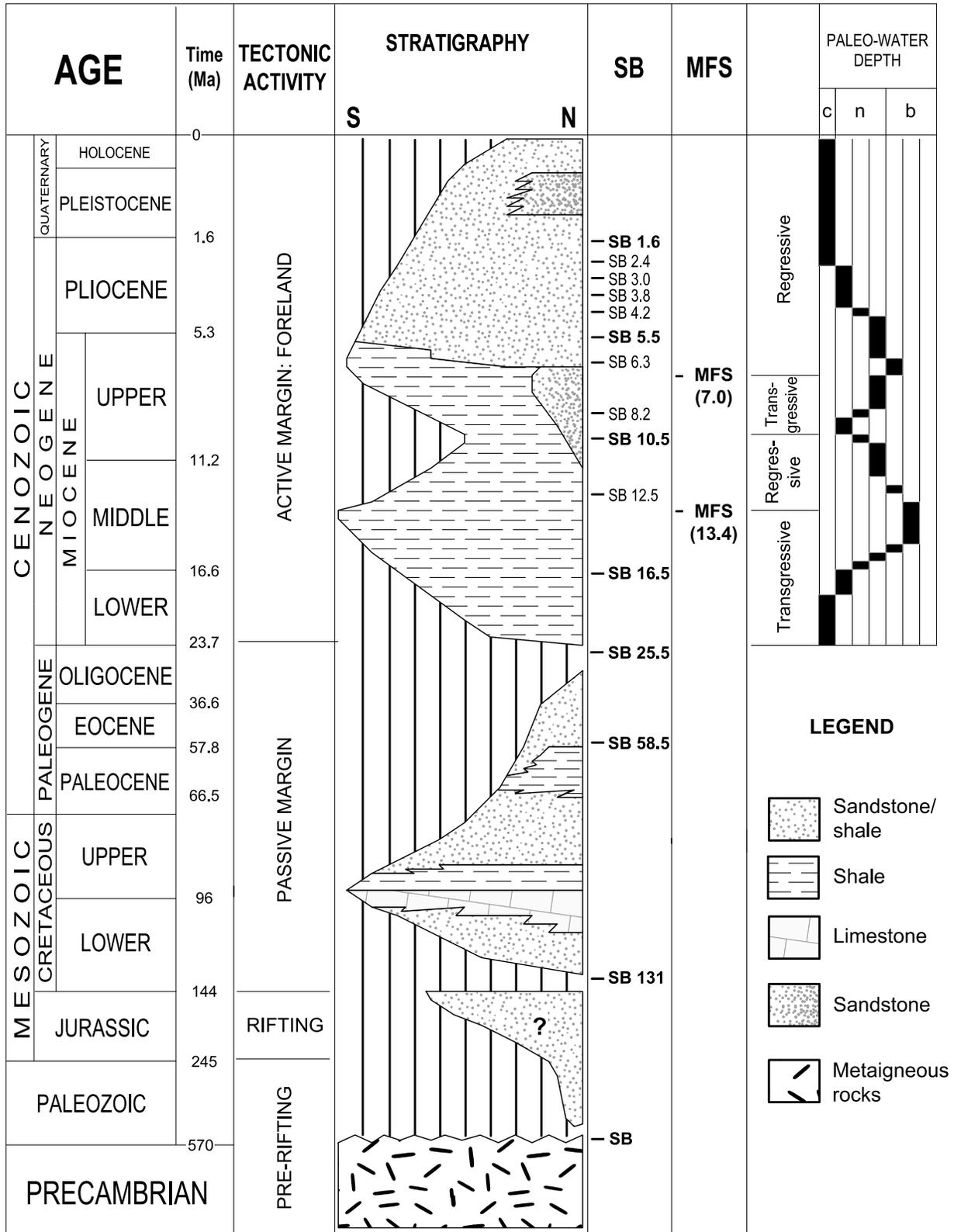
Pre-Cretaceous rocks form the basement in Eastern Venezuela. To the south of the Maturín Basin and to the east, in the Atlantic offshore, well logs and seismic information confirm that Tertiary and Cretaceous sediments onlap Precambrian rocks (Audemard et al., 1985; Di Croce, 1995). In this area, the Precambrian basement is defined as the deepest horizon dipping gently toward the north (Figure 4). To the north, the seismic reflectivity decreases, making

it difficult to identify the nature of the basement underneath the Maturín Basin or the Serranía del Interior Thrust Belt. Feo-Codécido et al. (1984) concluded that in this area, there is no clear evidence that the Precambrian basement is directly overlain by Mesozoic-Tertiary sediments. The presence of Paleozoic and Jurassic rocks in Western Venezuela (Table 1) and in the Espino Graben (Figure 1) and strong seismic reflectors underneath the lower Cretaceous unit suggest that Paleozoic and Jurassic structures might form the basement in the center of the Maturín Basin and the Serranía del Interior.

Cretaceous-Paleogene Passive Margin

The passive margin in Eastern Venezuela was produced by post-rift thermal subsidence during the Cretaceous to Paleogene (González de Juana et al., 1980; Erickson and Pindell, 1993). Siliciclastic and carbonate sediments were deposited in response to both tectonic subsidence and global eustatic sea-level changes (Rosales, 1967; Lilliu, 1990). Well-log information confirms that the source of sediment was principally from the south (Guyana Shield) and west (Baul Arc). No major tectonic episodes occurred

Table 1. Regional chronostratigraphic chart of Eastern Venezuela. The sequence boundaries (SB) and maximum flooding surfaces (MFS) identified in the well-log correlation are displayed. Second-order sequences are highlighted in bold. Paleo-water depth estimations are from a well located in the center of the Maturín Basin (Di Croce, 1995). Modified after Di Croce et al. (1999) and Linares (1992). Abbreviations: c = continental, n = neritic, and b = bathyal.



during this time. As a result, it is possible to interpret the passive-margin stratigraphy in Eastern Venezuela (Di Croce et al., 1999) and in the Serranía (Metz, 1969; Rossi, 1985; Potié, 1989; Erickson and Pindell, 1998) as being controlled by sea-level changes. The top of the passive-margin succession is the major regional unconformity SB-25.5 (Figures 2 and 3). Di Croce et al. (1999) defined this sequence boundary as the basal foredeep unconformity that separates the overlying foreland-basin succession from the underlying passive-margin unit (Table 1). Pindell et al. (1998) argued, however, that this sequence boundary marks the drowning of the Caribbean peripheral bulge, which passed through Eastern Venezuela during the middle Eocene to Oligocene. From the seismic cross sections (Figure 4), it can be observed that the passive margin shows a wedge geometry in which thicker sequences are found in the north (beneath and in the Serranía del Interior) and thinner sequences in the south (Orinoco Belt). This unit overlaps crystalline basement over most of the area, and only locally overlies the inferred Jurassic rift unit (González de Juana et al., 1980; Di Croce, 1995) and/or probably the Upper Jurassic shelf (Erickson and Pindell, 1993).

