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RICE UNIVERSITY

TERTIARY EVOLUTION OF THE NORTHEASTERN VENEZUELA OFFSHORE

by

RAUL YSACCIS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE DOCTOR OF PHILOSOPHY

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ABSTRACT
Tertiary Evolution of the Northeastern Venezuela Offshore

by

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On the northeastern offshore Venezuela, the pre-Tertiary basement consists of a deeply subducted accretionary complex of a Cretaceous island arc system that formed far to the west of its present location. The internal structure of this basement consists of metamorphic nappes that involve passive margin sequences, as well as oceanic (ophiolitic) elements.

The Tertiary evolution of the northeastern Venezuela offshore is dominated by Paleogene (Middle Eocene-Oligocene) extension and Neogene transtension, interrupted by Oligocene to Middle Miocene inversions. The Paleogene extension is mainly an arc-normal extension associated with a retreating subduction boundary. It is limited to the La Tortuga and the La Blanquilla Basins and the southeastern Margarita and Caracolito subbasins. All of these basins are farther north of and not directly tied to the El Pilar fault system. On a reconstruction, these Paleogene extensional systems were located to the north of the present day Maracaibo Basin.

By early Miocene the leading edge of the now overall transpressional system had migrated to a position to the north of the Ensenada de Barcelona. This relative to South
America eastward migration is responsible for the Margarita strike-slip fault and the major inversions that began during the Oligocene and lasted into the Middle Miocene.

The Bocono-El Pilar-Casanay-Warm Springs and the La Tortuga-Coche-North Coast fault systems are exclusively Neogene with major transtension occurring during the Late Miocene to Recent and act independently from the earlier Paleogene extensional system. They are responsible for the large Neogene transtensional basins of the area: the Cariaco trough, the Northern Tuy-Cariaco and the Paria sub-basins, and the Gulf of Paria Basin.

This latest phase is characterized by strain-partitioning into strike slip faults, a transtensional northern domain and transpressional southern domain that is responsible for the décollement tectonics and/or inversions of the Serranía del Interior and its associated Monagas foreland structures. Part of the latest (Middle Miocene to Recent) phase is the formation of a large arch that corresponds to the Margarita-Testigos-Grenada zone which perhaps was subject to mild lithospheric compression during the Plio-Pleistocene.
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CHAPTER 1

INTRODUCTION

1.1 Objective of study

The Cariaco and Carúpano basins constitute the central and eastern parts of the Venezuelan continental shelf (Figure 1.1). Together with the Caribbean Mountain System of mainland Venezuela, they are part of the Caribbean-South American plate boundary, which is far from being clearly defined. While several studies (e.g., Molnar and Sykes, 1969; Dewey, 1972) interpret a group of major dextral transcurrent faults such as the Bocono, Oca, Sebastian and El Pilar faults as the Caribbean-South America plate boundary, there are other studies (e.g., Mascle et al., 1979; Ostos, 1990) which consider this boundary as an approximately 500 km wide zone, extending from the South Caribbean Deformed Belt to the Caribbean Mountain System (North Venezuela).

A variety of structures has been recognized in the Cariaco-Carúpano area but the definition, timing and orientation of the structures remain to be incorporated in a consistent geologic model. The E-W dextral transcurrent fault zone (i.e., the San Sebastian-El Pilar right lateral strike-slip fault zone) is certainly the most prominent feature of northern Venezuela (e.g., Bellizzi, 1984). It extends from the Gulf of Triste to Paria peninsula. This strike-slip dominated regime overprinted an earlier system, which
Figure 1.1. Northern Venezuela, physiographic provinces and sedimentary basins. Abbreviations refer to the following: AF= Anaco Fault; BAP= Barbados Accretionary Prism; BF= Bocono Fault; EPF= El Pilar Fault; IF= lcotea Fault; LBF= Los Bajos Fault; OF= Oca Fault; SER. INT.= Serranía del Interior Oriental; SF= San Francisco Fault; SMBF= Santa Marta - Bucaramanga Fault; SSF= San Sebastian Fault; UF= Urica Fault; WSF= Warm Springs Fault. Adapted, with minor modifications, from DiCroce, 1995.
made it more difficult to define the structural framework of the Cariaco and Carúpano basins.

The data included in this study suggest that the major E-W transcurrent activity has occurred in the Cariaco-Carúpano area since the Eocene. It will be shown that the evolution of the Cariaco basin differs from that of the Carúpano basin. For example Late Eocene-Early Miocene extension in Cariaco is coeval with compression in Carúpano.

The Cariaco and Carúpano sedimentary basin fill ranges from Eocene to Recent and the basement itself consists mostly of Cretaceous metamorphic-igneous rocks. Important regional unconformities in the area are represented by the top of the basement and the top Middle Miocene boundary. Additional unconformities can be recognized based on the integration of seismic data, well logs and paleontologic reports. All these data provide a chronostratigraphic framework for the Cariaco and Carúpano basins that constrains the timing of the structural deformation.

The Cariaco and Carúpano basins are located between 10° and 12° north latitude, and between 61° and 66° west longitude (Figure 1.1 and 1.2). They are separated from each other by the islands Margarita and Coche; the regional setting of these basins is shown on Figure 1.1.

The Cariaco and Carúpano basins have a significant hydrocarbon potential. The first reference to oil shows in Venezuela was given by Gonzalo Fernandez de Oviedo y Valdés in his work, "Historia Natural y General de las Indias, Islas y Tierra Firme del Mar Océano", 1535. In book XIX, chapter II of that work of art, he mentioned that on the western edge of Cubagua Island, not far from the sea there was a flow of liquid or
Figure 1.2. Location of the Study Area
bitumen-like pitch. Since great quantities of this substance constantly flowed into the sea, numerous patches of it floated on the water from one place to another. Some people called it petroleum and others asphalt (Perez de Tudela Bueso, 1959).

In 1940, the Socony-Vacuum oil company of Venezuela drilled the first two exploratory wells, Cubagua-1 and Cubagua-2, with negative results (Kugler, 1957; Bermudez and Bolli, 1969). From 1975 to 1982 a more comprehensive exploration campaign was undertaken in the Cariaco-Carúpano area. By 1982, 32 wells were drilled, 20 of them encountered either oil or gas. Even so, a better definition of the hydrocarbon plays needs to be established. Understanding the structural framework and the geologic history of the Cariaco-Carúpano area from a regional perspective will help to accomplish this.

This detailed study of the Cariaco and Carúpano basins aims to clarify the geologic evolution of these basins in the context of the tectonic evolution of the southern Caribbean boundary. A new seismic interpretation of these two basins will be presented and combined with previous regional studies. A tectonic model will be proposed for the Cariaco and Carúpano basins and its implications for the evolution of the Caribbean-South American plate boundary will be assessed.

1.2 Data Base

Seismic reflection profiles, well information and paleontologic reports were kindly provided by the national Venezuela petroleum companies LAGOVEN S.A. and
CORPOVEN S.A., both affiliates of PDVSA (Petroleos de Venezuela Sociedad Anonima). Over 10,000 line km of seismic reflection profiles were interpreted for this study. Geologic reports of the 32 wells drilled in the Cariaco-Carúpano area were consulted. Figures 1.3 and 1.4 show the geographical distribution of these data.

Surface geologic maps of Northern Venezuela were available and compiled on maps (see Figures 3.1 and 3.2).

1.2.1 Seismic profiles

The seismic surveys in the Cariaco-Carúpano area were made between 1975 and 1980. Records range from 5 sec. to 8 sec. and the quality of the profiles is reasonably good for most of the area, except for the northeastern part of the Carúpano basin where the data are poor.

Many of the seismic profiles are reproduced here in the form of line drawings, which are subjective interpretations. Selected details are shown on copies of the profiles to further document these interpretations.

Twelve panels were made, each comprising selected line drawings (enclosure 1-12) to illustrate the overall configuration of the area. These panels form the backbone of this study.
Figure 1.3. Location map of the seismic data used for this work.
1.2.2 Well data

Figure 1.4 shows the location of the wells used to calibrate the seismic units. The well data include electric logs, curves of time-versus-depth, and paleontologic and stratigraphic reports. Most of these geologic reports were generated by 1985; correlation problems and stratigraphic nomenclature are discussed in these reports. The quality of paleontologic data is reasonably good, except for the area near Cubagua where the scarcity of fossils prevents the precise definition of the Paleogene and Early Miocene section (Kugler, 1957).

1.3 Methodology

The seismic stratigraphic principles of Vail et al. (1977), Vail (1987), Van Wagoner et al. (1987; 1990) and Mitchum et al. (1993) form the basis for the stratigraphic interpretation of the seismic profile. Sequence boundaries were defined through the integration of seismic, well log and biostratigraphic data. They are geometrically represented as onlap and/or truncation surfaces on reflection configuration patterns (Vail, 1987)[Fig. 1.5]. The velocity surveys of the wells were used to calibrate the seismic interpretation. The strong seismic reflectors of the top of the basement and the Middle Miocene unconformity, which constitute major sequence boundaries in the Cariaco-Caripano area, are helpful reference levels. The consistency of the seismic
Fig. 1.5. Diagram showing reflection patterns and types of discontinuities (after Vail, 1987).
interpretations is revealed by the mapping of major faults and the geometry of the structures, at the top basement level.

In addition stratigraphic cross-sections and some isotime and paleogeographic maps were prepared and combined to provide the regional geologic framework for the Cariaco and Carúpano basins.

1.4 Previous works in the Cariaco and Carúpano areas

1.4.1 Cariaco area

In 1799, Alexander von Humbolt suggested that the Cariaco depression, which connected the Gulfs of Cariaco and Paria, was a fault trace. Liddle, in his publication on the geology of Venezuela and Trinidad (1946, p. 569-570), accepted this hypothesis and named the inferred fault the El Pilar after a small village in the depression.

Rod (1956) and Alberding (1957) provided evidence to support the strike-slip character of the El Pilar fault. Both of them suggested a large right lateral displacement for this fault. Alberding noted the similarity of the Mesozoic igneous and metamorphic rocks of the Cordillera de la Costa with those of the Araya and Paria Peninsulas, north of the El Pilar fault (Figure 1.1). According to him, the rocks of the Araya and Paria Peninsulas reached their current position by a 475 km right-lateral strike-slip from an initial position near the Cordillera de la Costa. Therefore, he proposed that the El Pilar fault extended into the Cariaco Basin and ran along shore north of the Cordillera de la Costa.
Later studies proposed that the El Pilar fault is one of several right-lateral strike-slip faults that define the southern boundary of the Caribbean. This idea was reinforced by Sykes and Ewing (1965) who described the seismicity of the area. However, Ball (1971) proposed that the marine geophysical measurements in the Cariaco area revealed normal faulting as the predominant style of faulting.

Russomano (1979) emphasized the active role played by major strike-slip faults of the transform zone in shaping the Cariaco trough. Schubert (1982) provided evidence for interpreting the Cariaco trough as a pull-apart basin of probably Quaternary age surrounded by a bifurcating shelf.

During 1985 and 1986, PDVSA carried out regional studies on the Venezuelan margin; one of the most important resulting publications was by Goddard (1986). He detailed the stratigraphic framework of the Cariaco Basin and the surrounding shelf by recognizing five stratigraphic units ranging in age from Eocene to Pleistocene.

Bianco and Giraldo (1992) identified two provinces in the Cariaco area: (a) Margarita-Tortuga platform, and (b) Tuy-Cariaco Basin “sensu-strictu”. They also suggested four major tectonic phases in the area: (1) Extension (Late Cretaceous to Paleocene), (2) Compression (Paleocene to Middle Eocene), (3) Extension (Middle Eocene to Middle Miocene) and (4) Compression (Middle Miocene to Recent).

1.4.2 Carúpano area

The Carúpano Basin and the surrounding offshore areas to the north of the Araya and Paria peninsulas constitute the Margarita-Tobago continental shelf (Feo Codecido,
1977). On the basis of geophysical data, Lattimore et al. (1971) suggested that the Los Testigos Platform extends into the Lesser Antilles arc, and that the Carúpano Basin continues towards Tobago Basin.

Feo Codecido (1977) referred to the Carúpano basin as the Margarita-Barbados depression. Based on a bibliographic compilation, he pointed out that this depression is largely filled with a Tertiary sedimentary section, more than 6,000 meters thick in its deepest part to the northeast. According to him, this sedimentary column overlies an igneous-metamorphic basement of Mesozoic age; and major normal faults cut the basement surface longitudinally.

González de Juana et al. (1980), principally based on information from the Corporación Venezolana de Petróleo CVP (Petroleum Venezuelan Corporation), defined three sedimentary cycles in the Margarita-Tobago shelf. In their analysis, the oldest cycle is a turbiditic sediment sequence which is correlative with the flysch of the Punta Carnero Group in Margarita island (Eocene). The second cycle is probably Oligocene and comprises an alternation of limestone, sandstone and shale; and the youngest one is considered correlative with the Upper Miocene- Pliocene Cubagua Formation.

Castro and Medero (1985), in their study “Litoestratigrafía de la Cuenca de Carúpano”, introduce the names of three new formations in the eastern Venezuelan offshore: Tigrillo Formation (Eocene), Caracolito Formation (Oligocene) and Tres Puntas Formation (Middle Early Miocene). They also define and describe for the first time the igneous-metamorphic complexes: Bocas (Jurassic (?) to Early Cretaceous), Mejillones (Early to Late Cretaceous), and Los Testigos (Late Eocene to Lower Early Oligocene).
The Bocas complex comprises mid-oceanic ridge basalts and sedimentary rocks that underwent low-grade metamorphism. The Mejillones and Los Testigos complexes consist predominantly of basaltic rocks of island arc affinity.

Pereira (1985) suggests two tectonic phases for the evolution of the Carúpano Basin: 1) transpression (Eocene to Oligocene) and 2) transtension (Miocene to Pliocene). A new interpretation of the Neogene development of the Carúpano Basin is presented by Ramírez et al. (1992). They propose that the Margarita-Los Testigos shelf was not a significant source of sediment after the Middle Miocene; instead, the southern margin, along the Paria Peninsula, appears to be the major sedimentary source.
CHAPTER 2

PLATE TECTONIC FRAMEWORK: GEOLOGY OF THE CARIBBEAN REGION

2.1. Introduction

The tectonic evolution of the Cariaco and Carúpano Basins is constrained by their plate boundary regimes; consequently, the nature and timing of folding and faulting in these basins need to be placed into a plate tectonic framework.

The Caribbean plate has long been a subject of controversy because of its tectonic complexity. The Caribbean is separated from adjoining plates by subduction zones on the east and west and by strike-slip boundaries to the north and south (Figure 2.1). Over much of the Caribbean basin, seismic refraction measurements reveal crustal thicknesses of 10 to 25 km, i.e., much greater than the 6-km thickness typically observed in the main ocean basins (Fox and Heezen, 1975). The thicker-than-normal crust of the Caribbean has been attributed to the emplacement of a massive basalt flow (Stoffa et al., 1981) and the top of this basaltic layer is recognized on seismic reflection profiles as the B” horizon (Ewing et al., 1967; Burke et al., 1978).

The purpose of this chapter is to describe the major geological provinces that make up the Caribbean plate. A summary of the kinematic evolution and the paleogeographic reconstruction of the Caribbean plate is also included in this chapter.
Figure 2.1  (A) Map of the Caribbean region showing the relative positions of plates, physiographic regions and major islands. Direction of subduction shown by solid triangles. (B) Geologic provinces of the Caribbean region, as defined in the present chapter. Key: AP = Anegada Passage; AR = Aves Ridge; BeR = Beata Ridge; BP = Bahamas Platform; BR = Barbados Ridge and Lesser Antilles Deformed Belt; C = Cuba; CA = Colombian Andes; CB = Chortís Block; ChB = Choco Block; CO = Cuban Orogenic Belt; CoB = Colombian Basin; CT = Cayman Trough; CtB = Chorotega Block; EPFZ = El Pilar Fault Zone; GA = Greater Antilles; GAOB = Greater Antilles Orogenic Belt; GB = Grenada Basin; GM = Gulf of Mexico; H = Hispaniola (Haiti + Dominican Republic); J = Jamaica; LA = Lesser Antilles; MPFZ = Montagua Polochic Fault Zone; NP = Nazca Plate; NPD = North Panama Deformed Belt; NR = Nicaraguan Rise; OTF = Oriente Transform Fault; PR = Puerto Rico; SCD = South Caribbean Deformed Belt; SITF = Swan Island Transform Fault; VB = Venezuelan Basin; VBo = Venezuelan Borderland; YB = Yucatán/Maya Block; YBa = Yucatán Basin. From Draper, G., Jackson, T.A. and Donovan, D.A. (1994).
2.2. Physiographic provinces

The Caribbean is a small sea surrounded by the South American continent in the south, Central America to the west, and to the north and east by the Caribbean Island Arc (Figure 2.1). The topography of the sea floor enclosed by these boundaries is highly varied; but five deeper water basins can be recognized. They are from northwest to southeast: the Yucatán Basin, the Cayman Trough, the Colombian Basin, the Venezuela Basin and the Grenada Basin. These are separated by several more or less linear ridges and rises; i.e., by the Cayman Ridge, the Nicaraguan Rise, the Beata Ridge and the Aves Ridge, respectively (Draper et al., 1994).

Figure 2.1 shows the location of the major physiographic and geologic provinces in the Caribbean region.

2.3. Geologic provinces

2.3.1. Interior Caribbean basins and vicinity

The main interior basins of the Caribbean Sea are underlain by oceanic crust. The crust beneath the Colombian and Venezuelan basins is Late Cretaceous or older and the crust beneath the Yucatán Basin is Eocene or older (Case et al., 1984).