Lower Miocene

The lower Miocene was deposited during a long-term transgression marked by coastal to shelf facies in the west and bathyal deep-water facies to the east and north-northeast (Di Croce et al., 1999). The lower Miocene sediments are thick to the west, related to the foreland basin fill in the Guárico Sub-basin, and thin toward the east-southeast (Figure 2), overlapping Precambrian rocks to the south. They were deposited just before the compressional episode that created the Serranía Thrust Belt.

Middle Miocene

North of the deformation front, the sediments in the Maturín Basin reach their maximum thickness during the middle Miocene, which is associated with the fastest rate of sedimentation. This thickness increases from west to east (i.e., 4.5 sec TWT in transect 1 and 6.4 sec TWT in transect 5, Figure 4). During this time, the Maturín Basin developed an east-trending "U" shape, shallower to the west-northwest where the paleo-Serranía was undergoing uplift, and deeper to the east toward the Atlantic Ocean (Metz, 1965; Rosales, 1967; González de Juana et al., 1980; Audemard et al., 1997). The Serranía del Interior uplift and loading resulted in flexure and deformation of the Maturín Basin crust, creating accommodation space

for the first synorogenic deposit. To the west, in piggyback basins above the thrust (e.g., transect 1, Figure 4) and north of the Orinoco River, sediments were deposited in coastal to littoral environments (Di Croce et al., 1999). To the southeast and in front of the deformation front, deep-marine sediments have been interpreted from well-log signatures. A complete transgressive-regressive cycle characterises the uppermost lower Miocene to top middle Miocene (wells m and n in Figure 2). MFS 13.4 marks the end of the transgressive phase with paleo-water depth estimates on the order of 3 km (Di Croce et al., 1999), and SB-10.5 culminates the regressive phase. This is based on decompacted seismic data (which include age, lithology, and thickness of each sedimentary unit) and well-log information (Figures 2 and 3).

Upper Miocene

This unit is characterized by continental prograding systems (Combellas et al., 1998) represented by coarsening-upward patterns on the well logs (wells l, n, and o in Figure 2 and well p in Figure 3). In this long-term regression event, a fining-upward pattern suggests a transgressive phase. Di Croce (1995) correlated the peak transgression of this phase to a maximum flooding event at 7 Ma (wells l, m, and o in Figure 3 and wells p and n in Figure 4). The lower part of this unit is formed by siltstone and shale interbedded with fine- to medium-grained sandstone deposited in continental to coastal environments. The upper part is formed by shale, siltstone, and sandstone deposited in a shallow-marine to upper-bathyal setting (Audemard et al., 1997). Toward the south of the basin, seismic reflectors in the middle and upper Miocene units show divergence, and a system of eastward-dipping growth faults and their corresponding rollover anticlines have been interpreted (Figure 4). The listric faults are interpreted to have been produced through growth faulting caused by the eastward progradation of the Orinoco River during the middle to upper Miocene (Di Croce, 1995; Audemard et al., 1997). The main décollement is located in the lower Miocene (Lilliu, 1990; Daza and Prieto, 1990). Di Croce (1995) pointed out that the faults are younger toward the west, suggesting that they were generated by gravitational collapse on a gentle submarine slope.

Pliocene-Pleistocene

The Pliocene-Pleistocene represents the shallow-marine to continental fill of the Maturín Basin because of the southeastward migration of the Serranía

del Interior Thrust Belt. The unit is bounded at its base by sequence boundary SB-5.5, and its top is the present-day geomorphology (Table 1 and Figure 2 and 3). Ages of these sequence boundaries are poorly constrained. Based on the progradation indicated from GR and SP curves and biostratigraphic information from Di Croce (1995), it is possible to estimate paleo-water depths on the order of 0–50 m for the Pliocene-Pleistocene sediments. Toward the south in transect 5 (Figure 4), there is evidence of recent compression and inverted structures that affected and deformed Pliocene-Pleistocene sediments.

Time-depth Conversion

Time-depth conversion is important in order to determine the depth and thickness of the sedimentary sequences in the Maturín Basin and the depth of the main décollement levels in the Maturín Foreland Thrust Belt. The eight interpreted horizons (Figure 4) were depth converted using the time-depth curves obtained from 16 wells located in the basin (Figure 5). An average time-depth curve has been approximated by the following mathematical function:

$$D = 0.0003T^2 + 3.003T - 163.97 \quad (1)$$

Where D is the vertical depth from sea level in feet of each horizon and T is TWT/2 in milliseconds. Equation 1 was used to depth convert the seismically interpreted horizons. The results are plotted in three different cross sections: transects 1, 3, and 5 (Figure 6). Variations in shortening and thickness of foreland basin sediments from west to east are observed: the total shortening in the Monagas Foot-

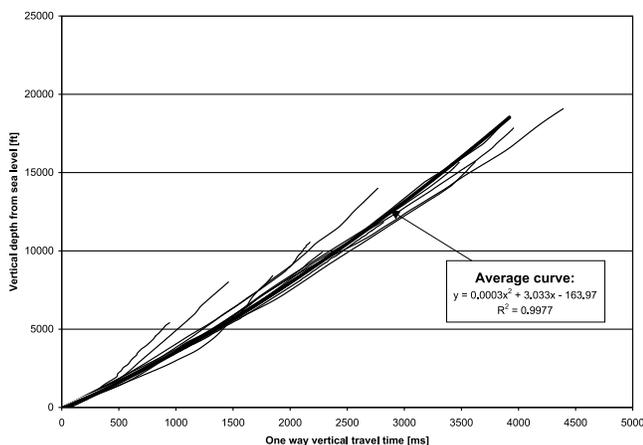


Figure 5. Time-depth curves of 16 wells located in the Maturín Basin. See Figures 2 and 3 for location.

hills and Foreland Thrust Belt, calculated in this study, decreases from the west (50 km) to the east (35 km). The thickness of the Maturín foreland sediments, however, increases from the west (~7 km) to the east (~10 km). These results show that shortening in the thrust belt is not directly related to sediment accumulation in the Maturín Basin.

SUBSIDENCE HISTORY OF THE MATURIN BASIN

Isopach Maps

Regional 2-D seismic reflection profiles covering an area of 60,000 km² have been used to produce a series of isopach maps in order to understand the regional 3-D distribution of the tectono-stratigraphic units in this area and to relate them to accommodation space generation and sediment supply (Figures 7 and 8). These maps were created from the depth-converted seismic interpretations of the Maturín Basin of this study, together with existing interpretations by other workers for offshore Venezuela and Trinidad (Payne, 1991; Rohr, 1991; Di Croce, 1995; Ysaccis, 1997; Ysaccis and Audemard, 2000).