Seismic reflection profiles in the interior Caribbean basins show two prominent reflectors: an upper reflector A” and a lower reflector B”. Borehole data from Deep Sea Drilling Project Leg 15 indicates that the B” horizon consists of the uppermost layers of a
large oceanic basalt plateau with a crustal thickness of between 15 and 20 km (Draper et al., 1994). ODP Leg 165 (Figure 2.2) recovered the basalt/sediment contact on the Hess Escarpment (site 1001) and reported a succession of twelve submarine lava flows of Mid-Campanian age. Massive sheet flows in this succession are attributed to high mass eruption rates and pillow lavas. The assemblage of benthic microfossils in the overlying limestones and in limestone lenses within the lavas constrains the timing of this volcanic event. Accordingly, the Caribbean Oceanic Plateau volcanism continued at least until 77 Ma, and volcanism on the plateau may have persisted until 74 Ma (ODP Leg 165 Scientific Party, 1996). Donnelly (1994) also proposed that magmatism continued for an additional few million years in the west. His idea was based on data from DSDP Leg 15 which suggested that the age of sedimentary rocks above the basalt is somewhat younger towards the west.

The A" horizon is recognized in the Venezuelan Basin as the boundary between soft, semiconsolidated Eocene and younger pelagic oozes above and Eocene and older lithified cherts and chalks below (Ladd et al., 1984). However, the correlation of the reflector A" into other basinal portions of the Caribbean suggests that this horizon is slightly diachronous, being Middle Eocene (about 50 Ma) in the east, but Late Paleocene (about 58 Ma) in the west (Donnelly, 1994).

The interior of the Caribbean Sea comprises basinal areas (Yucatán, Colombian and Venezuelan Basins) separated by shallower areas (the Nicaraguan Rise and Beata Ridge). The Yucatán Basin will be discussed later as a part of the northern Caribbean geologic provinces.
Figure 2.2 Map of the Caribbean showing major features within the basinal portion. Filled circles with numbers are drillings sites (DSDP Leg 15) that reached the basaltic crust; open circles are DSDP sites not reaching basement. ♦️ are the sites drilled during ODP Leg 165. (From Donnelly, 1994).
**Nicaraguan Rise**

The Nicaraguan Rise is located in the northwestern part of the Caribbean Sea extending northeastward from Honduras and Nicaragua to Jamaica and southern Haiti (Arden, 1975). The northern edge of the rise is defined by the Cayman Trough and the transform fault of the northern Caribbean plate boundary. To the south, the northeast-southwest trending Hess Escarpment separates the rise from the Colombian Basin.

The Nicaraguan Rise is subdivided by the Pedro Bank Escarpment or Pedro Bank Fracture zone into a shallow northern part, upper rise, and a deeper southern part, the lower rise (Case et al., 1990).

The nature and age of the crust beneath the northern Nicaraguan Rise are not clear. According to Arden (1975), the Paleocene-Miocene carbonate platform of the northern Nicaraguan Rise is underlain by Late Cretaceous age island-arc rocks. They are described as andesitic and basaltic rocks associated with volcanioclastics and sediments, locally intruded by granodiorite. These calc-alkaline magmatic complexes continue westward into the continental crust of the Chortíts block (Case et al., 1990).

The southern Nicaraguan Rise appears stratigraphically to be an uplifted portion of the Colombian Basin. Ross and Scotese (1988) suggested that this uplift might be due to latest Eocene to Quaternary east-west extension between the Chortíts block and the Caribbean plate. DSDP site 152, drilled in the eastern portion of the southern Nicaraguan Rise (see location on Figure 2.2), demonstrated the continuation of the seismic horizon B" into the area (Donnelly, 1994).
Colombian Basin

The Colombian Basin forms the western part of the Caribbean Sea. Its eastern boundary with the Beata Ridge is defined by a normal-fault controlled escarpment (Figure 2.3). To the south, the Colombian Basin is bounded by the Neogene volcanic belt of Central America, the Northern Panamá Deformed Belt and the Southern Caribbean Deformed Belt (Figure 2.1).

The oceanic crust of the Colombian Basin is overlain by Campanian and younger sedimentary rocks (e.g. Case et al., 1984). Seismic reflection profiles acquired in this basin suggest the presence of the A’’ reflector in the sedimentary column (e.g. Ludwig et al., 1975); however the deeper B’’ basement reflector has been more difficult to recognize in the Colombian Basin than in the Venezuelan Basin (Donnelly, 1994). Instead of a very smooth reflector, the B’’ horizon is rough, or highly faulted, or too deeply buried to register clearly on seismic reflection profiles.

The crustal section of the Colombian Basin exhibits an anomalous thickness ranging from 10 to 25 km (Case et al., 1990). Seismic refraction measurements show that the excessive thickness of the Caribbean oceanic crust decreases towards the east; the entire crustal section is thicker in the Colombian Basin than in the Venezuelan Basin (Donnelly, 1994).

Several authors explain the unusual properties of Caribbean crust as characteristic of oceanic plateaus. Some of them (e.g., Mattson, 1969; Burke et al., 1978) propose analogies between the Caribbean and anomalously shallow oceanic plateaus in the Western Pacific, such as the Ontong Java and the Manihiki. In this hypothesis, the
Figure 2.3  East-west crustal cross-section at 15° latitude, bent to cross Central America at about S45°W. The ‘Caribbean basalt/sediment layer’ is the upper part of the thickened Caribbean crust; the sediment portion of this layer is conjectured. From Donnelly (1994).
Caribbean oceanic plateau could have formed over the Galapagos hotspot in mid to late Cretaceous time (100-75 Ma) on oceanic crust formed earlier at the Farallon-Phoenix spreading center (Duncan and Hargraves, 1984).

Oceanic plateaus represent bodies of basalt 20 or more km thick (Burke, 1988) and have a buoyant character that made them difficult to subduct (Vogt et al., 1976). This could explain why the Caribbean oceanic floor is 1-2 km shallower than would be predicted from thermal subsidence (Burke et al., 1978).

Beata Ridge

The Beata Ridge is an uplifted segment of oceanic crust that extends 400 km southwest from Cape Beata, Hispaniola (Draper et al., 1994). It divides the central part of the Caribbean into the Colombian and Venezuelan Basins (Figures 2.1 and 2.3); these two basins are connected by the Aruba Gap between the southern end of the Beata Ridge and the South American continental shelf.

The Ridge has a relief of about 2000 m and is characterized by block-faults that trend northwest and northeast (Case et al., 1984) and become less pronounced towards the south where the ridge approaches the South Caribbean Deformed Belt (Ladd et al., 1984).

Seismic reflection profiles on the eastern flank of the Beata Ridge show the same A" and B" reflectors recognized in the Colombian and Venezuelan Basins (Fox and Heezen, 1975). The Upper Cretaceous-Lower Eocene sedimentary section between the reflecting horizons A" to B" presents a nearly constant thickness across the Beata Ridge; it suggests that the ridge was formed after this depositional interval. This observation,
together with the occurrence of shallow-water Mid-Eocene limestone on top of the ridge, led to constrain the date of elevation of the Beata Ridge as Early to Middle Eocene. Later, the presence of Upper Oligocene to Holocene deep-sea pelagic carbonates indicates that by Late Oligocene the ridge had subsided to deep water (Fox and Heezen, 1975).

- **Venezuelan Basin**

The Venezuelan Basin represents the eastern portion of the Central Caribbean. This basin is the deepest (mainly between 3,000 and 5,000 m) and largest of the Caribbean basins. Its greatest depths occur to the north (Muerto Trough) and to the south (Venezuelan Plain), where the Venezuelan Basin converges with the North and South Caribbean Deformed Belts, respectively (Case et al., 1984; Draper et al., 1994).

Toward the east, the supra-crust sediments of the Venezuelan Basin thicken dramatically towards the Aves Ridge (Officer et al., 1959), which defines its eastern boundary. This sedimentary succession includes Cretaceous-Paleogene rocks with apparent island-arc affinity from the western margin of the Aves ridge. Based on this information, Donnelly (1989) proposed that the eastern margin of the Venezuelan Basin is a zone where basinal crust had been subducted beneath the Aves Ridge during the Cretaceous and Paleogene.

DSDP drilling and seismic surveys allow to distinguish at least two major sedimentary units (Biju-Duval et al., 1978):

1) A Turonian (?)-Lower Eocene pelagic consolidated sequence, with few cherts. The horizon A" (of Middle Eocene age in DSDP hole 146) is interpreted as the top of this sequence.
2) A Middle Eocene-Recent semiconsolidated to unconsolidated pelagic sequence.

Ladd and Watkins (1980) subdivide the second sequence into two seismic units: a) Middle Eocene-Lower Miocene and b) Middle Miocene-Recent. They traced these two units southward to the Venezuelan abyssal plain and found that the lower unit can be followed beneath the turbidites, but that the upper unit interfingers with the turbidites. This suggests that the turbiditic sedimentation in the southern Venezuelan Basin was post Early Miocene. It could be related to the tilting of the basin toward the south as a result of the initiation of underthrusting north of the Venezuela margin. However, it is also possible that older turbidites may have been included in the accretionary prism.

The sedimentary section in the Venezuelan Basin overlies Campanian basalts (e.g., Saunder et al., 1973), the top of which coincide with the B" reflector. This reflector appears to be far smoother on seismic profiles than the typical oceanic crust; only in the southeastern corner of the basin the B" reflector has a rough morphology. Also in this southeastern part, a near normal thickness has been reported for the crustal section.

Magnetic anomalies in the Venezuelan Basin have been identified by Ghosh et al. (1984) who fitted them to a sea-floor spreading event between 157 and 127 Ma (Late Jurassic to Early Cretaceous); however, these anomalies may be related only to topographic features (Donnelly, 1989).

2.3.2. Northern Caribbean

In broad terms, the current North Caribbean margin consists of a Neogene left-
lateral strike-slip deformation zone extending from the northern Lesser Antilles volcanic arc in the east to the Middle America volcanic arc (in western Guatemala and southern Mexico) in the west (Mann et al., 1990). This margin is characterized by intermediate crustal thickness, high seismicity, Late Cenozoic volcanic activity on central Hispaniola, and active volcanism in the Cayman trough spreading center (Lewis and Draper, 1990).

The major geological provinces along the northern Caribbean are: the Yucatán Basin, Cayman Trough and Greater Antilles. The Gulf of Mexico and the Florida and Bahamas platforms could also be included among these geological provinces. They were related to the tectonic evolution of the northern Caribbean during Mesozoic and Paleogene time.

- **Gulf of Mexico**

While the northern margin and southern margin of the Gulf of Mexico are underlain by a broad zone of stretched and thinned continental crust, its central part is underlain by Upper Jurassic to Lower Cretaceous oceanic crust (Draper et al., 1994).

It is suggested that the Gulf of Mexico is the result of the rifting of the North American plate from the Yucatán/Maya block (Pindell and Dewey, 1982; Ross and Scotese, 1988; Pindell and Barrett, 1990) during the Triassic to the Late Middle Jurassic. Extensive grabens, developed during the early stage of rifting in the Gulf, were the depositional sites of thick continental clastic rocks and tholeitic basaltic volcanism (White and Burke, 1980). During a later stage of the rifting, the grabens formed restricted basins, marine flooding began and evaporites were deposited in these basins.

In the Late Jurassic, sea-floor spreading occurred in the central Gulf of Mexico
(Ross and Scotese, 1988) and it generated oceanic crust that separated the older salt basins. Synsedimentary salt movements with associated faulting and folding began to occur during this time (e.g., Worrall and Snelson, 1989). Sedimentation during the Late Jurassic is represented by shallow-water limestone on the margins of the Gulf and deep-water carbonates in the central areas. A similar pattern of sedimentation continued through the Cretaceous. These carbonate sequences are overlain in the western and central Gulf of Mexico by continental clastic rocks derived as a result of Late Cretaceous orogenic uplift in western North America and Mexico (Draper et al., 1994).

**Florida and Bahamas Platforms**

The Florida and Bahamas Platforms are separated from Cuba and Hispaniola by the Old Bahamas Channel, which is topographically an extension of the Puerto Rico Trench. Seismic data suggest thickness of from 5 to 12 km of Jurassic to Recent sedimentary rocks in this basin (Sheridan et al., 1981). The Florida and Bahamas Platforms consist of shallow-water limestones and dolomites, evaporites and deep-water limestones. The accumulation of these carbonate sequences resulted from the subsidence accompanying the rifting that formed the Atlantic Ocean and the Gulf of Mexico (Sheridan et al., 1988).

The crustal nature of the Bahamas is controversial and may be oceanic in the south and continental in the north (Case et al., 1984). Seismic lines reveal a faulted, rifted basement in the northern part of this basin, extending from Florida to an inland projection point of the Blake Spur magnetic anomaly in the Bahamas (Sheridan et al., 1981). To the
southeast of this point, the basement appears no longer to be faulted, but instead has the appearance of a hummocky surface interpreted as oceanic crust (Sheridan, 1989).

Faulting and folding are also recognized in the southern Bahamas; they have been related to the Cuban orogeny in the Late Cretaceous and Early Tertiary. The faulting apparently segmented what was once a broader megabank beneath the Florida/Blake Bahamas area (Sheridan, 1989).

- Greater Antilles orogenic belt

The Greater Antilles orogenic belt comprises Hispaniola, Puerto Rico, the Virgin Islands and southeastern Cuba. Western and central Cuba form another orogenic belt, which possibly involved continental crust and was developed during Middle Cretaceous to Early Cenozoic.

The Greater Antilles consist of a core of Cretaceous through Paleogene island-arc volcanic rocks and a moderately deformed Neogene sedimentary sequence (Donnelly, 1989) overlying Jurassic basement rocks (Draper et al., 1994). The geographic distribution and geochemical characteristics of these early rocks indicate oceanic crust to the southwest with a parallel belt of an island-arc sequence to the northeast. According to Lewis and Draper (1990), this geometry lends support to subduction of the early Caribbean plate beneath the North American plate, forming the proto-Greater Antilles during the Early Cretaceous. Later a subduction polarity reversal occurred by Late Cretaceous; the distribution of ultramafic and metamorphic rocks along the northern margin of the arc suggests a south-dipping subduction of the North American plate beneath the Caribbean plate. New data from the ODP Leg 165 [see location of the wells
on Figure 2.2] suggest continuation of oceanic plateau volcanism until 77 Ma, the polarity flip could take place about 80 Ma.

Subduction-related volcanism progressively ceased from west to east, from the Middle Eocene in Cuba to Late Eocene or perhaps Oligocene in the Virgin Islands (Pindell and Barrett, 1990). This cessation of magmatism seems to be related to the collision of the Florida-Bahamas platform with the northeastward-migrating Greater Antilles arc (Lewis and Draper, 1990).

From the Oligocene to the present, the Greater Antillean islands have undergone another major orogenic phase due to sinistral transpression caused by the eastward movement of the Caribbean plate with respect to the North American plate (Draper et al., 1994).

**Yucatán Basin**

The Yucatán Basin is enclosed by the island of Cuba to the north, the Yucatán Peninsula to the west and the Cayman Ridge and Honduras Rise to the south. This basin is separated into a deeper (4,000 to 4,600 m) northwestern part containing the Yucatán Plain and a shallower (2,000 to 3,500 m) southeastern part mainly represented by a pair of ridges (Camaguey Ridges).

Examination of seismic sequences reveals four major intervals, possibly separated by unconformities (Holcombe et al., 1990). The upper three intervals are turbidites interbedded with pelagic sediments. The lowermost unit is more likely composed entirely of pelagic deposits and fills in basement lows.

Rosencrantz (1990) divided the Yucatán Basin and its borderland into 9 domains
based on seismic reflection data and surface topography. These domains occurred on three distinct crustal types or blocks. The first underlies the western edge of the basin and represents the offshore continuation of the adjacent Yucatán platform, which has a continental to transitional crust (Case et al., 1984). The second is represented by the topographically heterogeneous basement of the eastern two-thirds of the basin and is dominated by the Cayman rise, a subsided volcanic arc resting upon pre-Tertiary oceanic (?) crust. In the east, the third type of crustal block is thrust beneath the Cuban margin; the crust is oceanic and probably formed during the Late Paleocene to Middle Eocene.

Heat flow and depth of the basin (Rosencrantz et al., 1984) and the magnetic anomaly pattern (Hall and Yeung, 1980) support an interpretation that the Yucatán Basin was formed by Late-Cretaceous-to-Eocene interarc spreading between Cuba and the Cayman Ridge (Pindell and Barrett, 1990).

■ Cayman Trough

The Cayman Trough is a 1100-km-long depression that extends from the Belize margin to north of Jamaica (Leroy et al., 1996) marking the present-day position of the northern Caribbean boundary. The Cayman Trough is bounded to the north by the active Oriente transform fault south of Cuba. The southern margin of the trough is formed by the active Swan transform fault and the Walton fault, which is the dead trace of the Swan fault reactivated since the Miocene (Rosencrantz and Mann, 1991).

The Cayman Trough is the product of an Eocene sea-floor spreading along a short (100-km) north-south spreading center (Leroy et al., 1996). Based on topographic characters of underlying basement, Rosencrantz and Sclater (1986) postulated that
spreading has occurred in two major phases. The later (and present) phase formed an extensive topographic relief of the basement and very slow spreading (15 mm/yr); the earlier phase is characterized by a reduced topographic relief, no appreciable differential subsidence and faster spreading rate [probably 30 mm/yr (Draper et al., 1994)]. The change from faster to slower spreading rate took place during Oligocene time, about 30 Ma.

The total opening of the Cayman Trough is about 1100 km (Rosencrantz and Sclater, 1986; Pindell and Barrett, 1990). The central 950-1000 km of that displacement are accommodated by spreading and the remaining 100 km are attributed to crustal extension during the initial rifting stage.