Cretaceous to Paleogene Passive Margin

The Lower and Upper Cretaceous sections (Figures 7a and 7b, respectively) attain their greater thicknesses onshore toward the north (1.4 km each). The Lower Cretaceous unit shows its maximum thickness offshore toward the east and into the Atlantic Ocean (Figure 7a). These units form a wedge-shaped, carbonate-siliciclastic, passive-margin succession that thickens to the north and toward the Atlantic Ocean and thins toward the south, where it onlaps Precambrian rocks. Maximum thickness of the Paleogene (Figure 7c) is located in the north and northeast (1.2 km). Offshore, the thickest sequence is related to the development of the passive-margin platform. The Paleogene was deposited to the north of the area (offshore and onshore) and thins toward the south, where it is truncated at an erosional surface (Figure 4) related to the “foredeep unconformity” (Di Croce et al., 1999) or to the passage of the Eastern Venezuelan peripheral bulge (Pindell et al., 1998). This unit represents the most evolved stage of passive-margin development in the Maturín Basin. The source of sediments during the passive-margin development in Eastern Venezuela was mainly the Guyana Shield to the south; evidence of this is the northward progradation of the clastic sequences observed in seismic lines and reported by Di Croce et al. (1999).

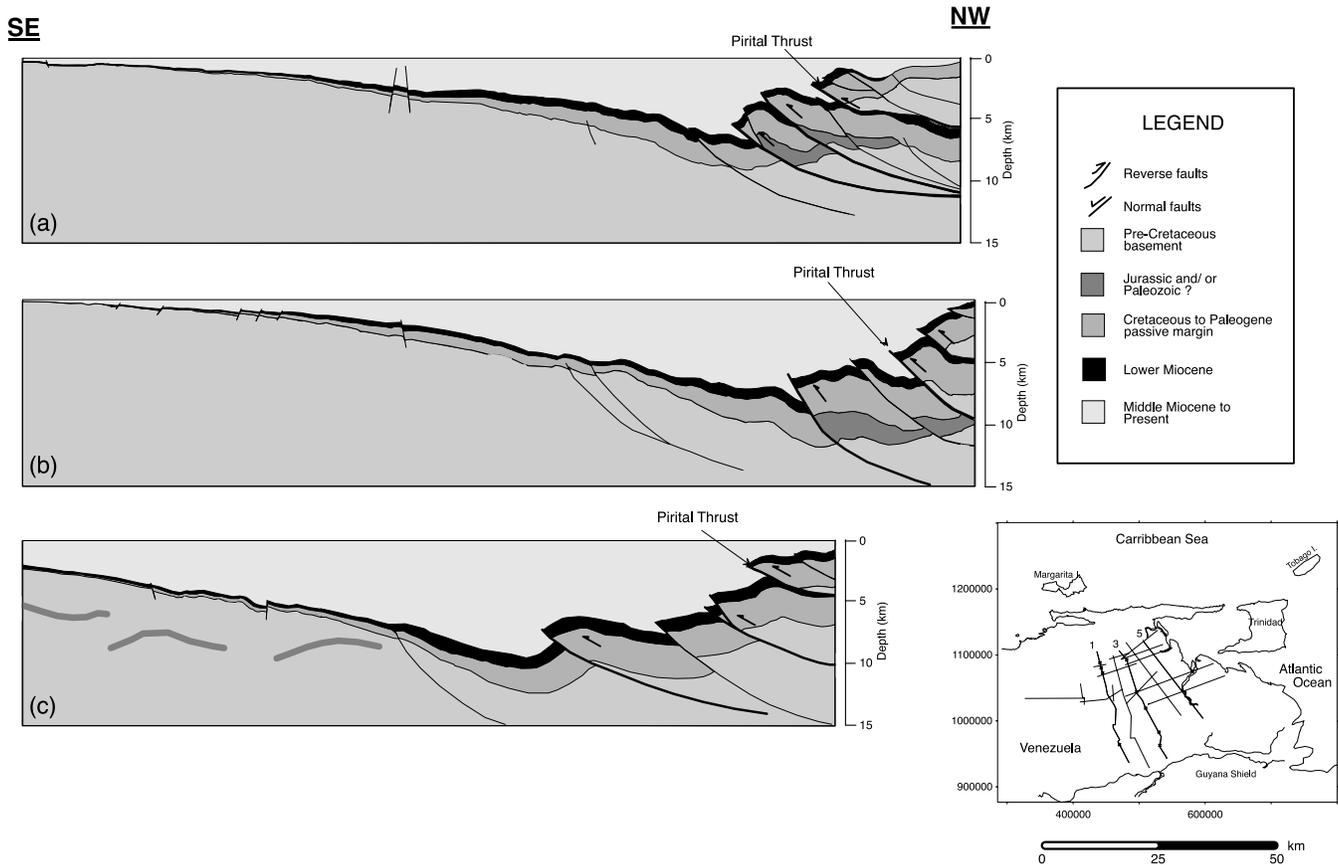


Figure 6. Simplified depth-converted seismic regional transects. (a) Transect 1, (b) Transect 3, (c) Transect 5.

Miocene Thrusting

The lower Miocene was deposited in the northern and western parts of the Maturín Basin (Figure 7d). This unit thins toward the south (offshore and onshore), where it onlaps Precambrian rocks; toward the north it thickens to 1.6 km, similar to the Cretaceous-Paleogene passive-margin configuration. In the west (Guárico Subbasin), however, the thickest unit of the lower Miocene is associated with the first syn-orogenic deposits (2.4 km). In this area, the sediments were deposited as a result of the first uplift related to the Serranía del Interior emplacement during the Tertiary. In this part of Eastern Venezuela, the lower Miocene marks the change from passive-margin basin to a foreland basin with active subsidence and deposition. The middle Miocene syn-orogenic deposits are located in an elongated area south of the Serranía Thrust Belt and north of the deformation front (Figure 8a). The present-day Serranía del Interior was uplifted during this time with an orientation of N70°E (Metz, 1965; Rossi, 1985; Rossi et al., 1987; Potié, 1989; Chevalier et al., 1995), which is parallel to the axis of sedimentation. South

of the Serranía Thrust Belt, three depocenters separated by topographic highs can be distinguished. These depocenters were formed at different times, indicating the migration of the Serranía thrusts from west to east and the subsequent foreland subsidence of the Maturín crust, caused by thrust-sheet loading. The deepest depocenter (6 km, Figure 8a) is located to the northeast, indicating an intensification of loading in this area during the middle Miocene. The thinnest sequences are located toward the northwest (because of erosion as the result of younger thrusting) and toward the south (offshore and onshore), where they onlap the lower Miocene unit. The upper Miocene section is thinner (Figure 8b) than the middle Miocene, Pliocene, and Pleistocene units, which may indicate that the upper Miocene sediments were deposited in a less active tectonic environment with a lower subsidence rate. Onshore, the thickest sequence (2 km) is found in the middle of the basin and is related to a system of listric faults that affected the Maturín Basin during this time (Daza and Prieto, 1990). Toward the northwest, the units are thinned and eroded. To the south, upper

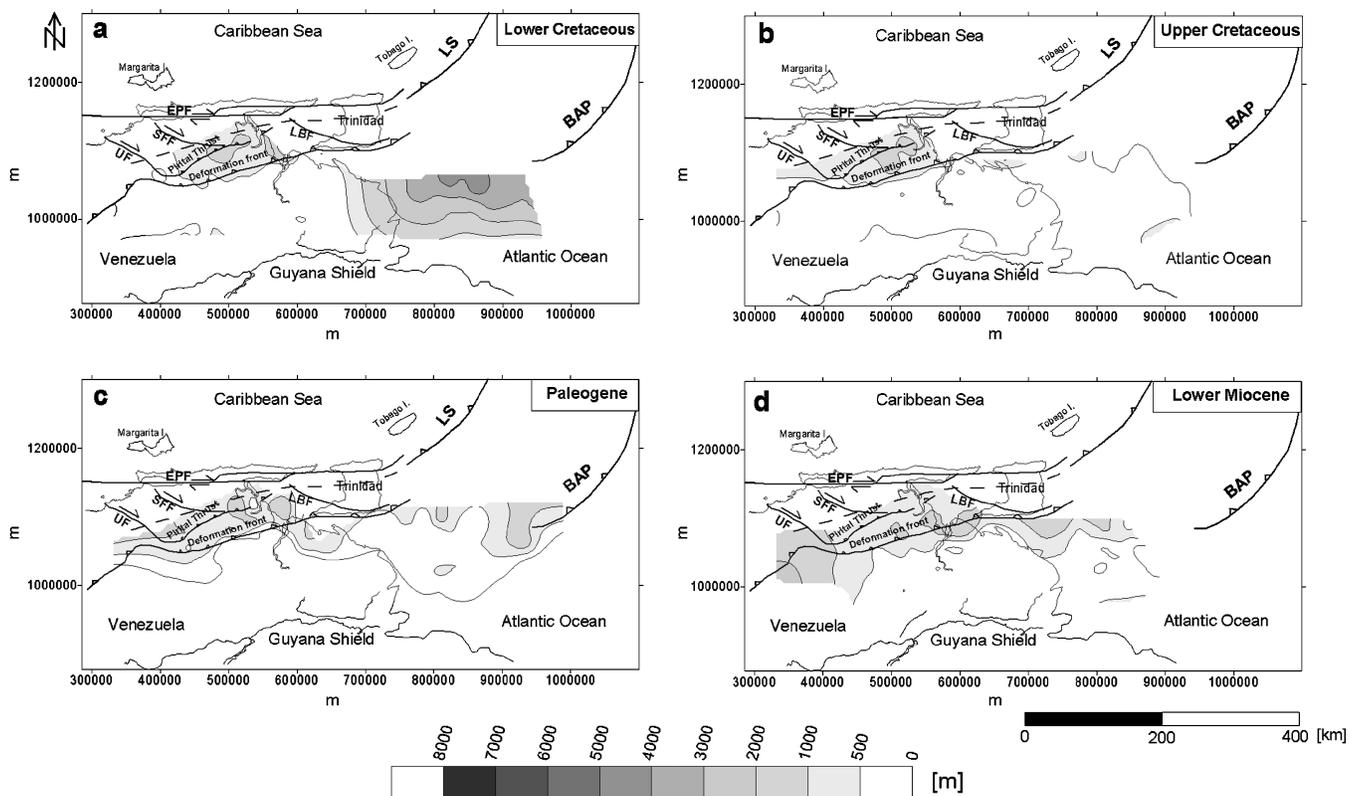


Figure 7. Thickness of main tectono-stratigraphic units. (a) Lower Cretaceous, (b) Upper Cretaceous, (c) Paleogene, and (d) Lower Miocene. Abbreviations: EPF = El Pilar Fault, UF = Urica Fault, SFF = San Francisco Fault, LBF = Los Bajos Fault, LS = Lithospheric Subduction, BAP = Barbados Accretionary Prism.

Miocene sediments onlap Precambrian rocks of the Guyana Shield. Offshore, in the Gulf of Paria, a thick unit (1.2 km) is related to collapsed structures in the Serranía del Interior, which today is located under water (Ysaccis, 1997; Flinch et al., 1999). The thin sequences offshore and onshore (200 to 400 m) can be related to a platform or basement high.

Pliocene to Pleistocene Continental Subduction

Pliocene sediments were deposited over a wide area of the Maturín Basin with the exception of the western area, where there was neither erosion nor deposition (Figure 8c). To the north-northwest, this unit thins and onlaps above the thrust. The principal axis of sedimentation changed from southwest-northeast (during middle to upper Miocene) to a west-east orientation (during the Pliocene to Pleistocene). This axis of sedimentation has a different orientation than the Serranía Thrust Belt. The source of sediments was the Serranía del Interior from the north and the Guyana Shield from the south. Three depocenters can be identified: (1) south of Gulf of Paria, (2) south of Trinidad, and (3) south of the Barbados Accretionary Prism (Figure 8c). Compared with

the middle Miocene depocenter, Pliocene depocenters are wider and migrated from west to east. Onshore and in the southern of Gulf of Paria, the depocenter is related to the Orinoco Delta deposits. Offshore, south of Trinidad and south of the Barbados Accretionary Prism, more than 6 km of Pliocene sediments were deposited in a system controlled by growth faults (Di Croce, 1995) and accretionary prism environments, respectively. During the Pleistocene, sediments were deposited in two localized depocenters (Figure 8d). Onshore, southwest of Trinidad, more than 4 km of sediments were deposited as the result of the Orinoco Delta progradation toward the east. Offshore, in eastern Trinidad, another depocenter is associated with growth faults (Di Croce, 1995), and with the Barbados Accretionary Prism. There is no continuous axis of sedimentation, and the two depocenters probably are divided by a basement high located offshore in the Atlantic Ocean. Pleistocene sediments were deposited regionally in the area, onlapping Precambrian rocks of the Guyana Shield to the south, and eroded by thrusting in the northwest. The axis of sedimentation was west-east, and the source of sediments was the Guyana Shield from