2.3.3. Western Caribbean: Central America and Northwest Colombia

The western Caribbean has been divided into two major geologic provinces: 1) Northern Central America and 2) Southern Central America-northwestern Colombia (Figures 2.4.a, 2.4.b and 2.5). The first province was subdivided by Dengo (1969) into the Maya and Chortís blocks (Figure 2.4.b). The second was subdivided into the Chorotegas and Chocó blocks (Dengo, 1985)[Figure 2.5]. The boundary between the Northern and Southern Central America provinces is a fault system situated south of the Nicaragua-Costa Rica border. This major east-west trending fault has been interpreted as a crustal suture (Dengo, 1985); it is represented to the west by the Santa Elena Peninsula fault system of Costa Rica, which brings to the surface a body of serpentinized peridotite (Escalante, 1990). To the east, the fault is the southernmost extension of the Hess
Figure 2.4.a  Geographic map of southern Mexico and Central America. From Mills and Barton (1996).
Figure 2.4.b Index map of Central America showing regional tectonic features.
(From Donnelly et al., 1990).
Figure 2.5 Structural elements of southern Central America and western Colombia (From Escalante, 1990).
Escarpmcnt.

The Cenozoic volcanism and deformation that characterized the western Caribbean are thought to be the product of the convergence of the Nazca and Cocos plates with continental blocks to the north and south and with oceanic blocks in southern Central America (Case et al., 1984).

**Yucatán/Maya Block**

The Yucatán or Maya block is part of the North American continental plate (Dengo, 1973). To the south, it is separated from the Chortís Block by the Motagua-Polochic fault system (Figures 2.1 and 2.4b). The Maya block includes Guatemala north of the Motagua suture zone, Belize, the Yucatán Peninsula, and Mexico west to the Isthmus of Tehuantepec (Donnelly et al., 1990).

The Maya block is commonly accepted to originate in the present Gulf of Mexico (e.g. Donnelly et al., 1990). Its (pre-Carboniferous) basement crops out near the Motagua suture zone and has been penetrated by several wells. The basement consists of gneissess, schists with minor marbles, quartzites and granitoids. Overlying this basement is an extensive late Paleozoic sedimentary series (Santa Rosa); also the occurrence of a Pennsylvanian-Permian volcanic series has been found in Guatemala and Belize [the Bladen volcanic series] (Donnelly, 1989).

Unconformably overlying the metamorphic basement and the Paleozoic series is a rifted Jurassic ‘red bed’ sequence (Todos Santos Group, e.g., Garcia Molina, 1994) passing upward into thick Lower Cretaceous dolomitic limestones. In the southern part of the block, the carbonates are overlain by locally thick clastic flysch of Late Cretaceous to
Early Cenozoic age (Draper et al., 1994; Donnelly, 1989). In the northern part (across the northern Yucatan Peninsula), Pemex wells have penetrated an unusual breccia, mixed with fragments of altered glass or melt rock, shocked quartz and feldspar, and basement rock, near the top of the Cretaceous. Ward et al. (1995) point out that the most likely origin of this breccia is an impact by an asteroid or comet with the northwestern Yucatan platform at about the Cretaceous-Tertiary boundary; the evidence for this timing is a layer (about 18 m thick) of Maastrichtian marls overlying the breccia unit.

Near the Pacific coast, the Maya Block has local continental clastic rift-basin units of Eocene age that are overlain by mid-to late Cenozoic volcanic cover (Donnelly, 1989).

Most of the structures recognized in the Maya Block were developed during Late Cretaceous to Early Cenozoic and their pattern suggests southwest-northeast compressions. The major compressive deformation in the southern Maya Block resulted from the collision of the Chortís Block with the Maya Block that began in the Early Maastrichtian. Also related to this collisional event are the retrograde metamorphism and the emplacement ophiolite onto both blocks.

During the Late Cenozoic, transcurrent motions in the southern boundary of the Maya Block were distributed between two major strike-slip fault systems (Figure 2.4b): the Polochic system and the Motagua system. The total Cenozoic offset on the Polochic system is about 130 km (e.g., Burkart and Self, 1985), and on the Motagua system is no more than a few tens of kilometers (e.g., Donnelly et al., 1990).

**Chortís Block**

The Chortís Block is bounded on the northwest by the Motagua-Polochic fault
system, which is also the boundary between the Caribbean and North American Plates, and on the southwest by the Middle American Trench boundary with the Cocos Plate (Figure 2.4b). The block includes southern Guatemala, El Salvador, Honduras, and northern Nicaragua.

The Chortís Block basement consists of pre-Mesozoic metamorphic rocks intruded by Mesozoic granitoid plutons (Donnelly, 1989). The basement is overlain by a clastic unit that has been correlated with the Todos Santos Group of the Maya Block (Draper et al., 1994). This unit is in turn overlain by massive limestones (Yojoa) of dominantly Albian age. Overlying these limestones are coarse clastic rocks (Valle de Angeles), with a widespread Cenomanian limestone dividing the clastic rocks into a lower and upper section.

The Cenozoic sequence of the Chortís Block comprises mainly a widespread Miocene ignimbrite unit and extensive Neogene volcanic deposits derived from the volcanic centers of the Pacific margin (Donnelly, 1989).

Evidence for the original position of the Chortís Block is limited, but the prevalent view is that it was part of southwestern Mexico. Some affinities exist between the basements of the Chortís and Oaxaca blocks (e.g., Dengo, 1985) [see Figure 2.4a for geographic location]. Mills and Barton (1996) proposed that the current northern coast of Chortís was on the seaward side of the Chortís-Oaxaca terrane. They suggest that an oblique subduction prior to the Late Eocene caused the outer edge of Chortís to break up and displace the block to the southeast along a sinistral fault. The Chortís Block rotated along the Mexican coast, probably in a counterclockwise sense [based on paleomagnetic
studies by Gose (1985), and eventually collided with the Maya Block.

After the Late Cretaceous-Early Tertiary collision (Donnelly et al., 1990), the Cenozoic tectonic history of the Chortís Block was controlled by the interaction of the western margin of the Caribbean Plate with both the North America and the Cocos Plates (Molnar and Sykes, 1969). In the first case, sinistral transform motion between the Caribbean and North American Plates occurred along the Polochic-Motagua strike-slip fault systems. In the second case, Caribbean Plate oblique-convergence with the Cocos Plates has been expressed by a volcanic front along the Pacific margin, and crustal extension with internal block rotation within the Chortís Block (Burkart and Self, 1985).

- **Chorotega and Chocó Blocks (Southern Central America-Northwestern Colombia)**

This geologic province includes Costa Rica, Panamá and northwestern Colombia. The boundary between the Chorotega and Chocó blocks is placed in central Panamá, at the narrowest part of the isthmus, where according to the contrasting gravity values (Case, 1974), a tectonic break is suggested. Case and Holcombe (1980) considered a northwest-trending sinistral fault system as the boundary between these blocks (Figure 2.5).

The Chorotega-Choco province is bounded to the west by the Middle America Trench, which separates it from the Cocos and Nazca Plates. To the east, this province is separated from the Caribbean Plate by the North Panamá Deformed Belt and from the main South American craton by the Romeral fault zone (Figure 2.5). To the north, the separation of the Chorotega Block from the Chortís Block is defined by an east-west
trending fault situated south of the Nicaragua-Costa Rica boundary; this fault system also represents the boundary between Northern Central America and Southern Central America terrains.

In southern Central America and western Colombia, the pre-Cretaceous and Cretaceous stratigraphic sequence may be divided into two groups (Escalante, 1990). A first and very important group comprises mafic, mainly ophiolitic complexes; and a younger and more restricted group consists of a number of well-defined marine formations of Middle to Late Cretaceous age. An example of the first group is the Nicoya Complex, of the Nicoya Peninsula, Costa Rica. Kuijpers (1980) divided the Nicoya Complex into two major units; he interpreted the upper unit to be a nappe of younger oceanic crust (Cenomanian to Santonian age) that has been thrust over the older oceanic crust of the lower part of the complex.

The Cenozoic stratigraphic sequence of the Chorotega and Chocó Blocks consists of volcanic units that are interbedded with sedimentary rocks. The Cenozoic volcanism is related to subduction at the Middle America Trench (Draper et al., 1994)

Among the differences between the Chorotega and Chortís Block, Escalante (1990) points out the following:

1) The northwest-southeast trend of the structural units identified in Chorotega Block is not recognized in the Chocó Block.

2) The basement rock in the Chorotega Block (mostly Cretaceous and pre-Cretaceous age) is somewhat older than that in the Chocó Block. Basement rocks as young as $41 \pm 3$ Ma have been recognized in the Chocó Block (Bourgois et al., 1982).
3) While ignimbritic volcanic rocks and igneous intrusive bodies of Cenozoic age are abundant in the Chorotega Block, they are scarce in the Chocó Block.

4) Quaternary volcanism in the Choco Block has been scant in comparison with the Chorotega Block.

It is interpreted that the tectonic history of the Chorotega and Chocó Blocks implies the uplift of oceanic crust in Latest Cretaceous to Early Tertiary (see Draper et al., 1994). These blocks probably formed as uplifted blocks associated with the ancestral Middle American Trench (in the case of the Chorotega Block) and with the ancestral Colombia trench (in the case of the Chocó Block).

The orogenic phase in southern Central America and western Colombia reaches its peak with very intense folding and the emplacement of intrusive rocks during the Miocene, especially Late Miocene (Escalante, 1990). It is likely that the increased tectonic activity at this time has to do with the accretion of the Chorotega Block onto the Chortís Block to the north, and the accretion of the Chocó Block onto the northwestern South America craton to the south.

2.3.4. Southern Caribbean

The southern boundary of the Caribbean plate is a broad zone of deformation involving strike-slip faulting and compressional and extensional features. This boundary is about 600 km wide in Colombia and western Venezuela, 400 km at the longitude of Curaçao Ridge and approximately 200 km in width around Trinidad and Tobago (Ladd et al., 1990). In general, the southern Caribbean margin may be divided into two major
provinces: Colombian Andes and Venezuela borderland (Draper et al., 1994).

- **Colombian Andes**

The Colombian Andes form three great ranges: The Cordillera Oriental, Central and Occidental (Figure 2.6). Other major tectonic blocks related to the Colombian Andes are the Sierra Nevada de Santa Marta, Guajira Peninsula, Sierra de Perijá and the Cordillera de Merida (Venezuelan Andes). The Sierra de Perijá and the Cordillera de Merida are considered physiographic extensions of Cordillera Oriental (Case et al., 1990).

The Cordillera Occidental is underlain by oceanic crust intruded by Tertiary granitoid plutons. It is separated from the Cordillera Central by the Romeral fault zone, which is characterized by a melange of oceanic and continental fragments beneath a Tertiary cover (Case et al., 1971; Case et al., 1984; Draper et al., 1994; Donovan, 1994).

Most of the Cordillera Central, Cordillera Oriental, Sierra de Perijá, and Cordillera de Merida are underlain by continental crust; the Sierra Nevada de Santa Marta and the Guajira Peninsula Block are probably underlain by both types of crust (Case et al., 1990; Audemard, 1991).

The basement of the Cordillera Central consists of metamorphic rocks of Precambrian and Paleozoic age. In the Cordillera Oriental, the basement also consists of Precambrian-Paleozoic metamorphic rocks, in this case with some igneous rocks.

A succession that consists of red beds, volcanic rocks, marine clastic rocks and local carbonates, is developed from Jurassic to Early Cretaceous, both in the Cordillera Central and Cordillera Oriental. This sedimentary volcanic sequence suggests a rifting
Figure 2.6 Index map showing major geologic provinces or terranes in the northern Andes and vicinity. From Case et al. (1990).
phase which is most likely related to the breakup between North and South America (e.g., Case et al., 1990; Audemard, 1991). Then a passive margin phase continued until the Late Cretaceous.

The evolution of the present-day northern Andes and associated intermontane and foreland basin began in the upper Late Cretaceous. It was initiated by the accretion of the Cordillera Occidental to the northwest margin of South America along the Romeral suture zone. The uplift of the Andes is referred to as a Late Miocene event and is probably related to the collision of the Panama arc to the west (Audemard, 1991) and the convergence of the Caribbean plate to the north of the northern Andean block.

Venezuela Borderland

The Caribbean-South America boundary at the longitude of Venezuela consists of several east-west trending belts of Mesozoic and Cenozoic rocks. From north to south these are: South Caribbean deformed belt, Dutch and Venezuelan Leeward islands' terrane, the Caribbean Mountain system, and the Tertiary foreland fold and thrust belt of the Serranía del Interior (e.g., Rossi, 1985; Ostos, 1990; Avé Lallemant and Guth, 1990, Chevalier and Alvarez, 1991).

The South Caribbean deformed belt and its eastward extension (Curaçao Ridge) represent a zone of intense deformation and accretion as a result of Miocene and younger convergence of the Caribbean and South American Plates (Ladd et al., 1984). The sedimentary sequence of the South Caribbean deformed belt includes a thick section of Paleogene(?) and Neogene pelagic and turbiditic deposits (e.g., Holcombe et al., 1990).
The Dutch and Venezuelan Leeward islands' terrane is defined as a ruptured chain of blocks; it consists of Lower to Middle Cretaceous oceanic rocks and Upper Cretaceous (and locally Paleogene) volcanic rocks of island arc affinity (Ostos, 1990).

The Caribbean Mountain System extends from Sierra de Santa Marta in the west to the island of Tobago in the east (Bellizzia and Dengo, 1990). It has been subdivided into the following tectonostratigraphic units: Cordillera de la Costa Belt, Caucagua-El Tinaco Belt, Loma de Hierro or Paracotos Belt and Villa de Cura. These units were emplaced southward onto Paleogene sedimentary rocks in a foreland basin setting (e.g., Stephan, 1985; Draper et al., 1994; Donovan, 1994; Audemard and Lugo, 1996). All these units will be discussed in detail in Chapter 3 (for their location, see Figure 3.1 and 3.2).

The Serranía del Interior belt consists of sedimentary rocks of Cretaceous and Tertiary age. They underwent compressional deformation during the Oligocene(?) and Miocene in the west (e.g., Audemard and Lugo, 1996) and during Miocene in the east (Chevalier and Alvarez, 1991).

More details about the geology of northern Venezuela will be given in the next chapter.

2.3.5 Eastern Caribbean

The eastern margin of the Caribbean plate is formed by a series of north-south trending ridges and troughs that lie between the Caribbean and the Atlantic Ocean basins. The most prominent of these ridges is the Lesser Antilles island arc which is the result of
the subduction of the Atlantic oceanic lithosphere beneath the Caribbean lithosphere. Interior to the arc are the Grenada Basin and west of it the Aves Ridge; the latter forms the eastern margin of the Venezuelan Basin (Figure 2.1). External to the arc is the Barbados Ridge, which appears as a relative narrow topographic feature northeast of Guadeloupe widening to the south.

■ Grenada Basin

The Grenada Basin is well developed in its southern portion where it is characterized by a very flat and regular seabottom with depths of about 3000 m (Pinet et al., 1985). To the north, the water depth decreases and the Aves Ridge and Lesser Antilles merge to form the basement of Saba Bank, a shallow water carbonate platform.

The crustal thickness of the basin [± 18 km (Boynton et al., 1979)] is greater than that of typical Atlantic oceanic crust. Case et al. (1984) considered that the crust is either oceanic or transitional. However, Pinet et al. (1985) suggested that the crustal structure in the southern portion of the Grenada Basin (south of 14° N parallel) is made up of an anomalously thick two-layer oceanic crust similar to the oceanic crust of the Venezuelan Basin. To the north, the basin consists of folded and block faulted Cretaceous arc rocks (e.g., Case et al., 1984; Pinet et al., 1985).

Sediments in the Grenada Basin become progressively thicker from north to south. In the north the basement is overlain by about 2 km of sediments and sedimentary rocks; in the south up to 6 km of volcanioclastic turbidites and pelagic deposits cover the basement (Draper et al., 1994).

There are two hypotheses for the origin of the Grenada Basin:
1) that it was formed by sea-floor spreading in a back arc (inter-arc) basin, which split a previous arc into two parts, the Aves Ridge and the Lesser Antilles (e.g., Holcombe et al., 1990; Pindell and Barrett, 1990).

2) that the Grenada Basin is a former forearc basin that became isolated by an eastward jump of the subduction at the beginning of the Eocene (e.g., Kearey, 1974).

According to Holcombe et al. (1990), the second hypothesis is hard to accept because:

- There is no sign of any previous accretionary complex in the Grenada Basin, and the geometry does not fit a forearc basin.

- Geophysical data show that the Lesser Antilles continue southwestward from Grenada to Margarita. Plutonic rocks in Margarita have been dated as Late Cretaceous showing that this part of the arc was also active at the same time as the Aves Ridge.

- There is no evidence for the transform fault that should form the northern boundary of the Grenada Basin.

### Lesser Antilles

The Lesser Antilles island arc is about 850 km long; it extends from Anegada Passage in the north to Grenada and perhaps even to the los Testigos and Margarita Islands in the south (Figure 2.7).

Based on seismic refraction data, the crust of the arc has been broadly divided into three layers (Officer et al., 1959; Boynton et al., 1979). The uppermost layer is interpreted to be mainly composed of volcanics and sediments. The middle layer is suggested to be
Figure 2.7  The Lesser Antilles area: a: Bathymetric map (modified from Bouysse, 1984). 1 = Volcanic Caribbees; 2 = Limestone Caribbees; 3 = axis of the inner arc; 4 = axis of the outer arc; 5 = deformation front (after Case and Holcombe, 1980). Isobaths in m. From Maury et al. (1990).
plutonic rocks of intermediate composition and the lowest layer is interpreted as the old ocean crust upon which the island arc has been built, subsequently thickened by the addition of mafic plutonic rocks (Maury et al., 1990). According to gravity models (e.g., Westbrook, 1975), the total thickness of the crustal section in the segment between St. Vincent and Guadeloupe is estimated between 30 and 37 km.

Except for the Upper Jurassic and Lower Cretaceous units found on the la Désirade, the oldest igneous rocks exposed in the Lesser Antilles area are Late Cretaceous volcanic and plutonic island-arc rocks. They are defined as a Pre-Eocene basement and occur in the northern Lesser Antilles. These rocks lend support to the idea that this part of the arc, at least, formed part of an arc system along the margin of the Caribbean that included the Greater Antilles and Aves Swell and that was active in the Mesozoic (Maury et al., 1990).

As a result of the distribution of Cenozoic and Quarternary magmatism, the Lesser Antilles have been described as a double arc (Bouysse and Westercamp, 1990). In the southern part the two arcs coalesce to form a single row that includes from south to north the islands of Grenada, the Grenadines, St. Vincent, St. Lucia, and Martinique (Figure 2.7). These islands contain volcanic and sedimentary rocks that range in age from middle Eocene to Holocene. From Martinique northwards, the two arcs diverge and they are separated by a corridor some 50 km wide, the Kallinago depression. These two northern branches have been called the Outer arc to the east (i.e. Limestone Caribbeans from Marie Galante to Anguilla) and the Inner arc to the west (i.e., Volcanic Caribbeans from Dominica to Saba) [Bouysse and Westercamp, 1990]. The Outer arc was active from
Eocene to Early Oligocene, at which time volcanism ceased and limestone was deposited through the Middle Miocene. In the Late Miocene, a general uplift ended widespread limestone deposition and the volcanic activity was renewed along an axis shifted to the west, forming the Inner arc (Tomblin, 1975). From Early Pliocene through Recent time, the volcanic activity in the Lesser Antilles has remained relatively constant in character and in location.

■ Aves Ridge

The Aves Ridge is located approximately 200 km west of the Lesser Antilles island arc. Its western flank is defined by the Aves Escarpment, which is a 600-km-long rectilinear feature joining the Venezuelan margin to the Greater Antilles (Figure 2.7). Its eastern flank is convex toward the east, with a curvature closely parallel to that of the Lesser Antilles arc (Holcombe et al., 1990).

The crust of the Aves Ridge has an estimated thickness between 28 and 31 km (Case et al., 1990) and its upper crustal structure is suggested as a heterogeneous section dominated by volcanic centers with plutons beneath them (Holcombe et al., 1990).

The Aves Ridge is interpreted as an extinct island arc that was active from Late Cretaceous to Paleocene (Nagle, 1972; Fox and Heezen, 1975; Pinet et al., 1985). The ridge comprises numerous seamounts containing basalts, andesites and granites of Late Cretaceous to Paleogene age (e.g. Draper et al., 1994). Local basins in the central region of the ridge are filled with neritic Paleogene and bathyal Neogene sediments (e.g., Bertrand and Bertrand, 1985).
The Tobago Forearc Basin

This NNE trending feature lies between the Lesser Antilles volcanic arc to the west and the Barbados Accretionary Prism to the east (Figure 2.7). This basin deepens towards the northeast and extends to the southwest into the shelf of northeast Venezuela where it intersects the Carúpano Basin (Ramroop, 1982; Bertrand and Bertrand, 1985).

The Tobago Basin contains as much as 12 km of sediments overlying an oceanic crust that is probably of middle Eocene age (Speed, 1994). A large part of the Paleogene section is in terrigenous and pelagic facies. The Neogene section contains an upwardly increasing amount of volcanogenic sediment and ashfalls from the Lesser Antilles (Speed, 1994).

The uncertain origin of the Tobago forearc basin includes the possibility of either an old Caribbean or Atlantic oceanic crust upon which the magmatic arc platform developed (Speed et al., 1984).

Barbados Ridge

The ridge is a N-S trending thick accretionary sedimentary prism in front of the Lesser Antilles Island Arc (Figures 2.1 and 2.7). This accretionary prism is the product of a continuous subduction of the Atlantic oceanic lithosphere beneath the Caribbean plate. The Atlantic ocean evolved over 50 Ma, leading to the accumulation of thick sediments on the Demerara Abyssal Plain (Bertrand and Bertrand, 1985; Speed, 1994).

The Barbados accretionary prism thickens southward and this variation is accompanied by a widening of the complex. In the northern part (at the latitude of
Antigua), the accretionary prism is about 8 km thick (Westbrook, 1975) and some 100 km wide. But in the southern part, the accretionary prism is 20 km thick and up to 300 km wide at the latitude of Barbados island where it emerges locally above sea level (Biju-Duval et al., 1978). The increase in the volume of accreted sediment, from north to south, is explained by terrigenous sediment supplies from the south, i.e., the Orinoco delta. Also, the northern and southern parts present different tectonic styles in front of the Barbados Ridge. To the south where at least 4000 m of sediments are involved, broad anticlines and thrusting to the east occur. To the north, for example between Barracuda and the Tiburón Rise, the tectonic style of deformation is far less obvious.

On the Barbados island, the sediments of the Barbados Ridge consists of Eocene turbidites, of pelagic Eocene-Miocene sediments and of Neogene coral rock (Bertrand and Bertrand, 1985).

2.4 Plate-Tectonic Reconstructions

The tectonic evolution of the Caribbean region involved five distinct plates as follows: the North American Plate, the South American Plate, the Cocos Plate, the Nazca Plate, and the Caribbean Plate (e.g., van der Hilst, 1990). The tectonic history began in Early Jurassic time and is constrained by seafloor spreading, plate convergence, and large transform fault displacement (e.g., Duncan and Hargraves, 1984).

Various reconstructions, based on kinematic data and geological information (e.g., Pindell and Dewey, 1982; Pindell and Barrett, 1990; Stephan et al., 1990; Dercourt et al.,
1993), define the relative motions between South America and North America as follows:

(1) **Jurassic to Late Cretaceous (Campanian)**, the motion vector corresponds to a rapid divergence between North America and South America (Figure 2.8 from Pindell and Barret, 1990).

This stage includes the continental breakup of South America from the Yucatan block which occurred over Triassic-Jurassic times (Pindell, 1994). The breakup (Figure 2.9) is recorded by rifting events such as the Espino, Takatu, and Uribante/Tachira grabens and by continental red bed deposition. From then on the northern margin of South America subsided to permit the development of an extensive passive margin (Figure 2.10). A sedimentary wedge (3 to 4 km thickness) built out over the northern margin of South America with the deposition of predominantly marine clastic rocks, although the early Cretaceous section also contains some carbonates.

During the divergence between the American plates, an important slowdown is estimated at about 80 Ma. This slowdown is associated with the cessation of spreading between the American plates during the Santonian-Campanian (~ 85 Ma). At this time the Proto-Caribbean plate reached its maximum size (Pindell et al., 1988; Ross and Scotese, 1988), and the southernmost part of the Caribbean island arc system collided with the Sebastopol block in northwestern South America (Ostos, 1990).

The spreading on the hypothetical ridge running through the Caribbean essentially terminates when the equatorial Atlantic spreading begins, approximately 119 Ma (e.g., Duncan and Hargraves, 1984).
Figure 2.8 Relative motion vectors of South America with respect to North America, giving the relative paleoposition of these two plates since Jurassic time (From Pindell and Barrett, 1990). Note that this diagram does not show the proposed path of the eastward indenting Caribbean plate.
LEGEND FOR CARIBBEAN EVOLUTIONARY MAPS

- Deep Marine
- Shallow Marine
- Evaporites
- Terrestrial Red Beds
- Active Arc
- No Record

abs. = Absent
V = Volcanism
Rock Units in italics

Mid Ocean Ridge
Transform
Subduction zone (edge of plate)
Thrust Fault / accretionary prism
Peripheral Bulge (ahead of thrust front)
Suture
Registered Present day geography

Triassic - Early Jurassic ~200Ma

Palaeogeography, late Triassic-early Jurassic.

Fig 2.9.a Caribbean Mesozoic evolutionary maps, from Pindell, 1994.
Palaeogeography, Bathonian.

Late Oxfordian ~160Ma
J. Pindell, 11/92

Palaeogeography, late Oxfordian.

Fig 2.9.b Caribbean Mesozoic evolutionary maps, from Pindell, 1994.
Figure 2.10  Upper Jurassic to Late Paleocene development of the northern and southern Caribbean area. A) Breakup of western Pangea, between North and South America at the end of Jurassic; b) Development of the passive margin of northern South America; c) Continued development of northern South America passive margin and incipient paleo-Antillean arc system; d) Arc collision of Greater Antilles from the north-west around the western corner of the passive margin of South America. Abbreviations refer to the following: EVB = Eastern Venezuela Basin; FL = Florida; GA = Greater Antilles; MB = Maracaibo Basin; SA = South America and YU = Yucatán. From DiCroce (1995) simplified after Stephan et al. (1990).
(2) **Late Cretaceous (Campanian) to Early Eocene;** the relative motion between both Americas is negligible from Campanian to Late Paleocene but NE-SW convergence begins during Paleocene and Late Eocene (Stephan et al., 1990). This period (Late Cretaceous to Early Eocene) is characterized by subduction and collision (Figures 2.10.d and 2.11.a).

The Greater Antilles Arc moves northeastward, consuming the Caribbean ocean floor of Mesozoic age beneath it; this motion ceases when the Greater Antilles collide with the Bahamas Platform. The age of collision is controversial; Burke et al. (1984) proposed an Early Eocene age (53 Ma) while Pindell (1994) suggested that the Bahamian-Antillean collision began in the Paleocene. After this collision, the Caribbean plate moves eastward (Figure 2.11.a). This causes the clockwise rotation of the transpressional terrane of Venezuela (Ostos, 1990; Avé Lallémant, 1990).

(3) **Middle Eocene to Present;** during this period North and South America were converging in a NNW-SSE direction (see Figure 2.8). At the same time, the Caribbean plate was moving eastward relative to the Americas along strike-slip dominated plate boundaries in the north and in the south of the Caribbean sea.

Diachronous transpression occurred along the northern border of South America as a result of the eastward Caribbean migration (Pindell and Barrett, 1990). The onset of transpression in western Venezuela occurred during Early-Middle Eocene (Figure 2.11.a) and progressively younger toward the east. The transpression is suggested to affect Eastern Venezuela and Trinidad during Late Oligocene-Middle Miocene (DiCroce, 1995)[Figure 2.11.b-c].
Figure 2.11 Four stages of the development of the northern and southern Caribbean boundary from Eocene to Present associated with the eastward migration of the Caribbean Plate. a) Compressional deformation due to Caribbean-South American convergence affected much of northwestern Venezuela; b) and c) Continuation of the oblique convergence of Caribbean plate and South America. The result is the emplacement of a transpressional folded belt and the associated development of an eastward migrating foredeep depocenter; d) From Late Pliocene to Present kinematic change in the Eastern Venezuela Basin is associated with a decrease in contraction and increase in the strike-slip deformation. Abbreviations: AC = Andes Cordillera; AR = Aves Ridge; BeR = Beata Ridge; BR = Barbados Ridge; CA = Central America; CB = Colombian Basin; CCC = Central Colombian Cordillera; CP = Cocos Plate; CT = Cayman Trough; CU = Cuba; EVB = Eastern Venezuela Basin; GB = Grenada Basin; GYB = Guyana Basin; HI = Hispaniola; LA = Lesser Antilles; MB = Maracaibo Basin; NP = Nazca Plate; OCC = Occidental Colombian Cordillera; PR = Puerto Rico; SA = South America; VB = Venezuelan Basin; YB = Yucatán Basin; YU = Yucatán. From DiCroce (1995) simplified after Stephan et al. (1990).
Another consequence of the eastward migration of the Caribbean plate is the emplacement of thrust sheets and associated foredeeps over the former Cretaceous passive margin sequence of the northern border of South America (see Lugo and Mann, 1995; Audemard and Lugo, 1996). Major events recorded during Eocene time include the initiation of volcanism in the Lesser Antilles Arc (Pindell and Barrett, 1990) and emplacement of the Lara Nappes in northwestern Venezuela (Stephan et al., 1990).

The Oligocene to Early Miocene is a tectonically quiet period all around the Caribbean that could represent a pause, or an important slowdown, of the eastward motion of the Caribbean plate (Stephan et al., 1990). This quiescence corresponds to a temporary interruption (between 30 Ma and 22 Ma) of the volcanism related to the eastern subduction in the Caribbean region.

During the Early-Middle Miocene to Present, the volcanism revived in the Lesser Antilles and the strike-slip deformation is accentuated on the north and south Caribbean boundaries. The Eastern Venezuela Basin, which survived as a passive margin until Late Oligocene, was finally defined in response to southeastward thrusting and foreland loading (Figure 2.11.c-d).
CHAPTER 3

REGIONAL TECTONIC SETTING OF NORTHERN VENEZUELA AND
THE PRE-EOCENE BASEMENT OF THE VENEZUELAN PLATFORM

3.1. Introduction

In contrast to oceanic plate boundaries, which are generally well-defined, continental plate boundaries are often represented by a wide diffuse zone (Burke et al., 1980; Dewey and Pindell, 1985). Bally (1975) and Bally and Snelson (1980) used the term megasuture for overall compressional diffuse plate boundaries. The southern Caribbean megasuture is typically between 300 and 400 km wide. In this chapter the major tectonostratigraphic subdivisions of the southern Caribbean megasuture and its foreland will be briefly reviewed. The principal objective is to provide a better understanding of the nature of the basement that underlies the Northern Venezuela offshore platform and its neighboring provinces.

The southern Caribbean megasuture consists of several elongate easterly to northeasterly trending belts which are shown in Figure 3.1 and Figure 3.2, which are sketch maps based on many publications (e.g., Bell, 1971 and 1974; the Geologic map of Venezuela, compiled by Bellizzia and Pimentel, 1976; González de Juana et al., 1980; Stephan, 1985; Beck 1985; Ostos, 1990; and DiCroce, 1995) and compiled with the assistance of A.W. Bally and J. DiCroce. The following description proceeds from south
Figure 3.1 Tectonic map of northern Venezuela showing the distribution of magnetic anomalies in the offshore. (Compiled by Raul Ysaccis, 1995).
OFFSHORE IGNEOUS AND METAMORPHIC ROCKS

LEGEND

- ◆ PRE-EOCENE CALC-ALKALINE INTRUSIONS AND VOLCANICS
- ◆ POST-EOCENE CALC-ALKALINE VOLCANICS
- ▼ CRETACEOUS PRIMITIVE ISLAND ARC SEQUENCES
- ▲ MESOZOIC MAFICS
- □ OPHIOLITES
- ☑ MESOZOIC METAMORPHICS

Figure 3.2.a. Legend for the tectonic sketch map of north Venezuela related to the offshore igneous and metamorphic rocks.
Figure 3.2.b  Tectonic sketch map, North Venezuela, by A.W. Bally, R. Ysaccis, J. DiC...
NORTH VENEZUELA
TECTORIC SKETCH MAP
A.W. BALLY, R. YSACCIS, and J. DICROCE, 1997
to north, i.e., from the undisturbed foreland to the progressively more deformed internal parts and from lower units to higher structural units of the megasuture.

3.2. Onshore Venezuela:

3.2.1. The Eastern Venezuela foredeep

The foredeep is subdivided into the Guárico Basin (or Guárico foredeep) to the west and the Maturín Basin (or Maturín foredeep) to the east (see Figure 1.1). The two basins are separated by the poorly understood Anaco inversion fold trend.

The basement underlying most of the Maturín subbasin and its offshore Atlantic continuation is the Guyana shield which in its westernmost part appears to be overlain by the remnants of an undeformed Paleozoic foreland basin (Feo Codecido et al., 1984; DiCroce, 1995). This Paleozoic basin extends into the Guárico subbasins, where it forms the pre-rift sequence of the Jurassic Espino graben system. The western Paleozoic foreland folds and a metamorphic zone involving a Precambrian basement and Paleozoic metasediments form the basement of the Guárico Basin which outcrops to the west on the El Baul uplift. These important basement subdivisions are show on Figure 3.2.

The Maturín subbasin is underlain by a truncated Cretaceous-Oligocene passive margin sequence that is separated by a basal foredeep unconformity from the overlying Lower Miocene-Recent foredeep infill. The Guárico subbasin is an earlier foredeep. It is underlain by a thin wedge of Cretaceous to ?Middle Eocene passive margin clastic rocks
that are separated by a basal foredeep unconformity from the Oligocene-Middle Miocene siliciclastics which fill the foredeep itself.

3.2.2. "Autochthonous" Units of the Merida Andes and their Cretaceous to Paleogene cover

The term "autochthonous" is here used to suggest that the compressional Andean uplift involves a basement that is deformed by dextral transtension but was not transported over great distances. The basement of the Merida Andes is the same Paleozoic/Precambrian basement that underlies the western Guárico subbasin. In Figure 3.2 the Jurassic halfgrabens are included in that basement. As pointed out by Audemard (1991), in the Maracaibo area inversions of these Jurassic extensional systems are quite common.