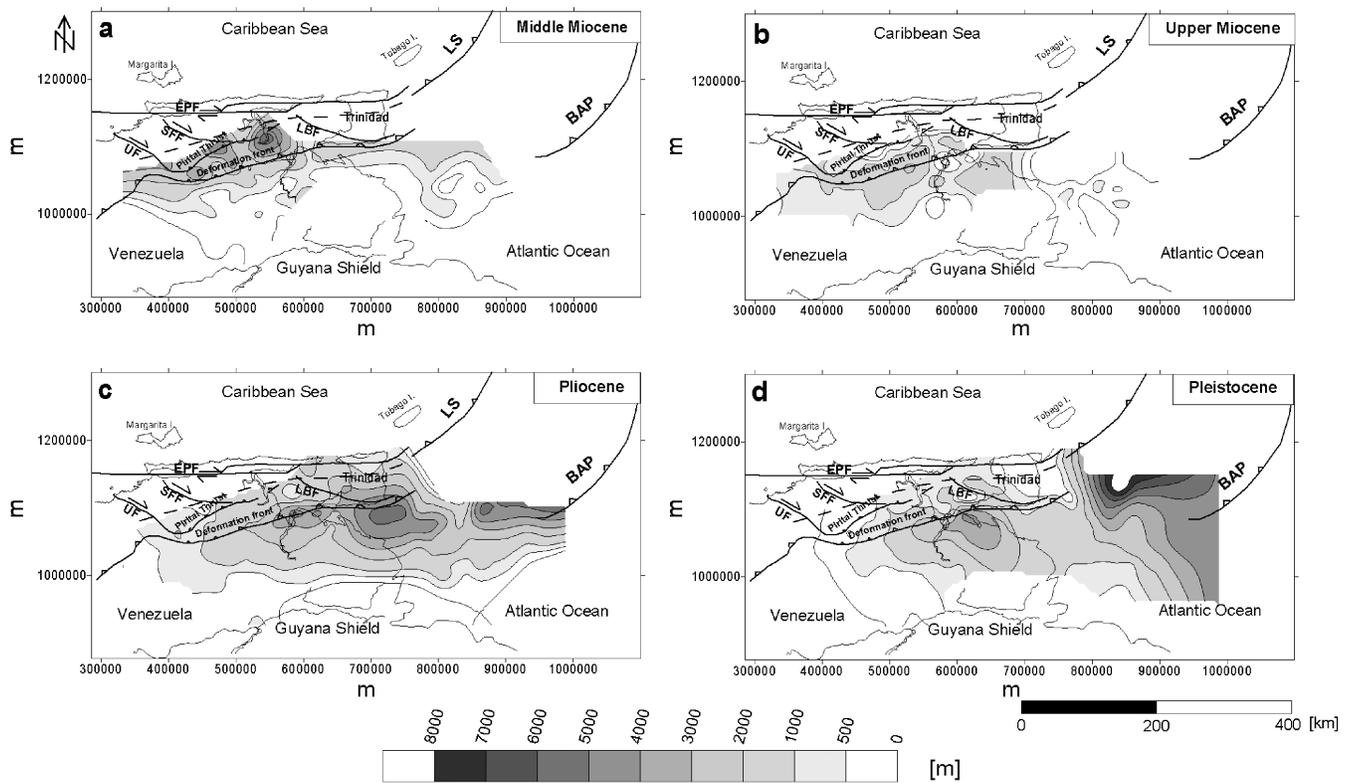


Figure 8. Thickness of main tectono-stratigraphic units. (a) middle Miocene, (b) Upper Miocene, (c) Pliocene, and (d) Pleistocene. Abbreviations: EPF = El Pilar Fault, UF = Urica Fault, SFF = San Francisco Fault, LBF = Los Bajos Fault, LS = Lithospheric Subduction, BAP = Barbados Accretionary Prism.

the south and the Serranía del Interior from the north, in a configuration similar to that of the Pliocene. Pliocene and Pleistocene subsidence has been localized to the east of the Maturín Basin, where there is no evidence of major thrust-sheet loading, implying that the geodynamic process associated with the Lesser Antilles Subduction Zone may have produced more than 10 km of subsidence in that area.

Decompaction

Decompaction has been carried out in order to analyze the burial history of the Maturín Basin and to determine the original thicknesses of the tectono-stratigraphic units. Decompacted thicknesses give information on the total subsidence associated with each stratigraphic unit, assuming that the accommodation space in the foreland basin is completely filled with sediments (i.e., assuming paleo-water depths were near sea level). The subsidence analysis for the Maturín Basin is summarized in Table 2 and was carried out using information from the representative thicknesses and ages for each sedimentary unit (obtained from the seismic and well-log information) and from previously reported lithology (Aude-

mard et al., 1997). Paleo-water depths for the tops of the stratigraphic units were assumed to be zero, because of a lack of accurate regional paleo-water depth estimations. The decompacted thickness of each sedimentary unit (i.e., from Pliocene to Lower Cretaceous) was calculated using the porosity-depth function from Sclater and Christie (1980). A series of decompacted “true thickness” isopach maps for the Maturín Basin was generated. Decompaction increases sediment thickness by at least 1 km (see Table 2).

DISCUSSION

The Maturín Basin traditionally has been understood to have formed as a result of the Serranía del Interior thrust-sheet loading, and it is often regarded as a good example of a peripheral foreland basin. However, the thickness of foreland-related sediments (more than 10 km in the east) indicates that thrust-sheet loading alone is unlikely to have been the only geodynamic process responsible for the generation of the accommodation space found in the basin. Subduction of the South American Plate under the Caribbean Plate (imaged by seismic tomography in

Table 2. Summarized subsidence history of the Maturín Basin. The subsidence rate is calculated with the maximum decompacted thickness for each unit. Unit thicknesses were taken from the interpretation of the regional seismic cross sections. Well-log stratigraphy and published lithological data (González de Juana et al., 1980, and Di Croce, 1995) provide information on the lithology of each unit. Compaction decay coefficient and surface porosity were taken from common sediment lithologies (Sclater and Christie, 1980).

<i>Unit</i>	<i>Maximum isopach thickness (km)</i>	<i>Maximum decompacted thickness (km)</i>	<i>Maximum subsidence rate (m/Ma)</i>	<i>Style of subsidence</i>	<i>Dominant tectonic subsidence mechanism</i>
Lower Cretaceous	1.4	2.0	43.01	Regional	Passive margin
Upper Cretaceous	1.4	2.0	64.3	Regional	Passive margin
Paleogene	1.2	2.0	46.84	Regional	Passive margin
Lower Miocene	1.6	2.6	366.2	Local depocenters	Thrust-sheet loading
Middle Miocene	6.0	7.0	1259.3	Local depocenters	Thrust-sheet loading
Upper Miocene	2.0	3.4	508.5	Local and regional	Local growth faults
Pliocene	4.2	4.6	1243.3	Local depocenters	Subduction
Pleistocene	4.6	4.6	2875.0	Local depocenters	Subduction

Van Der Hilst, 1990) may be an important process that generated additional subsidence in the basin (i.e., the Maturín crust may have been pulled downward by the subduction processes). Recent numerical modeling of Eastern Venezuela confirms that the Maturín Basin subsidence was produced by the Serranía del Interior thrust-sheet loading and by the South American subduction-related dynamic topography (Jacome et al., 2003).