The Cretaceous - Paleocene cover of the Merida Andes and the Maracaibo Basin is the landward part of a passive margin sequence that in the Maracaibo area and farther east is overlain by an Eocene foredeep sequence that was emplaced in response to loading by the allochthonous units of the Cordillera de la Costa and the associated Lara nappes (e.g., Audemard, 1991; Lugo, 1991; Lugo and Mann, 1995; Parnaud et al., 1995). The setting of the foredeep sequence is unusual as it is characterized by extensive Eocene WNW striking normal faults and northerly striking transfer faults (see Lugo, 1991). It is not yet clearly demonstrated whether the transfer faults are in part re-activated Jurassic normal faults. In any event the Eocene transfer fault system is commonly inverted during
the Late Neogene to form the northerly striking faults that dominate Lake Maracaibo and at the eastern termination of the Andes (i.e., the Lama Icotea, Puebla Viejo and Valera faults (Audemard and Lugo, 1996). The transpressional uplift of the Andes is associated with extensive Plio-Pleistocene crustal wedging and the Bocono right-lateral strike-slip system (Audemard, 1991).

3.2.3. Western Guárico and the Monagas foreland folds.

The gentle foreland folds of Western Guárico involve Paleogene to Middle Miocene clastic rocks. The Monagas foreland folds, located between the Pirital front of the Serranía del Interior and the foreland, display a different and more complex style of deformation but the zone is homologous to the Guárico foreland folds. The Monagas foreland folds involve multiple décollement levels that first deform the Miocene and later the underlying Cretaceous - Oligocene passive margin sequence (e.g., Hung, 1997).

3.2.4. Outer Faja Piemontina and Serranía del Interior

To the north of the Guárico basin folds, thrusts and imbricates of the outer Faja Piemontina involve Cretaceous passive margin carbonates and clastic rocks and the Paleocene to Middle Eocene Guárico flysch. The Guárico flysch may in part be correlated with the Eocene Misoa / Trujillo of the Maracaibo foredeep and is also in part equivalent to the Eocene Matatere units of Stephan (1985). The southern boundary of the area is
bounded by the Guárico thrust which is associated with a narrow zone of overturned Paleogene and Neogene beds (Faja volcada).

Farther east in the Serranía del Interior lower Cretaceous to Oligocene passive margin sediments are involved in broad décollement folds. The deep structure of the Serranía del Interior is the subject of much speculation (e.g., Passalacqua, 1995; and Hung, 1997) with interpretations ranging from basement-involvement to complex duplex structures overlying a northward dipping basement monocline. To the south the Serranía del Interior is bounded by the Pirital duplex system which is onlapped by Upper Miocene satellite (piggyback) basins (e.g., González de Juana et al., 1980; Lilliu, 1990; Hung, 1997). The NW-SE striking Urica fault system is interpreted as a compressional lateral ramp (e.g., Roure et al., 1994; Parnaud et al., 1995). To the north the Serranía is mainly bounded by the Neogene El Pilar strike-slip fault except for a small window that exposes Serranía elements north of that fault (Vierbuchen, 1984) and El Cantil type rocks that were encountered in well 21 in the southern Carúpano area, Bucas High (see Foldout 7).

Important for this study, the tectonic sketch map (Figure 3.2) shows that the outer Faja Piemontina, the Urica fault system and the northwestern corner of the Serranía all project under the southeasternmost part of the Ensenada de Barcelona to be directly overthrust by the Villa de Cura thrust sheet farther south.
3.2.5. The Inner Faja Piemontina and the Los Cajones "Wildflysch"

This zone consists of imbricates that involve the slightly metamorphosed Upper Cretaceous Mucaria phyllitic shales, the Upper Cretaceous Querecal shales and limestones, and the thick uppermost Cretaceous to Lower Eocene Guárico turbidites ("Guárico flysch"). The Guárico flysch is best interpreted as a trench fill located between the advancing nappes of the Cordillera de la Costa and the westernmost end of the north Venezuelan passive margin (see earlier comments under 3.2.4. on the Guárico flysch).

To the north of the Inner Faja Piemontina is the Los Cajones "Wildflysch unit" which is described (e.g., González de Juana et al., 1980) as a chaotic unit involving olistostromes with olistoliths embedded in a turbidite sequence. Olistolithic blocks range from a few meters to several kilometers in diameter. Components include Lower Cretaceous El Cantil, Upper Cretaceous Querecal, Mucaria formations, Garrapata turbidites, Maastrichtian/Paleocene and Paleocene/Eocene carbonates as well as Eocene volcanic rocks (Tiara volcanics) and serpentinites. The origin of these "wildflysch" is uncertain and interpretations range from blocks and slumps derived from a rising mountain front to an origin from submarine passive margin scarps. This unit is overthrust by the Villa de Cura belt.
3.2.6. The Lara nappes and the Matatere units

Stephan (1982; 1985) has made a detailed study of these units and their regional setting along the Barquisimeto transversal zone. His concepts are summarized by his diagram (Figure 3.3). According to Stephan, the Lara nappes are a set of relatively flat epi- to non-metamorphic thrust sheets involving Lower Cretaceous carbonates and clastic rocks, and Upper Cretaceous clastic rocks that were emplaced during and covered by Paleocene to Middle Eocene turbidite sequences including abundant olistoliths. Most of these units were emplaced during the upper Paleocene to late Middle Eocene, i.e., they are coeval with the deposition of the Eocene Misoa foredeep of the Maracaibo area. Stephan includes the Tinaco - Tinquillo unit and the Squisique ophiolites as part of this complex but in the following these units will be discussed separately.

3.2.7. The Cordillera de la Costa Nappes

The Cordillera de la Costa nappes constitute a significant part of the onshore Caribbean Mountain System (Bellizzia and Dengo, 1990) to the south of the San Sebastian-El Pilar strike-slip fault system. Its western and central parts extend from the Caribbean coast, i.e., the right lateral San Sebastian fault to right lateral La Victoria fault to the south.
Figure 3.3. Block diagram showing the organization of the tectono-sedimentary complex of Lara nappes and its relations with the Caribbean allochthonous, the Andean autochthonous and the Paleocene-Eocene of the Maracaibo basin. (From Stephan, 1985).
3.2.7.1. The lower Caracas Group

From bottom to top this group includes the following units (following the description of González de Juana et al., 1980; and Ostos, 1990):

- The Sebastopol complex consisting of granitic gneiss in greenschist facies yielding Rb/Sr whole rock of 425 Ma (e.g., Ostos, 1990). Crystallization ages of 494 ± 52 Ma and 467 ± 30 Ma (Ordovician) were reported by Avé Lallemant and Sisson (1993) based on U/Pb analyses of granitic bodies in the Caracas and Puerto Cabello region.

- The Peña de Mora Group consisting of augengneiss, biotite gneiss, quartz muscovite schist, minor amphibolite and marble yielding a Rb/Sr whole rock age of 220 ± 20 Ma.

- The Las Brisas Group consisting of metasediments in greenschist facies and some marble. A Late Jurassic age for the marbles is based on the occurrence of Exogyra virgula.

3.2.7.2. The upper Caracas Group

A tectonic contact probably separates the lower Caracas Group from the Upper Caracas Group which is described on the basis of the compilations by González de Juana et al. (1980) and Ostos (1990), from bottom to top:

- The Antimano/Nirgua unit consists of graphitic marbles, micaschists, garnet/epidote amphibolites, glaucophanites and eclogitic amphibolite. Stephan (1985)
assigned this zone to his northern Coastal fringe/Margarita belt which consists predominantly of rocks with oceanic affinities. Sisson et al. (1997) suggest temperatures between 500 and 700 °C and pressure ranging between 1800 and 2200 Mpa for the metamorphic conditions responsible for the formation of eclogites in this zone. This structural unit retrograded to amphibolite and greenschist facies conditions (Ave Lallemant and Sisson, 1993). A tectonic contact perhaps separates this unit from the overlying unit.

- The Las Mercedes/Aroa unit consists of quartz-muscovite-calcite-graphite schist, phyllite and marble and is associated with amphibolite marbles and glaucophane schists.

### 3.2.7.3. Lower Cretaceous metamorphic rocks

The geological map of Venezuela (Bellizzia and Pimentel, 1976) differentiates a widespread unit of Lower Cretaceous metamorphic rocks, which are described under various names such as the Bobare / Marney, Cojedes / Agua Blanca /Araure units in the western part of the Cordillera de la Costa and Chuspita unit in the eastern part of the Cordillera de la Costa. According to González de Juana et al. (1980), these units consist of phyllites, quartz-mica-sericite meta-conglomerates, sandstones, and calcareous conglomerates.

Stephan (1985) includes the Albian Bobare siliciclastic turbidites and its Upper Cretaceous pelagic cover with its olistoliths in his San Pablo - Buenos Aires unit of the Lara nappes, which is being sealed by Lower to Middle Eocene Matatere III turbidites. According to Stephan, the relationship of this formation and its more metamorphic
equivalents still needs to be clarified. This is why this unit was shown separately on the map of Figure 3.2.

According to Bellizzia and Rodriguez (1968), the contact between the Mamey metasedimentary rocks and the underlying Aroa is concordant and these authors visualize a lateral transition with the Bobare Formation. Like Stephan (1985), they suggest that this relationship be re-examined. Taken at face value and combining and accepting the thoughts of Bellizzia and Rodriguez (1968) and Stephan (1985) a transitional contact from Aroa to Mamey to Bobare would imply that the Aroa / Las Mercedes metasedimentary unit would be the lateral continuation and structural equivalent of the San Pablo - Buenos Aires unit of Stephan's Lara nappes, thus dating the final emplacement of Aroa / Las Mercedes unit within the Early to Middle Eocene. Such dating constraints are very important and would justify an effort to better document the relationships between all these units.

Farther east the quartzitic siliciclastics and conglomerates of the Chuspita Formation, which by some authors is included in the Caucagua-El Tinaco unit, also appear to have a transitional contact with the Las Mercedes Formation, which in that area has yielded Abian fossils. Thus the relationship of the Chuspita to the Las Mercedes Formation appears to be comparable to the Aroa - Mamey relationship.

In the context of this study, it is concluded that the frontal portions of the metamorphic units of the Cordillera de la Costa and its equivalents on Margarita Island and the Araya-Paria Peninsulas following their Cretaceous metamorphism could well have been involved in post-Cretaceous, or intra-Eocene overthrusting that led to the
formation of the Lara nappes. Obviously this speculation needs to be further verified in
the field.

3.2.8. Caucagua - El Tinaco belt (Lower Aragua nappe of Beck 1985)

The Caucagua-El Tinaco belt is bounded by a right-lateral strike-slip system (La
Victoria fault zone) in the north and by the Santa Rosa fault in the south (e.g., Menendez,
1966; Schubert, 1984). Together with the Paracotos, and Villa de Cura unit, this unit is by
Beck (1985) described as the lowest of a series of klipeen-like units all included in his
Aragua nappes. The following subdivisions proposed by many authors (e.g., Bell, 1972,
1974; González de Juana et al., 1980; Beck, 1985; and Ostos, 1990) are from bottom to
top:

- The (?)Precambrian / Paleozoic basement of the Tinaco complex (La Aguadita
gneiss, Menendez 1966) consists of hornblende-plagioclase gneiss, in
epidote/amphibolite metamorphic facies with local glaucophane and some
metaconglomerate and marble intruded by trondhjemite, aplite and diorite (the La
Guacamaya pluton). Radiometric ages as compiled by Ostos (1990) are shown on Table
3.1 and suggest a Precambrian / Paleozoic basement age for this unit.

- A mafic - ultramafic complex (the Tinaquillo peridotites) is proposed by some
authors to be intruded into the El Tinaco complex as a comformable sheet (González de
Juana et al., 1980; Seyler and Mattson, 1989) or else to be at the base, but Ostos (1990)
emphasizes a mid-oceanic setting for these ultramafics.
Table 3.1 Radiometric ages from the Caucagua-El Tinaco belt. (Compiled by Ostos, 1990)

<table>
<thead>
<tr>
<th>ROCK TYPE</th>
<th>METHOD</th>
<th>MIN./ROCK</th>
<th>AGE</th>
<th>REGERENE</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Aguadita Gneiss</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio. GNEISS</td>
<td>K/Ar</td>
<td>Biotite</td>
<td>112.4 ± 3.0 Ma</td>
<td>A</td>
</tr>
<tr>
<td>Bio. GNEISS</td>
<td>K/Ar</td>
<td>Hornblende</td>
<td>117.5 ± 3.0 Ma</td>
<td>A</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K/Ar</td>
<td>Hornblende</td>
<td>235.8 ± 13 Ma</td>
<td>B</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K/Ar</td>
<td>Pyroxene</td>
<td>684.0 ± 55 Ma</td>
<td>C</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K/Ar</td>
<td>Plagioclase</td>
<td>191.1 ± 15 Ma</td>
<td>B</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K/Ar</td>
<td>Hornblende</td>
<td>204.0 ± 12 Ma</td>
<td>A</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K/Ar</td>
<td>Actinolite?</td>
<td>210.0 ± 10 Ma</td>
<td>A</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>Rb/Sr</td>
<td>Whole rock (4)</td>
<td>945 ±178 Ma</td>
<td>D</td>
</tr>
<tr>
<td>METADIORITE</td>
<td>Rb/Sr</td>
<td>Whole rock (4)</td>
<td>892 ±520 Ma</td>
<td>D</td>
</tr>
<tr>
<td>GNEISS</td>
<td>F.T.</td>
<td>Apatite</td>
<td>49.0 ± 5.8 Ma</td>
<td>E</td>
</tr>
<tr>
<td>DIORITE</td>
<td>F.T.</td>
<td>Apatite</td>
<td>41.9 ±4.9 Ma</td>
<td>E</td>
</tr>
<tr>
<td>DIORITE</td>
<td>F.T.</td>
<td>Apatite</td>
<td>43.4 ±5.6 Ma</td>
<td>E</td>
</tr>
<tr>
<td>TRONDHJEMITE</td>
<td>F.T.</td>
<td>Apatite</td>
<td>6.9 ±1.3 Ma</td>
<td>E</td>
</tr>
<tr>
<td>Tiramuto Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METABASALT</td>
<td>K/Ar</td>
<td>Whole rock</td>
<td>64.2 ± 2.4 Ma</td>
<td>A</td>
</tr>
<tr>
<td>METABASALT</td>
<td>K/Ar</td>
<td>Pyroxene</td>
<td>77.0 ± 8.0 Ma</td>
<td>A</td>
</tr>
<tr>
<td>Pilancones Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METALAVA</td>
<td>K/Ar</td>
<td>Whole rock</td>
<td>67.5 ± 4.0 Ma</td>
<td>F</td>
</tr>
<tr>
<td>METALAVA</td>
<td>K/Ar</td>
<td>Whole rock</td>
<td>88.0 ± 2.5 Ma</td>
<td>F</td>
</tr>
<tr>
<td>Tucutunemo Formation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METALAVA</td>
<td>K/Ar</td>
<td>Whole rock</td>
<td>73.5 ± 1.9 Ma</td>
<td>F</td>
</tr>
</tbody>
</table>

- A series of schists and quartz phyllites (i.e., Tinapu) and some metaconglomerates of unknown age are believed by some authors to overlie the La Aguadita gneiss. Even younger metavolcanics phyllites and marbles in greenschist facies (The Tucutunemo / Candelaria) include non-orogenic tholeites with K/Ar ages 73.5 Ma, i.e., Campanian / Turonian (e.g., Ostos1990).

3.2.9. Tinaco - Tınaquillo elements of the Siquisique area

Bellizzia (1986) expanded the Caucagua-El Tinaco Belt to include the Siquisique ophiolite. According to Bartok et al. (1985), these ophiolites are of Mid Jurassic age. Stephan (1985) includes this unit together with the Yumare pre-Mesozoic complex which outcrops farther east (González de Juana et al., 1980) and the Caucagua - El Tinaco unit as the highest element of his Lara Nappes.

3.2.10. Loma de Hierro or Paracotos Belt

The Loma de Hierro or Paracotos belt forms a narrow, about 200 km, long zone limited by the Santa Rosa fault on the north and the Agua Fria fault on the south. According to Beck (1985), this belt includes from bottom to top:

- An oceanic assemblage: the Loma de Hierro Ophiolite that is composed of harzburgite, serpentinite and gabbro (e.g., Bellizzia, 1986; Ostos, 1990).
- A Neocomian-Albian sequence: the Capas de Rio Guare which consists of basic volcanic breccias, tuffs and pillow lavas intercalated with limestone, shale and radiolarian cherts.

- A thick sequence of basaltic lavas intruded by microgabbric dykes: the Tiara Formation; these lavas are interpreted as MORB volcanic rocks (mid-oceanic ridge basalt) [Girard et al., 1982; Loubet et al., 1985].

- An unconformable sedimentary cover, i.e., the Paracotos Formation of Campanian to Paleocene age (e.g., Loubet, 1985; Bellizzia, 1986). More generally, the Paracotos Formation is a flysch or wildflysch composed of phyllites, lithic metaconglomerates, black siltstone, metagraywacke and pelagic marbles (e.g., Shagam, 1960; Beck, 1985; Ostos, 1990).

3.2.11. The Villa de Cura Belt

This thick volcanic unit is by most authors shown as an allochthonous klippe which forms the highest unit of the Aragua nappes of Beck (1985). Ostos (1990) and Smith (1996) have thickness estimates ranging from 7 km to a possible 12-13 km even though the klippe itself appears to be no more than 1 km thick. The large thickness estimates are due to the fact that the metavolcanic rocks within the klippe are steeply inclined towards the south (Smith, 1996).

Originally, Shagam (1960) divided the Villa de Cura belt into two groups, i.e., the Villa de Cura Group s.s. and the Las Hermanas (or Tiara Sur) Formation. Overall the
Villa de Cura Group is composed of mafic lavas, metatuff, keratophyres and intercalated meta-cherts, chlorite schists, and phyllites (Bellizzia and Dengo, 1990).

The superposition of four units is debated by various authors, with Shagam (1960) placing the El Caño and El Chino Formations at the base and Navarro (1983) placing the Santa Isabel Formation at the base, followed by the El Carmen, El Caño and El Chino Formations. The following summary is based on Shagam’s (1960) original version as reported by González de Juana et al. (1980), from bottom to top:

- El Caño: Basic metatuff, tuffaceous phyllite and volcanic conglomerate, minor spilitic andesitic basalt. Geochemically similar to Washikemba Formation on Bonaire (Primitive Island Arc association of Beets et al. [1984]).

- El Chino: dominant metatuff, minor basaltic metalava, graphitic phyllite, glaucophane lawsonite schist, meta-flanite. Primitive island arc according to Beets et al (1984); mid ocean ridge affinity according to Navarro (1983).

- El Carmen: dominant spilitic metabasalt, minor metatuff of island arc affinity (Girard, 1981).

- Santa Isabel: Rare spilitic basalt and metaflanite at the base. Epidote/quartz/albite glaucophane schists, chlorite, quartz/albite schists and granulites again similar to Washikemba volcanic rocks.

The original tectonic setting of the Villa de Cura rocks is uncertain. Many workers have pointed out a primitive island arc (PIA) affinity for them and have proposed the Villa de Cura to be part of the Leeward Antilles-Tobago Cretaceous paleo-arc. Thus
Beets et al. (1984) date ultramafics of the Villa de Cura (K/Ar on hornblende) as 107 ± 3 Ma, 99.2 ± 3 Ma and 97.5 ± 3 Ma and interpret these rocks as subvolcanic cumulate below an andesitic volcanic island arc complex subsequently metamorphosed under HP/LT conditions. This metamorphism to lawsonite-albite-chlorite facies, blueschists and greenschist facies was according to Beets et al. (1984) acquired during the Late Cretaceous.

Others have indicated that the rocks of the Villa de Cura Group have mid-ocean ridge basalt (MORB) or back-arc affinity (e.g., Navarro, 1983). Ostos (1990) suggested a mid-oceanic ridge setting for Villa de Cura rocks in Early Cretaceous.

Smith (1996) considered that the rocks of the Villa de Cura Group were metamorphosed to blueschist facies in a subduction zone between the Caribbean plate and the Proto-Caribbean lithosphere. Based on ⁴⁰Ar/³⁹Ar data ranging from 97 to 78 Ma, he concluded the age of metamorphism of the Villa de Cura Belt might coincide with a polarity change from west-verging subduction to east-verging subduction of the Villa de Cura Island arc system. Exhumation of the Villa de Cura Group occurred in the Late Cretaceous.

The Villa de Cura Group according to some authors (e.g., Girard, 1982; Ostos, 1990) is overlain by the Tiara South / Dos Hermanas Formation. Smith (1996) suggests that this formation is separated by a thrust from the Villa de Cura. The Tiara south / Dos Hermanas Formation consists of volcanic ash breccias, lithic tuffs and lavas of island arc affinity metamorphosed to prehnite-pumpellyite facies. Radiometric dating on metalavas (K-Ar on plagioclase) yielded ages of 119 ± 4 Ma and 112 ± 4 Ma (Loubet et al., 1985).
On the basis of clinopyroxene composition and trace-element abundance, these rocks are believed to be typical of island arcs (e.g., Navarro, 1983; Loubet et al., 1985; Ostos, 1990).

Skerlek and Hargraves (1980) based on their paleomagnetic studies postulate that the Villa de Cura underwent a 90 degree clockwise rotation from N/S to E/W between 95 Ma and the final emplacement in Maastrichtian/Paleocene time.

The distribution of the Villa de Cura Group is important for this study because the basaltic volcanic rocks encountered in four wells of the Ensenada the Barcelona shelf are in the strike continuation of the Villa de Cura belt which cut against the Neogene El Pilar fault, providing a pierce point which should reappear farther east to the north of the El Pilar faults. Indeed in the Carúpano Basin, we encounter similar Primitive Island arc sequences of Cretaceous which may extend all the way to similar outcrops in Tobago (see Donnelly et al., 1990b).

3.3. Venezuelan Platform

The northern offshore Venezuelan Platform includes the Gulf of La Vela to the east of Paraguaná Peninsula, Gulf Triste north of Puerto Cabello, the Tuy- Cariaco Basin and the Carúpano Basin (Figure 3.1). Different subdivisions are offered by various authors. For instance Avé Lallemant (1997) lumps the volcanic rocks of the basement of the Carúpano and Cariaco basins together with the Leeward Antilles terranes; on the other hand, Talukdar and Bolivar (1982) suggest a possible correlation between the Cariaco
volcanic basement and the allochthonous Villa de Cura belt. Furthermore Beets et al. (1984) point out the similarity in chemistry between the volcanic rocks of Bonaire (Leeward Antilles Island) and the Villa de Cura Group (mainland Venezuela). Based on these observations and geochemical analyses (e.g., Santamaría and Schubert, 1974; Talukdar and Bolivar, 1982; Talukdar, 1983; Beets et al., 1984; Loubet et al., 1985; Ostos; 1990), it seems likely that the igneous rocks of the Leeward Antilles islands, the Venezuelan platform Mesozoic basement and the Villa de Cura belt were originally generated within a larger tectonomagmatic province which involved MORB's magmatism during Late Jurassic to Early Cretaceous followed by primitive island arc (PIA) volcanism and mature island arc volcanism later in the Cretaceous. The MORB volcanic rocks and the PIA volcanic rocks were all involved, deformed and metamorphosed during the Late Cretaceous in a wide accretionary wedge.

3.3.1. La Vela and Triste Gulf

The basement of the La Vela Gulf consists of metasedimentary and metaigneous rocks metamorphosed in the greenschist facies (Kiser et al., 1984). A quartz phyllite yielded a K/Ar whole-rock age of 83.5 Ma and feldspar from metagabbro has a 114 Ma age (González de Juana et al., 1980; Kiser et al., 1984). The basement unconformably underlies a "post-tectonic" Tertiary-Quaternary sedimentary sequence.

In the Triste Gulf, the deepest wells reached flysch sedimentary rocks metamorphosed to a very-low grade (González de Juana et al., 1980; Kiser et al., 1984).
There are no radiometric dates, but this flysch sequence has been correlated with the Urama Formation of the Cordillera de la Costa Belt in which foraminifera indicate a Paleocene-Eocene age (González de Juana et al., 1980). Continental red beds of Eocene (?) age and/or Upper Oligocene-Lower Miocene shallow water deposits unconformably overlie the flysch unit (Kiser et al., 1984).

3.3.2. Tuy-Cariaco Basin

The Tuy-Cariaco Basin, as well as the Carupano Basin, are the main subject of this study and will be discussed in detail in the following chapters.

The basement of the Tuy-Cariaco Basin is mainly composed of metamorphosed volcanic-subvolcanic rocks of Cretaceous age (Talukdar and Bolivar, 1982; Evans, 1983; Monsalve et al., 1984). It was penetrated by nine of the twelve exploration wells, and basement cores were obtained from eight of these wells. As can be seen from Figure 3.4, up to 1,062' of pre-Tertiary volcanic rocks (andesites/basalts/diorites) were penetrated in a well drilled in the Ensenada de Barcelona shelf, a geological province located to the south of the El Pilar fault in the Cariaco area.

With the exception of a single well near Cubagua Island, the basement cores consist of volcanic to subvolcanic rocks of basic-intermediate composition (andesites, basalts and diorites) which have been affected by a relatively low degree of metamorphism (Evans, 1983). This volcanic complex has been correlated with terranes that were developed in an island arc setting, like the Villa de Cura Group (Talukdar and
Figure 3.4 Distribution of basement, Cariaco area.
Bolivar, 1982), the Los Frailes Formation on the Los Frailes Archipelago (Evans, 1983), and the Leeward Antilles arc (Avé Lallemant, 1997). Three K-Ar whole-rock datings for volcanic samples indicate ages of 78.3 Ma, 69.5 Ma, and 65.4 ± 3.9 Ma (Campanian-Maastrichtian ages) [Talukdar and Bolivar, 1982]. As these ages probably represent the time of metamorphism, a pre-Campanian age for the volcanic activity would be reasonable.

The basement core of the well drilled near Cubagua Island (see Figure 3.4) consists of quartzites, amphibolites, mica schists, and sheared serpentinized hornblende pyroxenite with quartz veins (Talukdar and Bolivar, 1982). These rocks have been affected by a higher grade of metamorphism than the volcanic rocks described above (Evans, 1983).

The basement near Cubagua Island is correlated lithologically with the Juan Griego Group of the Peninsula Macanáo on Margarita Island (Evans, 1983); the Juan Griego Group is considered to be Jurassic (?)-Early Cretaceous (e.g., Chevalier, 1987).

As can be seen on Sections B10 and B13 of Panel-8, the acoustic basement on the southernmost part of the Ensenada de Barcelona shelf could be interpreted as highly deformed Cretaceous to Early/Middle Eocene sediments of the Serranía del Interior and highly deformed Paleocene-Eocene flysch of the Outer Faja.

On the basis of well data, outcrop information and seismic interpretation, Figure 3.4 shows the distribution of the different types of basement in the Tuy-Cariaco Basin. On the southern part of the Ensenada de Barcelona shelf, the contact between the sedimentary and igneous-metamorphic basements is interpreted as an overthrust of Early to Middle
Miocene age. This relationship will be discussed in Chapter 6 concerning structures in the Cariaco and Carúpano area.

As shown on Panel-1, the basement is generally overlain by Oligocene or Eocene sedimentary rocks in the structural provinces located to the north of the El Pilar strike-slip fault. To the south of this fault (e.g., in La Ensenada de Barcelona shelf), sedimentary units of Late Miocene and Pliocene time, and on few occasions of Middle Miocene age (e.g., Sections B13 and B15 in the Panel-8) directly overlie the basement.

3.3.3. Margarita Island and Araya-Paria Peninsulas

Margarita Island

Stephan (1985) includes Margarita Island in his Coastal Fringe/Margarita Belt which consists of serpentinites, metagabbros, amphibolites, schists, gneisses, and marbles intruded by granites and basaltic dykes (Avé Lallemant, 1997). Some of these rocks are genetically related to a divergent margin setting and others to a convergent margin setting.

The continuity of Stephan's (1985) coastal fringe belt is disrupted by the San Sebastian - El Pilar fault system so that it is not clear whether units that are mapped to the north of that fault (i.e., the Araya Peninsula or Margarita Island) may be correlated unambiguously with tectonic units mapped to the south of that fault.

Margarita Island has been the focus of many studies (e.g., Maresch, 1975; Chevalier, 1987; Avé Lallemant and Guth 1990; Guth, 1991; Guth and Avé Lallemant
1991; and Stöckhert et al., 1995). The tectonic evolution of the island has been summarized in a table by Stöckhert et al. (1995) [Table 3.2]. These authors appear to sum up an overall consensus that the structurally lower unit (the Juan Griego unit) is a metamorphosed complex of a Paleozoic (U/Pb age of 315 ± 24 Ma) continental crust and that the upper La Rinconada unit represents oceanic crust and associated mantle peridotites of an Albian-Aptian age. The lower "continental" unit and the upper "oceanic" unit were essentially joined together by mid Cretaceous time, when they were intruded by the Salado granite. The less metamorphic Robles and Manzanillo phyllites and schists were presumably involved by later deformation within the accretionary wedge. Avé Lallemant and Guth (1990), Avé Lallemant (1991), and Guth (1991) propose and document extensive syn-metamorphic arc parallel extension along the Margarita - Aves Ridge subduction complex.

The uplift and rapid cooling stage 6 of Stöckhert et al. (1995) occurred during the Paleocene and the Early Eocene and is completed by mid Eocene time, i.e., just prior to the deposition of the earliest non-metamorphic sediments in the area. It is therefore plausible to assume that this Early Paleogene cooling coincides with the formation of the peneplane which separates the metamorphic sequences of the Venezuelan platform from the overlying sediments.

Stöckhert et al. (1995) agree with the reconstructions of Ross and Scotese (1988), Pindell et al. (1988), and Pindell and Barrett (1990) that a Cretaceous island arc was located much farther west in the Pacific and there is also some agreement that the polarity
<table>
<thead>
<tr>
<th>Relative age</th>
<th>Absolute age</th>
<th>Tectonic processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>...</td>
<td>Protopith: Juan Griego unit is continental crust with Paleozoic basement (including 315 Ma granites). La Rinconada unit is oceanic crust. Mantle peridotites are associated.</td>
</tr>
<tr>
<td>Stage 2</td>
<td>U-Pb zircon (114 - 105 Ma)</td>
<td>Troilite-bearing intrusions, either as (1) plagiogranite in a mid-ocean-ridge setting (La Rinconada unit would be of Aptian-Albian age) or as (2) calcalkaline arc intrusion.</td>
</tr>
<tr>
<td>Stage 3</td>
<td>...</td>
<td>Pervasive ductile deformation and high-pressure metamorphism ($T = 500-600$ °C, $P = 10-14$ kbar). All units are joined together (Margarita Complex) in the deep level of a fore arc.</td>
</tr>
<tr>
<td>Stage 4</td>
<td>U-Pb zircon (86 Ma), Ar-Ar high-pressure white mica (90-80 Ma)</td>
<td>Intrusion of El Salado granite; the Margarita Complex shifts into an arc position and cools to below $-400$ °C.</td>
</tr>
<tr>
<td>Stage 5</td>
<td>Ar-Ar magmatic amphibole from gabbro (66 Ma, single determination only)</td>
<td>Strong deformation in an intermediate crustal level under upper to lower greenschist facies conditions: nearly pervasive in the Juan Griego unit, concentrated in shear zones in the basic rocks of the La Rinconada unit. The troilite-bearing, the El Salado granite, and minor gabbro intrusions are affected by ductile deformation in extensive shear zones. Steep foliation and horizontal northeast-trending stretching lineation suggest deformation at a transform margin.</td>
</tr>
<tr>
<td>Stage 6 and</td>
<td>K-Ar white mica formed in stage 5 (55-50 Ma)</td>
<td>Rapid cooling to below $-300$ °C and transition from ductile deformation under greenschist facies conditions to brittle faulting. Significant exhumation brings the Margarita Complex from an intermediate into a shallow crustal level. Major tectonic reorganization took place at 50 Ma. Deposition of Eocene sediments begins at about this time.</td>
</tr>
<tr>
<td>Stage 7</td>
<td>Fission track zircon (53-50 Ma)</td>
<td>Conjugate shear fractures form in brittle field; extension in east-northeast-west-southwest direction. Massive quartz veins.</td>
</tr>
<tr>
<td>Stage 8</td>
<td>...</td>
<td>Basaltic to andesitic melts intrude following fractures formed during stage 8.</td>
</tr>
<tr>
<td>Stage 9</td>
<td>Ar-Ar magmatic amphibole (52-47 Ma)</td>
<td>Reverse faults form in variable orientations, partly by reactivation of older fracture sets.</td>
</tr>
<tr>
<td>Stage 10</td>
<td>...</td>
<td>Normal faults develop in variable orientations, again mainly by reactivation of earlier fault and fracture systems.</td>
</tr>
<tr>
<td>Stage 11</td>
<td>...</td>
<td>Deposition of Neogene sediments; relative tectonic quiescence; widely spaced block faulting.</td>
</tr>
<tr>
<td>Stage 12</td>
<td>mid-Miocene, $-12$ Ma</td>
<td>TABLE 3.2. Tectonic evolution of Margarita Island summarized by Stöckhert et al. (1995).</td>
</tr>
</tbody>
</table>
of that arc flipped from east-dipping subduction during the Lower Cretaceous to west-dipping subduction sometime between the Albian and the Turonian.

There remains the question of the large scale internal structure of Margarita Island which has been addressed by Chevalier (1987) who, based on substantial field work, postulated a complex duplex-type stack of relatively flat folded ophiolitic nappes. Guth (1991) declares Chevalier's interpretation "inconclusive" mainly on the grounds that the poor outcrops on Margarita do not justify such an elaborate interpretation. Guth emphasized the overall allochthonicity of the Margarita complex but chose to ignore the large scale internal structure which according to many authors juxtaposed extensive oceanic terranes to continental terranes. This apparent disagreement is over matters that are beyond the scope of this thesis, which is focused on the Eocene-Recent evolution of the area because of the nature of the basic information available.

For this study it can be concluded that the Pre-Eocene basement of Margarita Island was formed in a deep subduction zone much farther to the west and that this subduction complex was extended and thinned in an arc parallel direction (Avé Lallemant and Guth, 1990).

The Araya - Paria Peninsulas

The Araya-Paria Peninsulas, and their continuation in the Northern Range of Trinidad, are bounded to the north by the Neogene Coche-North Coast fault and to the south by the El Pilar-Casanay strike-slip fault system which dies out in northern Trinidad as its displacement is transferred in part to the Warm Springs fault system of Trinidad
(Payne, 1991; Algar and Pindell, 1993; Flinch et al., in preparation). The Araya - Paria Peninsulas have been discussed by many authors (e.g., Schubert, 1971; González de Juana et al., 1980; Vierbuchen, 1984; Bellizzia, 1986; Chevalier, 1987; Avé Lallemant, 1997).

In agreement with Schubert (1971), Avé Lallemant (1997) divided the metamorphic rocks of the Araya Peninsula into four east-northeast lithotectonic belts or assemblages. From north to south, they are the Manicuare, Laguna Chica, Carúpano and Tunapuy assemblages. These assemblages are separated by steep faults along which both thrust and strike-slip displacements have occurred (Schubert, 1971; Beltran and Giraldo, 1989; Avé Lallemant, 1997). The metamorphism of the Manicuare assemblage consists of amphibolite facies rocks while the metamorphism of the El Copey, Carúpano and Tunapuy assemblages comprise a low-grade greenschist facies rocks.