Reconstruction of the Caribbean Plate history (e.g., Vierbuchen, 1978; Pindell and Dewey, 1982; Dewey and Pindell, 1985; Burke et al., 1984; Pindell and Barrett, 1990; Stephan et al., 1990; Ave Lallemand, 1997; Meschede and Frisch, 1998) demonstrates a relationship between eastward Caribbean trench migration and the observed east to southeastward migration of the Maturín Basin depocenter. Diachronous Caribbean–South American Plate oblique subduction, which started in the west during the Paleocene, affected Eastern Venezuela during the lower to middle Miocene and initiated the formation of the Maturín Basin. Moreover, the continuous negative gravity anomaly extending from the Barbados Accretionary Prism to Eastern Venezuela (Figure 9) suggests that the Lesser Antilles Subduction Zone extends under the Maturín Basin. The maximum amplitude of the negative gravity anomaly is located in the Maturín Basin (~–200 mGal), and is one of the lowest in the world associated with continental sedimentary basins. This large negative gravity anomaly is caused by the accumulation of 12 km or more of sediments in the foreland basin (Russo et al., 1993).

Depth-converted isopach maps of the middle Miocene and Pliocene sediments show three large depocenters that increase in thickness from west to east. These depocenters migrated from northwest in the middle Miocene to southeast in the Pliocene and Pleistocene. Middle Miocene depocenters can be correlated directly to three different stages of the Serranía Thrust Belt emplacement. Pliocene and Pleistocene depocenters, located in the northeastern part of the Maturín Basin and offshore Venezuela, are the thickest and show that the continental lithosphere subsided more than the adjacent western areas, indicating either greater shortening or influence of the subduction loading associated with the Lesser Antilles Subduction Zone. Since the shortening decreases to the east, as previously observed from the seismic interpretation, subduction of the South American Plate under the Caribbean could be responsible for the large sediment thickness found in the eastern part of the basin.

SUMMARY

The result of the regional seismic reflection interpretation constrained by well logs shows that the total shortening in the Monagas Foothills and Foreland Thrust Belt decreases from the west (50 km) to the east (35 km). The thickness of the Maturín foreland sediments, however, increases from the west (~7 km) to the east (~10 km). Two main décollement levels have been interpreted: one at a shallow level of ~5 km depth (Pirital Thrust) and one at a

Free Air and Bouguer Anomalies

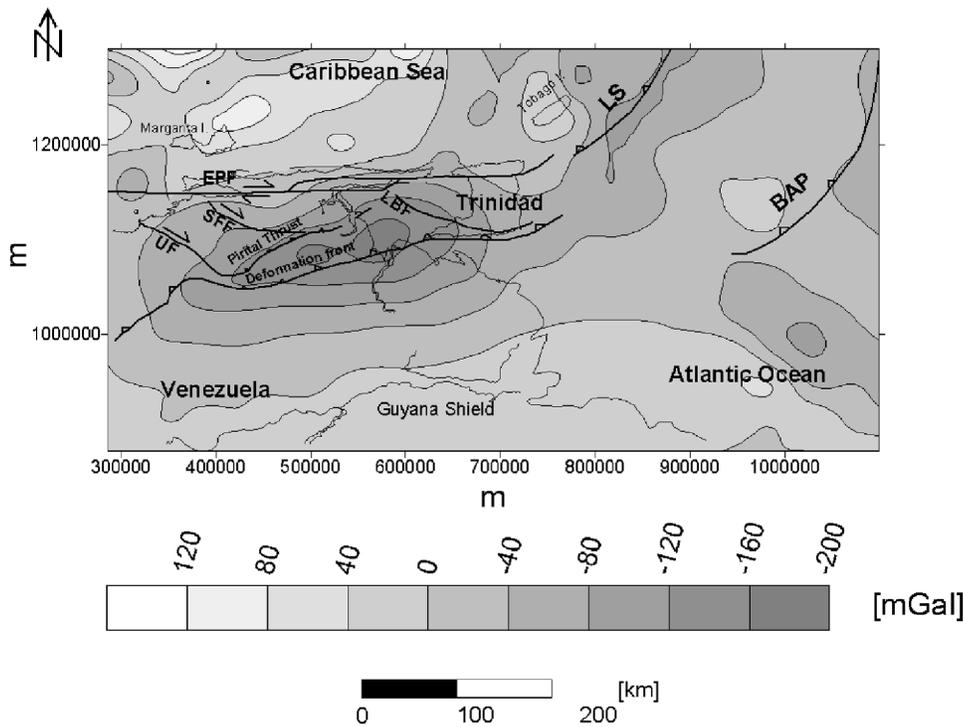


Figure 9. Free air gravity anomaly map (offshore) and Bouguer anomaly map (on-shore) for Eastern Venezuela. The negative gravity anomaly associated with the Barbados Accretionary Prism extends to the Maturín Basin, suggesting that the Lesser Antilles Subduction Zone may affect Eastern Venezuela. Abbreviations: EPF = El Pilar Fault, UF = Urica Fault, SFF = San Francisco Fault, LBF = Los Bajos Fault, LS = Lithospheric Subduction, BAP = Barbados Accretionary Prism.

deeper level of 10–15 km depth. The deeper décollement level is interpreted to lie within Paleozoic and Jurassic rocks. There were two phases of compression. The first stage used deep pre-Cretaceous and shallow intra-Cretaceous to Tertiary décollements, and the second phase involved deeper pre-Cretaceous to older structures. Folded Pliocene-Pleistocene sediments suggest that minor compressive deformation still is occurring and is affecting the sequence south of the foreland thrust belt deformation front.

Sequence stratigraphic well-log correlation demonstrates that the first synorogenic deposits are of middle Miocene age. The maximum bathymetric deepening of the Maturín Foreland Basin took place during this time (MFS 13.4). After SB-10.5, a regional long-term regression (with minor transgressive episodes) culminated with deposition of the shallow-marine to continental Pliocene-Pleistocene sediments.

Depth-converted isopach maps of middle Miocene, Pliocene, and Pleistocene units show large sediment thicknesses consistent with episodes of tectonically controlled subsidence, whereas the thickness of the upper Miocene indicates a more quiescent period. Decompacted thickness maps indicate maximum subsidence rates on the order of 1260 m/Ma, 1243

m/Ma, and 2875 m/Ma for the middle Miocene, Pliocene, and Pleistocene, respectively. The depocenters associated with tectonism have migrated from northwest to southeast and, more recently (middle Miocene to the present), toward the east.

This can be related to the migration of thrusting from northwest to southeast. The orientation of the depositional axis changed from southwest-northeast (during the middle and upper Miocene) to west-east (during the Pliocene and Pleistocene). Isopach maps show a greater thickness in the northeastern Maturín Basin than observed in the western Maturín Basin, adjacent to the Serranía del Interior Thrust Belt. The easternmost depocenters have changed from narrow and localized during the middle Miocene to wide and regional during the Pliocene-Pleistocene. The thickness of the Pliocene and Pleistocene units offshore to the east of Venezuela are not related to Serranian thrusting, since there is no evidence of major thrusting affecting the area south-southeast of Trinidad. Another geodynamic process must be responsible for more than 6 km of accommodation space in that area. Free-air gravity anomalies for the southeastern Caribbean offshore and Bouguer anomalies for Eastern Venezuela show a continuous negative-gravity anomaly extending from the Barbados Accretionary Prism to Eastern Venezuela, suggesting that the Lesser Antilles Subduction Zone may extend to and affect subsidence in the Maturín Basin by prism and subduction loading.

ACKNOWLEDGMENTS

This work forms part of Maria Jacome's Ph.D. research and is funded by Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICIT) and Simón Bolívar University, Venezuela. We are grateful to PDVSA and Simón Bolívar University for providing us with seismic, well-log, and gravity data.

REFERENCES CITED

- Audemard, F. E., I. Azpirtixaga, P. Bauman, A. Isea, and M. Latreille, 1985, Marco geológico del Terciario de la Faja Petrolífera del Orinoco de Venezuela: VI Congreso Geofísico Venezolano, tomo I, Caracas, Venezuela, p. 70–109.
- Audemard, F. et al., 1994, Exploración trampas estratigráficas, Anzoátegui-Monagas, Cuenca Oriental de Venezuela, Report INT-EPCT-0001394, Los Teques–Puerto La Cruz, Venezuela: Unpublished report, 210 p.
- Audemard, F., E. Cabrera, J. Di Croce, and A. Menéndez, 1997, Sinopsis de la Geología de Venezuela, *in* Léxico estratigráfico de Venezuela, 3rd Edition: Caracas, Venezuela, Comité Interfiliar de Estratigrafía y Nomenclatura (CIEN), v. 1, p. 18–28.
- Avé Lallemand, H., 1997, Transpression, displacement partitioning, and exhumation in the eastern Caribbean/South American Plate Boundary zone: *Tectonics*, v. 16, no. 2, p. 272–289.
- Bejarano, C., D. Funes, S. Sarzalejo, F. Audemard, and G. Flores, 1996, Sedimentary sequences evolution in a foredeep basin: Eastern Venezuela Basin, II Caracas AAPG/Sociedad Venezolana de Geólogos Conference: AAPG Bulletin, v. 80, no. 8, p. 1273.
- Burke, K., C. Cooper, L. F. Dewey, P. Mann, and J. Pindell, 1984, Caribbean tectonics and relative plate motions, *in* W. E. Bonini, R. B. Hargraves, and R. Shagan, eds., The Caribbean–South American Plate boundary and regional tectonics: Geological Society of America, M.162, p. 31–61.
- Chevalier, Y., 1994, A transverse section from the Orinoco Oil Belt to the El Pilar Fault System, tectonics and stratigraphy: Sociedad Venezolana de Ingenieros Geofísicos, Fieldtrip, V Simposio Bolivariano, Puerto La Cruz, Venezuela, 90 p.
- Chevalier, Y., G. Gonzales, S. Mata, N. Santiago, and F. Spano, 1995, Estratigrafía secuencial y tectónica del transecto El Pilar–Cerro Negro, Cuenca Oriental de Venezuela: VI Congreso Colombiano del Petróleo, Bogotá, Colombia, p. 115–125.
- Combellas, R., M. Aldana, A. Pilloud, J. Crux, and E. Novoa, 1998, Sequence stratigraphic analysis of a semiregional depth-migrated profile in Eastern Venezuela: Society of Exploration Geophysics Annual Meeting, New Orleans, p. 1759–1761.
- Crux, J., S. Sarzalejo, F. Audemard, C. Bejarano, S. De Cabrera, and D. Funes, 1996, Timing and sequence deposition related to the development of the Eastern Venezuelan Foreland Basin: II Caracas AAPG/Sociedad Venezolana de Geólogos Conference: AAPG Bulletin, v. 80, no. 8, p. 1284.
- Dewey, J. F., and J. L. Pindell, 1985, Neogene block tectonics of Eastern Turkey and northern South America: Continental applications of the finite difference method: *Tectonics*, v. 4, no. 1, p. 71–83.
- Daza, J., and R. Prieto, 1990, Fallas de crecimiento en el área de Mapirito-Monagas Central: V Congreso Venezolano de Geofísica, Caracas, p. 142–149.
- Di Croce, J., 1995, Eastern Venezuela Basin: Sequence stratigraphy and structural evolution: Ph.D. dissertation, Rice University, Houston, Texas, 225 p.
- Di Croce, J., A. W. Bally, and P. Vail, 1999, Sequence stratigraphy of Eastern Venezuelan Basin, *in* P. Mann, ed., Caribbean basins. Sedimentary basins of the world: Amsterdam, Elsevier Science B.V., p. 419–476.
- Erickson, J. P., and J. Pindell, 1993, Analysis of subsidence in northeastern Venezuela as a discriminator of tectonic models for northern South America: *Geology*, v. 21, p. 945–948.
- Erickson, J. P., and J. Pindell, 1998, Cretaceous through Eocene sedimentation and paleogeography of a passive margin in Northeastern Venezuela, *in* J. L. Pindell and C. L. Drake, eds., Paleographic evolution and non-glacial eustasy, Northern South America: Society for Sedimentary Geology (SEPM) Special Publication 58, p. 217–260.
- Erlich, R. N., and S. F. Barrett, 1990, Cenozoic plate tectonic history of the northern Venezuela-Trinidad area: *Tectonics*, v. 9, no. 1, p. 161–184.
- Feo-Codecido, G., F. D. Smith, N. Aboud, and E. Di Giacomo, 1984, Basement and Paleozoic rocks of the Venezuela Llanos Basin, *in* W. E. Bonini, R. B. Hargraves, and R. Shagan, eds., The Caribbean–South American Plate boundary and regional tectonics: Geological Society of America Memoir 162, p. 175–187.
- Flinch, J. F., V. Rambaran, W. Ali, V. De Lisa, G. Hernández, K. Rodrigues, and R. Sams, 1999, Structure of the Gulf of Paria pull-apart basin (Eastern Venezuela–Trinidad), *in* P. Mann, ed., Caribbean basins: Sedimentary basins of the world: Amsterdam, Elsevier Science B.V., p. 477–494.
- Funes, D., C. Bejarano, F. Audemard, and F. León, 1997, Tectono-sedimentary relationships of the Eastern Venezuela Guárico and Maturín Sub-basins: AAPG Annual Meeting, Dallas, Texas, p. 38.
- González de Juana, C., J. Arozena, and X. Picard Cadillat, 1980, Geología de Venezuela y de sus Cuencas Petrolíferas: Caracas, Venezuela, Foninves (eds.), v. 1, no. 2, p. 1–994.
- Hung, E. J., 1997, Foredeep and thrust belt interpretation of the Maturín Subbasin, Eastern Venezuela Basin: Masters thesis, Rice University, Houston, Texas, 185 p.
- Jacome, M. I., N. Kuszniir, F. Audemard, and S. Flint, 2003, The formation of the Maturín Basin, Eastern Venezuela:

- Thrust sheet loading or subduction dynamic topography: *Tectonics*, v. 22, no. 5, p. 1046.
- Lilliu A., 1990, Geophysical interpretation of Maturín Foreland, Northeastern Venezuela. Masters thesis, Houston University, Houston, Texas, 124 p.
- Linares, L. M., 1992, Sequence stratigraphy of Late Miocene—Pleistocene of Northern Monagas, Eastern Venezuela: Masters thesis, University of Texas at Austin, Austin, Texas, 82 p.
- Mariño, N., and G. Zannin, 1985, Volcanismo sedimentario en Venezuela nororiental: Memorias VI Congreso Geológico Venezolano, Caracas, p. 918–931.
- Meschede, M., and W. Frisch, 1998, A plate-tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean Plate: *Tectonophysics*, v. 296, p. 269–291.
- Metz, H., 1965, Stratigraphic and geologic history of extreme northeastern Serranía del Interior, State Sucre, Venezuela, *in* J. B. Saunders, ed., *Transactions: Fourth Caribbean Geological Conference*, Port of Spain, Trinidad, p. 275–292.
- Passalacqua, H., F. Fernandez, Y. Gou, and F. Roure, 1995, Crustal architecture and strain partitioning in the Eastern Venezuelan Ranges *in* A. J. Tankard, R. Suarez, and H. J. Welsink, eds., *Petroleum basins of South America: AAPG Memoir 62*, p. 667–679.
- Payne, N., 1991, An evaluation of Post-middle Miocene geological sequences, Offshore Trinidad: *Transactions of the 2nd Geological Conference of the Geological Society of Trinidad and Tobago*, Port of Spain, p. 70–87.
- Pindell, J. L., and J. F. Dewey, 1982, Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region: *Tectonics*, v. 1, no. 2, p. 179–211.
- Pindell, J. L., and S. F. Barrett, 1990, Geological evolution of the Caribbean region; A plate-tectonic perspective *in* G. Dengo and J. E. Case, eds., *The Caribbean region: Geological Society of America, The Geology of North America*, v. H, p. 404–432.
- Pindell, J. L., R. Higgs, and J. Dewey, 1998, Cenozoic palinspastic reconstruction, paleogeographic evolution and hydrocarbon setting of the northern margin of South America, *in* J. L. Pindell and C. L. Drake, eds., *Paleographic evolution and non-glacial eustasy, Northern South America: Society for Sedimentary Geology (SEPM) Special Publication 58*, p. 45–86.
- Potié, G., 1989, Contribution á l'étude géologique de la frontière sud-est de la plaque Caraïbes: La Serranía del Interior Oriental sur le transect Cumaná-Urica et le bassin de Maturín-Venezuela: Ph.D. dissertation, Université de Bretagne Occidentale, France, 254 p.
- Rohr, G. M., 1991, Exploration potential of Trinidad and Tobago: *Journal of Petroleum Geology*, v. 4, no. 3, p. 343–354.
- Rosales, H., 1967, Guía de la excursión geológica del área Barcelona–Río Querecual, Estado Anzoátegui: *Asociación Venezolana de Geología, Minería y Petróleo*, 20 p.
- Rossi, T., 1985, Contribution a l'étude géologique de la frontière Sud-Est de la plaque Caraïbes Etude géologique de la Serranía, La Serranía del Interior Oriental (Venezuela) sur le transect Cariaco-Maturín, *Syntheses Paleogéographique et Géodynamique: Ph.D. dissertation*, Université de Bretagne Occidentale, France, 350 p.
- Rossi, T., J. F. Stephan, R. Blanchet, and G. Hernandez, 1987, Etude géologique de la Serranía del Interior Oriental (Venezuela) sur le transect Cariaco-Maturin: *Revue de l'Institut Français du Pétrole*, v. 42, no. 1, p. 3–30.
- Roure, F., J. O. Carnevali, Y. Gou, and T. Subieta, 1994, Geometry and kinematics of the North Monagas Thrust Belt (Venezuela): *Marine and Petroleum Geology*, v. 11, no. 3, p. 347–362.
- Russo, R. M., R. C. Speed, and E. A. Okal, 1993, Seismicity and Tectonics of the Southeastern Caribbean: *Journal of Geophysical Research*, v. 98, no. 98, p. 14,299–14,319.
- Sclater, J. G., and P. A. F. Christie, 1980, Continental stretching: An explanation of the post-mid Cretaceous subsidence of the North Sea Basin: *Journal of Geophysical Research*, v. 85, p. 3711–3739.
- Speed, R. C., 1985, Cenozoic collision of the Lesser Antilles Arc and Continental South America and the origin of the El Pilar Fault: *Tectonics*, v. 4, no. 1, p. 41–69.
- Stephan, J. F. et al., 1990, Paleogeodynamic maps of the Caribbean: 14 steps from Lias to Present: *Bulletin of the Geological Society of France*, v. 8, p. 915–919.
- Van Der Hilst, R., 1990, Tomography with P, PP, and pP delay-time data and the three-dimensional mantle structure below the Caribbean region: Ph.D. dissertation, University of Utrecht, Utrecht, Netherlands, 250 p.
- Vierbuchen, R., 1978, The tectonics of the Northeastern Venezuela and the Southeastern Caribbean Sea: Ph.D. dissertation, Princeton University, Princeton, New Jersey, 175 p.
- Ysaccis, R., 1997, Tertiary evolution of the northeastern Venezuela offshore: Ph.D. dissertation, Rice University, Houston, Texas, 285 p.
- Ysaccis, R., and F. E. Audemard, 2000, A Neogene Orogenic float in Northern South America: Eastern Venezuela Basin vs. Caribbean Plate: *AAPG Annual Meeting*, New Orleans, Louisiana.