A fifth assemblage may be the Güinimita Formation which is characterized by metaconglomerates, meta-arenites, metalimestones, and quartz-sericite phyllites (González de Juana et al., 1965). This assemblage was recognized by Vierbuchen (1984) just to the north of the El Pilar fault separating the Tunapui assemblage from unmetamorphosed Cretaceous rocks to the south. Farther north is a second belt of Güinimita that is surrounded by the Tunapui. On the base of rudists, the Güinimita assemblage is assigned to the Barremian-Aptian (Campos, 1981; Vierbuchen, 1984).

The Manicuare assemblage consists of mica schist, kyanite schist, staurolite-garnet -biotite schist, amphibole schist, quartzite, marble, and two-feldspar gneiss (Avé Lallemant, 1997). A synthetic stratigraphic column of this assemblage is shown on Figure
3.5. The assigned stratigraphic ages are entirely speculative. Chevalier (1987) roughly correlates the Manicuare assemblage with the Juan Griego Formation of Margarita Island.

The Laguna Chica assemblage contains quartzite, chlorite schist, amphibole schist, phyllite and serpentine. Chevalier (1987) correlated it with the El Copey assemblage and included metavolcanic rocks and meta-ophiolites that occur in a narrow zone closely associated with the Punta Salazar-Punta Los Carneros fault. This oceanic affinity association is the unit which Stephan (1985) encompasses in his Coastal fringe/Margarita belt and which following González de Juana et al. (1980) extends into scattered outcrops on the north coast of the Paria Peninsula and the Sans Souci metavolcanics of northern Trinidad. The age of deposition of these rocks may be Early Cretaceous (Vierbuchen, 1984).

The Carúpano assemblage consists of calcareous phyllites interbedded with dark-colored recrystallized limestone, graphitic and calcareous mica schist, and rarely serpentine and microconglomerates of dark quartz (e.g., Vierbuchen, 1984; Avé Lallemant, 1997). No fauna has been found in this unit; however Vierbuchen (1984) proposed it to be a more distal, lateral facies equivalent of the Albian/Aptian Tunapui assemblage.

The Tunapui assemblage comprises quartz-mica schist, phyllite, metaconglomerate, graphitic phyllite, quartzite and some limestone. An Albian fauna was tentatively identified in this assemblage (Vierbuchen, 1984). Figure 3.6 shows a synthetic stratigraphic column of Carúpano, Gúinimita and Tunapuy assemblages.
Figure 3.5. Synthetic stratigraphic column of the Manicuare Formation. From Chevalier (1987).
Figure 3.6. Stratigraphic column of Carúpano, Güinimita and Tunapuy formations. From Chevalier (1987).
Of particular interest is the only outcrop of Serranía del Interior stratigraphy to the north of the El Pilar fault in a horse or else a window that has been described by Vierbuchen (1984).

Algar and Pindell (1993) review the stratigraphy and the deformation in the northern range of Trinidad. They do conclude that the Jurassic to Upper Cretaceous stratigraphy of the Northern Range corresponds to a passive margin stratigraphy much like the southeastern part of the Araya-Paria Peninsulas. An Late Jurassic age is inferred for an alternation of limestones and phyllites, which are overlain by Cretaceous siliciclastic and some carbonate turbidite sequences. Algar and Pindell's structural interpretation suggests that the generally north-verging structures were formed in post-Cretaceous times with cooling dates following metamorphism during Oligocene to Early Miocene, first followed by another cooling event during Middle-Late Miocene. Thus the metamorphism of northern Trinidad is later than the metamorphism that followed the juxtaposition of oceanic and continental margin units on Margarita Island; this is also in keeping with Algar and Pindell's contention that the metasediments of northern Trinidad may well represent the distal passive margin of the Mesozoic to Oligocene section that is deformed in the Serranía del Interior.

3.3.4. Carúpano Basin

The basement of the Carúpano Basin has been encountered in eight of the 20 wells drilled in the area. According to Talukdar (1983), volcanic rocks that were found
have three different affinities (Figure 3.7), i.e., mid-ocean ridge basalts (MORB), primitive island arc (PIA), and mature island arc.

The volcanic rocks of mid-oceanic ridge affinity are metabasalts that underwent a low grade of metamorphism. They are associated with metasedimentary rocks such as metaquartz, arenites, phyllites, quartzite and quartz schists (Furrer, 1984). This assemblage was defined as the Bocas Complex by Castros and Mederos (1985). They proposed Jurassic/Early Cretaceous as a probable age of deposition and correlated it with the El Copey Formation in the Araya Peninsula. Such a correlation is not clear because the El Copey Formation is involved in a convergent margin setting during Early Cretaceous (Vierbuchten, 1984).

The volcanic rocks of primitive island arc affinity are massive and/or pyroclastic basalts (Talukdar, 1983). They form a sequence with volcanoclastics and sedimentary rocks such as: pelagic limestone and shale, radiolarian chert, and calcareous sandstone. Castros and Mederos (1985) named this volcanic and sedimentary sequence the Mejillones Complex which was correlated with the Washikemba Formation of Bonaire (Furrer, 1984). K-Ar whole-rock ages of the basalts range between 102.2 ± 10.0 and 87.0 ± 9 Ma, i.e., Albian to Santonian (Talukdar, 1983). These rocks are probably also equivalent to the volcanic rocks described by Snoke et al. (1990) and Snoke et al. (1991) from Tobago. According to Donnelly and Rogers (1978) and Beets et al. (1985), primitive island arc (PIA) magmas represent the earliest volcanic system within the Caribbean island arcs formed by magmas that were generated by massive melting of hydrated mantle
BASEMENT INFORMATION

- **CALCALKALINE BASALTIC ANDESITES**
  - **Affinity:** Mature Island arc
  - **Age:** Eocene-Oligocene (K-Ar whole-rock ages of 38.6 ± 2.0 and 33.5 ± 1.8 MA)
  - **Comment:** Present hydrothermal alteration under submarine conditions

- **SUBMARINE BASALTS**
  - **Affinity:** Primitive Island arc
  - **Age:** Late Cretaceous (K-Ar whole-rock ages between 87.0 ± 9 and 102.2 ± 10 MA)
  - **Comment:** Massive and Pyroclastic rocks

- **METABASALTS**
  - **Affinity:** MORB
  - **Age of metamorphism:** probably Late Cretaceous
  - **Comments:**
    1. Basalts affected by a low grade regional metamorphism of high P/T
    2. Basalts might be part of the Jurassic ocean floor

**NOTE**
- **Black fill:** Core sample
- **White fill:** Cutting sample with the same material

---

**Figure 3.7.** Distribution of Basement, Carúpano Basin. Based on Talukdar (1983) and Pereira et al. (1984).
which rises from the descending edge of subducted slab at the initial stage of island arc genesis.

By way of contrast, volcanic rocks with mature island arc affinity have been drilled near the Los Testigos Islands. This assemblage of rocks will be described later under part 3.4.11. Castros and Mederos (1985) named these volcanic rocks the Los Testigos Complex.

As shown on Panel-11, the basement rocks in the Carúpano Basin are mainly overlain by volcanoclastics and sedimentary rocks of Eocene age, except for the Los Testigos Islands and the southeastern part of the basin, where Miocene sedimentary units directly overlie them.

3.4. Dutch and Venezuelan Leeward Antilles

The Leeward Antilles form a chain of islands in the southern Caribbean. This chain of islands consists from west to east of the following islands: Los Monjes, Aruba, Curaçao, Bonaire, Los Roques, La Orchila, La Tortuga, La Blanquilla, Los Hermanos, Los Frailes, and Los Testigos. Avé Lallémant (1997) also includes in the Leeward Antilles terrane the granitic and basaltic intrusives on Margarita Island and Tobago and volcanic rocks in the basement of the Carúpano and Cariaco Basins.

According to Santamaría and Schubert (1974), the igneous rocks in this province can be divided geochemically into two suites: (1) An olivine tholeiite and abyssal tholeiite suite and (2) a calc-alkaline suite. The tholeiitic rock suite is the older, ranging
between 130 Ma and 114 Ma (Early Cretaceous). The radiometric ages of the calc-alkaline rock suite range between 84 Ma and 30 Ma (Late Cretaceous to Oligocene). Bellizzia (1984) related the former to non-orogenic volcanism and the latter to orogenic volcanism. The following overview is mainly based on the review papers of Beets et al. (1984) and Donnelly et al. (1990).

3.4.1. Los Monjes Archipelago

The Los Monjes Archipelago is the westernmost Venezuelan island group. It is located northwest of the Gulf of Venezuela, some 40 km from the Paraguaná Peninsula of Venezuela. It consists of nine small islands. They are made up essentially of metagabbro (coarse-grained ortho-amphibolites) and metabasalt, i.e., amphibolites of subvolcanic to volcanic origin (Bellizzia et al., 1976) metamorphosed in greenschist facies (Bellizzia, 1972), which were intruded by hornblende-quartz gabbros (e.g., Ostos, 1990). The rocks of the Los Monjes Archipelago are classified as tholeiitic basalts related to a mid-oceanic ridge basalt (MORB) suite (Santamaría and Schubert, 1974) with a high percentage of aluminite and a low proportion of potassium (Bellizzia, 1984). Radiometric determinations (K/Ar) indicate ages between 116 ± 13 Ma and 114 ± 12 Ma for samples of orthoamphibolite (Santamaría and Schubert, 1974) [see Table 3.3 from Ostos, 1990]. These ages may represent a metamorphic age (e.g., Ostos, 1990).
**TABLE 3.3:** Isotopic ages from the Dutch and Venezuelan islands, the Peninsula of Paraguauna, Gulf of Venezuela, and the Venezuelan Platform. From Ostos (1990).

<table>
<thead>
<tr>
<th>ROCK TYPE</th>
<th>METHOD</th>
<th>MIN. ROCK</th>
<th>AGE</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ARUBA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TONALITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>74.5 ± 4 Ma</td>
<td>A</td>
</tr>
<tr>
<td>QZ. DIORITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>67.0 ± 4 Ma</td>
<td>B</td>
</tr>
<tr>
<td>TONALITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>85 to 50 Ma</td>
<td>C</td>
</tr>
<tr>
<td>TONALITE</td>
<td>Rb/Sr</td>
<td>Whole rock</td>
<td>72.5 ± 4 Ma</td>
<td>A</td>
</tr>
<tr>
<td>TONALITE</td>
<td>Rb/Sr</td>
<td>Biotite (3)</td>
<td>Whole rock (9)</td>
<td>72.0 ± 2 Ma</td>
</tr>
<tr>
<td><strong>CURACAO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOLERITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>118 ± 10 Ma</td>
<td>B</td>
</tr>
<tr>
<td>DOLERITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>126 ± 12 Ma</td>
<td>B</td>
</tr>
<tr>
<td>DIABASE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>93.0 ± 3 Ma</td>
<td>C</td>
</tr>
<tr>
<td>DIABASE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>73.0 Ma</td>
<td>C</td>
</tr>
<tr>
<td>DIABASE</td>
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<td>68.0 Ma</td>
<td>C</td>
</tr>
<tr>
<td>Qz. TRACHIANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>74.0 ± 5 Ma</td>
<td>B</td>
</tr>
<tr>
<td>TRACHIANDESITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>76.0 ± 6 Ma</td>
<td>B</td>
</tr>
<tr>
<td>TRACHIANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>64.0 ± 6 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LOS ROQUES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METADIASBASE</td>
<td>K-Ar</td>
<td>Amphibol</td>
<td>127 ± 15 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METALAMPROPHYTE</td>
<td>K-Ar</td>
<td>Amphibol</td>
<td>130 ± 14 Ma</td>
<td>B</td>
</tr>
<tr>
<td>PEGMATITE</td>
<td>K-Ar</td>
<td>?</td>
<td>66.0 ± 5 Ma</td>
<td>B</td>
</tr>
<tr>
<td>QZ. DIORITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>65.0 ± 3.6 Ma</td>
<td>B</td>
</tr>
<tr>
<td>Qz. DIORITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>66.0 ± 6 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LA BLANQUILLA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRONDJEMITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>64.0 ± 3.5 Ma</td>
<td>B</td>
</tr>
<tr>
<td>TRONDJEMITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>62.0 ± 2.2 Ma</td>
<td>B</td>
</tr>
<tr>
<td>PEGMATITE</td>
<td>K-Ar</td>
<td>Feldspar</td>
<td>64.0 ± 3.4 Ma</td>
<td>B</td>
</tr>
<tr>
<td>PEGMATITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>62.0 ± 3.2 Ma</td>
<td>B</td>
</tr>
<tr>
<td>TRONDJEMITE</td>
<td>K-Ar</td>
<td>Biotite</td>
<td>64.0 ± 3.4 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LOS HERMANOS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>71.0 ± 6 Ma</td>
<td>B</td>
</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>70.0 ± 5.4 Ma</td>
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</tr>
<tr>
<td>Hbl. GNEISS</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>67.0 ± 5.1 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LOS FRAILES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIABASE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>66.0 ± 5.1 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LOS TESTIGOS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>K-Ar</td>
<td>Feldspar</td>
<td>44.0 ± 4.5 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>47.0 ± 6.1 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>44.0 ± 5.4 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>K-Ar</td>
<td>Hornblende</td>
<td>44.0 ± 5.5 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>LOS MONJES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORTHOAMPHIBOLITE</td>
<td>K-Ar</td>
<td>Amphibol</td>
<td>116 ± 13 Ma</td>
<td>B</td>
</tr>
<tr>
<td>ORTHOAMPHIBOLITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>114 ± 12 Ma</td>
<td>B</td>
</tr>
<tr>
<td><strong>PENINSULA OF PARAGUANA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>U/Pb</td>
<td>Allanite</td>
<td>262 Ma</td>
<td>E</td>
</tr>
<tr>
<td>METAGRANITE</td>
<td>U/Pb</td>
<td>Allanite</td>
<td>265 Ma</td>
<td>E</td>
</tr>
<tr>
<td>METANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>63.0 ± 4.4 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METAGABRO</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>120 ± 11 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METADOLERITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>110 ± 10 Ma</td>
<td>B</td>
</tr>
<tr>
<td>METANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>73.5 ± 11 Ma</td>
<td>F</td>
</tr>
<tr>
<td><strong>GULF OF LA VELA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qz. - Ser. PHYLITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>83.5 Ma</td>
<td>G</td>
</tr>
<tr>
<td>Qz. METAGABRO</td>
<td>K-Ar</td>
<td>Feldspar</td>
<td>114 Ma</td>
<td>G</td>
</tr>
<tr>
<td><strong>TUY-CARIACO BASIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METAVOLCANIC</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>65.4 Ma</td>
<td>H</td>
</tr>
<tr>
<td>METAVOLCANIC</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>69.5 Ma</td>
<td>H</td>
</tr>
<tr>
<td>METANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>78.3 ± 3.9 Ma</td>
<td>H</td>
</tr>
<tr>
<td><strong>CARUPANO BASIN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>METANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>38.6 ± 2 Ma</td>
<td>I</td>
</tr>
<tr>
<td>METANDESITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>33.5 ± 1.8 Ma</td>
<td>I</td>
</tr>
<tr>
<td>METABASALT</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>87.0 ± 9 Ma</td>
<td>I</td>
</tr>
<tr>
<td>METABASALT</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>102.2 ± 10 Ma</td>
<td>I</td>
</tr>
<tr>
<td><strong>GULF OF VENEZUELA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRANITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>? 304 Ma</td>
<td>J</td>
</tr>
<tr>
<td>GRANITE</td>
<td>K-Ar</td>
<td>Whole Rock</td>
<td>138 ± 6.9 Ma</td>
<td>J</td>
</tr>
</tbody>
</table>

3.4.2. Aruba

The Aruba Lava Formation (or diabase-schist-tuff Formation) forms the basal complex of Aruba which has been intruded by the Aruba Tonalite Batholith (Beets et al., 1984; Bellizzia, 1984) [Figures 3.8 and 3.9]. The batholith was emplaced during 85-90 Ma (Beets et al., 1984).

The Aruba Lava Formation consists of a series about 3 km thick submarine basalt, diabase, pyroclastics and volcaniclastics (Lagaay, 1969) in which ammonites of Turonian age have been found (MacDonald, 1968). The chemical composition of the Aruba Lava Formation suggests a mid-ocean ridge basalt affinity (Beets et al., 1984).

The Aruba Tonalite Batholith consists primarily of a hornblende tonalite, with lesser amounts of trondhjemite, granitic pegmatite, norite and gabbro (Jackson and Robinson, 1994). Geochemical analyses of these rocks suggest a calc-alkaline affinity (Beets et al., 1984). The radiometric ages indicate that emplacement of the batholith took place at 88 ± 0.8 Ma (Priem et al., 1986). However Beets et al. (1984), based on an extensive radiometric dating program, suggest an emplacement of 85 - 90 Ma.

The Aruba Lava Formation and the Tonalite Batholith are unconformably overlain by Eocene limestones.
Figure 3.8. Correlation chart of the Cretaceous and Early Tertiary sequences of Curaçao, Aruba, and Bonaire. Except for the tonalite-gabbro batholith of Aruba, ages of all units are based on fossils: ammonites for the Curaçao and Aruba Lava Formations, ammonites, inoceramids, and planktonic foraminifera for the Washikemba Formation, and rudist and planktonic foraminifera for the Late Senonian units. An extensive radiometric dating program on rocks of the Aruban batholith has shown that emplacement of the batholith occurred in the 85-90 Ma interval and that the published age of 70-75 Ma (Priem and others, 1968, 1977; Santamaria and Schubert, 1975) is a reset age due to a low-grade thermal event in the Senonian and Early Tertiary (hatched field). From Beets et al. (1984).
Figure 3.9. Geologic sketch maps of Aruba, Curaçao, and Bonaire (from Lagaay, 1969).
3.4.3. Curaçao

The oldest sequence exposed on the island of Curaçao is the Curaçao Lava Formation (Figure 3.9) which includes over 5 km of pillow basalts, reworked hyaloclastites, dolerite sills, and a thin succession of siliceous shales and limestones (Jackson and Robinson, 1994). A pelagic limestone intercalation in this formation contains ammonites of Middle Albian age (Wiedmann, 1978). The basalts of the Curaçao Lava Formation are correlated with the Aruba Lava Formation (Figure 3.8) and are basically a mid ocean ridge basalt (MORB) sequence formed by shallow (<70 km) melting of mantle (Beets et al., 1984). This MORB sequence has yielded whole rock K/Ar ages of 126 ± 12 Ma and 118 ± 10 Ma and is metamorphosed to a zeolite / phrenite - pumpellyite facies.

The Curaçao Lava Formation is separated from the overlying Campanian/Maastrichtian Knip Group and Danian Midden-Curaçao Formation by an angular unconformity (Beets, 1972, 1977). The Knip Group consists of pelagic, silica-rich and clastic sedimentary rocks and the Midden-Curaçao Formation is described as a flysch type sequence (e.g., Lagaay, 1969). In both units, local associations of volcanic debris with detritus derived from a sialic source suggest the proximity of the South American continent (Beets et al., 1984). All of these rocks were folded and regionally metamorphosed to a zeolite and prehnite-pumpellyite facies (Beets, 1972; Beets, 1977; Beets et al., 1984).
Small intrusions of calc-alkaline composition are also exposed on Curaçao. The oldest is a Late Cretaceous diorite (K/Ar whole-rock age = 93 ± 3 Ma) which intrudes the Curaçao Lava Formation (e.g., Beets et al., 1984) and may be considered of the same age as the Aruba tonalite batholith (e.g., Lagaay, 1969). Younger, post Danian intrusions are furthermore found as sills in the Knip and Midden-Curaçao strata (Beets, 1972).

The unconformity between the Curaçao Lava Formation and the Knip Group (Figure 3.8) could be related to the beginning of the collision of the island arc with the continental margin of Venezuela (Bellizzia, 1984; Beets et al., 1984).

Only in a few places on Curaçao, limestones and calcareous marls of Middle and Late Eocene occur (Jackson and Robinson, 1994). Coral limestone terraces of Quaternary age are more common; and they are mainly exposed on the leeward (southwestern) side of the island.

### 3.4.4. Bonaire

The main part of the basal complex of Bonaire is formed by the Washikemba Formation, a unit more than 5 km thick, consisting mostly of submarine volcanic rocks (flows of basalts, basaltic andesites, dacites, rhyolites and tuffs) that alternate with pelagic and volcanoclastic sedimentary rocks of Albian to Coniacian age (Beets et al., 1984). The chemistry of the volcanic rocks shows a Primitive Island Arc (PIA) affinity (Donnelly and Rogers, 1978; Donnelly et al., 1990b). Therefore, these rocks are different in their
tectonomagmatic setting from the volcanic rocks of the Curaçao Lava and Aruba Lava Formations, which according to Jackson and Robinson (1994) have MORB affinities.

The rocks of the Washikemba Formation have been metamorphosed in the zeolite and prehnite-pumpellyite facies (Beets, 1972; Beets et al., 1984). The formation is unconformably overlain by the Rincon Formation, which consists of Maastrichtian limestone, conglomeratic limestone, and sandy marls (Santamaría and Schubert, 1974; MacGillavry and Beets, 1977; Beets et al., 1984). A younger (?Paleocene/Eocene) conglomerate mainly composed of fluvial deposits is called the Soebi Blanco Formation. Finally, there are Upper Eocene and Quaternary limestones (Figure 3.9) [Lagaay, 1969; Santamaría and Schubert, 1974].

3.4.5. Los Roques

Los Roques Archipelago is underlain by an igneous-metamorphic complex that crops out only on the island El Gran Roque (Kummerow and Odehnal, 1993), on which a fine-grained metadiabase forms the central and eastern hills, and metagabbro forms the western hill (Figure 3.10) [Santamaria and Schubert, 1974]. These basic igneous rocks were intruded by small quartz diorite masses and by dykes and veins of aplite and pegmatite.

The meta-igneous rocks are described as ocean floor tholeiites (MORB) and they have Neocomian K/Ar ages; the intrusives are described as calc-alkaline series and their
Figure 3.10. Geologic maps of Gran Roques and La Orchila Island (after Santamaria and Schubert, 1974).
K-Ar dates indicate Maastrichtian-Early Paleocene ages (Santamaria and Schubert, 1974; Bellizzia, 1984; Ostos, 1990).

The Quaternary on the Gran Roque is represented by conglomerate terraces, consisting of fragments from the underlying basement rocks and corals, cemented by a ferruginous and calcareous material (Schubert and Moticska, 1972).

3.4.6. La Orchila

Outcrops in the eastern part and on the western end of La Orchila Island show the basal complex consisting of chlorite schists and phyllites, quartz-epidote-garnet orthoamphibolite, hornblende gneiss, and micaceous epidote gneiss and schist (Figure 3.10) [Schubert and Moticska, 1972]. These metamorphic rocks were intruded by diabase, granitic and granodioritic rocks and pegmatite and aplite dykes. The metamorphism is transitional between the facies of greenschist and amphibolite (Bellizzia, 1984). Ultramafic rocks such as peridotite and serpentinite crop out in the center of the island (Figure 3.10); their relationship with the other rocks is unclear but they are suspected to be intrusive into the metamorphic rocks (Schubert and Moticska, 1972; Santamaria and Schubert, 1974). No radiometric ages have been acquired on the basement of La Orchila Island.

Quaternary deposits are constituted by terraces which consist of reefs composed mainly of coral and shell fragments (Schubert, 1972).
3.4.7. La Tortuga

The La Tortuga Island is formed by horizontal Pliocene sedimentary rocks and Pleistocene coral reefs and limestones which overlie a local structural basement high. Seismic refraction data from the area suggest a shallow igneous-metamorphic basement. It was confirmed by a stratigraphic hole drilled southeast of the island, which encountered gneiss at a depth of about 150 m (Galaviss and Louder, 1970), overlain unconformably by gray and mottled clays interlaminated with thin limestone beds and green sands. Boulders and crystalline pebbles were found on top of the basement.

3.4.8. La Blanquilla

The basal complex on La Blanquilla Island is composed predominantly of a trondhjemite-tonalite pluton called the Garantón batholith (Figure 3.11) [Schubert and Moticska, 1972; Jackson and Robinson, 1994]. This batholith was intruded by numerous pegmatite dykes and veins. Occurrences of amphibolite xenoliths were found within the tonalitic zone (Schubert and Moticska, 1972). K-Ar datings on trondhjemite and pegmatite rocks have given ages that range between 64 and 62 ± 3.5 Ma (Bellizzia, 1984). A sample of dredged granodiorite indicates a K-Ar age of 81 Ma (Peter, 1972). An interesting point to note is that the trondhjemitic rocks have only been described on the islands of La Blanquilla and Margarita; on the other southern Caribbean islands, plutonic
Figure 3.11. Geologic maps of La Blanquilla Island and Los Hermanos Archipelago (after Santamaria and Schubert, 1974).
rocks of similar ages are represented by granodiorites, granites and tonalites (Bellizzia, 1984).

The Garantón batholith has calc-alkaline affinity and is overlain by reefal Quaternary terraces (Santamaria and Schubert, 1974).

3.4.9. Los Hermanos Archipelago

Los Hermanos Archipelago, which is located 15 Km southeast of La Blanquilla Island, consists of hornblende tonalite gneiss, amphibolite, epidosite, and biotite-epidote gneiss and schist (Figure 3.11) [Schubert and Moticska, 1972; Santamaria and Schubert, 1974]. These rocks are believed to be the wallrock for the Garantón batholith of La Blanquilla (Schubert and Moticska, 1972; Jackson and Robinson, 1994). Their chemical composition indicates calc-alkaline affinity (Santamaria and Schubert, 1974; Ostos, 1990). They were metamorphosed in the greenschist and epidote amphibolite facies and intruded by numerous dykes and veins of pegmatite (Bellizzia, 1984). Radiometric determination on gneiss (K-Ar on hornblende) reveals ages between 71 and 67 ± 5 Ma (Santamaria and Schubert, 1974). These ages suggest a regional metamorphism during Late Cretaceous (Bellizzia, 1984).
3.4.10. Los Frailes Archipelago

Outcrops of basic volcanic and subvolcanic rocks occur on the Los Frailes Archipelago (Motiecka, 1972; Chevalier, 1987). The effusive volcanic rocks include fine-grained tholeiitic basalts, sometimes with vacuoles. The intrusive volcanic rocks include porphyritic tholeiitic basalts and diabase. A layer of aphanitic volcanic tuffs is also recognized in the area.

The volcanic complex of Los Frailes has not undergone any regional dynamothermal metamorphism (Motiecka, 1972; González de Juana et al., 1980; Bellizzia, 1984). Its chemical composition indicates a calc-alkaline affinity (Santamaría and Schubert, 1974; Ostos, 1990). A radiometric (K-Ar) determination for a diabase (on the whole rock) yielded an age of 66 ± 5.1 Ma.

3.4.11. Los Testigos Archipelago

The rocks exposed on Los Testigos Islands (Figure 3.12) consist mainly of a meta-andesitic volcanic complex (andesite, andesitic tuff, andesitic lava, and similar rocks), intruded by a metagranitic batholith (Schubert and Motiecka, 1972). The complex was later intruded by mafic and leucocratic dykes and metamorphosed to a very low metamorphic grade (González de Juana, 1980; Ostos, 1990). Isotopic (K-Ar) dating on the younger calc-alkaline intrusives (e.g., granitic rocks) yielded ages between 47 ± 6.1 Ma and 44 ± 4.5 Ma (Santamaría and Schubert, 1974; Bellizzia, 1984).
Figure 3.12. Geologic map of Los Testigos archipelagos. (After Santamaría and Schubert, 1974).
Two exploratory wells (see Figure 5.2), located approximately 45 km east of Los Testigos archipelago, drilled a basement consisting of calcalkaline basaltic andesites that correspond to explosive volcanic eruptions in an island arc setting at an advanced stage of development (Talukdar, 1983, Bellizzi, 1984). Two basaltic andesites dated by the K-Ar whole-rock method yielded apparent ages of Latest Eocene and Earliest Oligocene (38.6 ± 2.0 Ma and 33.5 ± 1.8 Ma) [Talukdar, 1983].

3.5. Summary about basement of northeastern Venezuela Offshore

The pre-Tertiary basement of the Tuy-Cariaco and Carúpano Basins of the northeastern Venezuelan offshore consists of a deeply subducted accretionary complex of a Cretaceous island arc that formed far to the west of its present location.

In the Ensenada de Barcelona shelf, to the south of the El Pilar fault, the continuation of the Villa de Cura Klippe probably directly overlies the frontal folds of the outer Faja Piemontina, which in turn are overlying the Paleozoic basement of the foreland. To the east and perhaps in front of the continuation of the Outer Faja Piemontina are the folds of the Serranía del Interior with their lateral ramp, i.e., the Urica fault system.

To the north of the El Pilar fault there is no obvious continuation of the units of the Ensenada de Barcelona. In a speculative manner it could be assumed that the primitive island arc (PIA) volcanic rocks that have been reported from the Carúpano Basin (Talukdar, 1983) could represent the continuation of the Villa de Cura Belt, with
the added caution that these volcanics appear to overlie a metamorphic basement. The only suggestion of Serranía-type Cretaceous is the isolated occurrence of El Cantil-type limestones in the Boca well (well-21, see Foldout 7). Note that these limestones overlie volcanic and metamorphic rocks, probably with a fault contact that is difficult to evaluate.

Most of the Venezuelan platform appears to be underlain by a metamorphic sequence of gneisses and metasedimentary rocks that involve former passive margin sediments, meta-ophiolites and MORB-type volcanic rocks of Jurassic to Early Cretaceous age, as well as primitive island arc (PIA), meta-volcanic rocks which underwent high P/low T metamorphism. These were subsequently intruded by Upper Cretaceous calc-alkaline igneous rocks and their volcanic equivalents. In the northern part of the Carúpano Basin and the eastern part of the Leeward Antilles terrane (e.g., Los Frailes and Los Testigos Archipelagos), island arc volcanic activity continued until Paleogene time.

Perhaps the most detailed structural and metamorphic studies have been done on Margarita Island, e.g., Maresch (1975); Chevalier (1987); Avé Lallemant and Guth (1990); Stöckhert et al. (1995). The main point to retain from these studies is that the high P/low T metamorphism occurred after the passive margin units and the oceanic (i.e., ophiolitic units) were assembled in mid Cretaceous time and that fission track data suggest uplift and peneplanation before the Eocene.

The larger scale internal structure of the North Venezuelan basement remains unknown with only Chevalier (1987) proposing and in part documenting a series of nappes, a concept which in principle is reasonable for the internal structure of any
accretionary complex. The data of Stöckhert et al. (1995) suggest that these structures were already assembled before they were metamorphosed. On an even larger scale it is unknown whether the whole accretionary complex is emplaced on the Paleozoic / Precambrian foreland basement (as suggested by Bally et al., 1995).

Figure 3.2 shows the distribution of metamorphics, ophiolites, MORB, PIA and calc-alkaline rocks in northern Venezuela as suggested by Stephan (1985), Beets et al. (1984) and Donnelly et al. (1990).

3.6. Seismicity and Tomography sections along the Southern Caribbean

3.6.1. Seismicity

The study of focal mechanisms and the distribution of earthquake hypocenters can provide important information about the geometry of the subduction-related seismic zones. However along the Southern Caribbean, the complete morphology of the subducted slabs cannot be obtained from analyses of seismicity, since the depths of earthquake hypocenters are restricted to the upper 250 km of the mantle (e.g., van der Hilst, 1990). Using tomographic images, the aseismic parts of subducted slabs can be investigated. The seismic tomography method will be discussed in the next section.

In northern Venezuela, the seismicity is localized in the Venezuelan Andes and in the central and eastern area of the Araya-Paria Peninsula. In the Venezuelan Andes, the focal mechanisms are related to the Bocono fault zone, while in the Araya-Paria
Peninsula they are associated with the El Pilar fault (e.g., Bellizzia, 1984). In central northern Venezuela, the seismicity is very dispersed (Figure 3.13).

3.6.2. Qualitative discussion about the Seismic Tomography Method

Global seismic tomography has the potential to sample the earth's structure by seismic waves that are originated at the source of an earthquake (the hypocenter), travel through the earth and are recorded at seismological stations. The principal objective of seismic tomography is to determine the difference (delay time) between the observed travel times and the predicted travel times. The latter have been estimated using a reference earth model of seismic velocities. After that, the variation of the velocity of wave propagation (x) relative to the reference model velocities is calculated from a system of linear equations (van der Hilst, 1990), which is expressed by the matrix equation:

\[ \mathbf{A}\mathbf{x}=\mathbf{d} \]

In this equation, the matrix \(\mathbf{A}\) contains information related to the spatial distribution of ray traces of the waves that sample the mantle structure under investigation. According to van der Hilst (1990), the matrix \(\mathbf{A}\) depends on: (1) the distribution of earthquake hypocenters and seismological stations; (2) the reference velocity model of the Earth; (3) the type of seismic wave considered in the tomography study; and (4) the discretization of the Earth's volume under study. As mentioned before, the vector \(\mathbf{x}\) represents the velocity perturbation relative to the reference model and is
Figure 3.13. The locations of the earthquakes
(a) Epicenters of earthquakes with focal depths < 70 km (b) Epicenters of earthquakes with focal depths > 70 km
CARIB Caribbean Plate, Cocos Cocos Plate, Nazca Nazca Plate, NOAM North American Plate, Pacif Pacific Plate, SOAM South American Plate. (From van der Hilst, 1990)
sought by solving the above equation. The data vector $d$ contains the delay times. For more information about the previous equation, the reader is referred to Spakman and Nolet, 1988 and Spakman et al., 1988.

Because of the velocity contrast between the cold subducted slab relative to the ambient mantle, the morphology of some of these slabs can be revealed by tomographic methods (Hirahara, 1981; Spakman et al., 1988; van der Hilst, 1990). In seismic tomographic results, high velocity structures may be interpreted as lithospheric slabs.

Figure 3.14 shows a cartoon illustrating how to read seismic tomographic images of a subduction zone. Positive (negative) values of velocity anomalies indicate that the resultant velocities of the seismic waves are greater (less) than the predicted velocities by the reference model of the Earth. As can be seen, the tomographic results are dependent on the reference model. To better image the lithosphere-asthenosphere system, the reference model should enhance the velocity variations (Kissling and Spakman, 1996). On the example of Figure 3.14, the Jeffreys-Bullen (JB) model is considered a better reference model than the PM2 model since the JB model does not suppress the image of the asthenosphere.

3.6.3. Application of Tomographic Method in the Caribbean Region

Van der Hilst (1990) obtained high resolution images of the variations in the propagation velocity of compressional waves [direct P waves and surface reflected (pP, PP) waves] in the mantle below the Caribbean region. He applied the tomography method
Figure 3.14. Cartoon to illustrate how to read seismic tomographic images of subduction zone. A: schematic lithospheric cross-section of Alpine orogen with absolute P-wave velocities. B: schematic lithospheric cross-section of A displayed as tomographic image (relative velocity changes) using PM2 one-dimensional model as final reference model. C: schematic lithospheric cross-section of A displayed as tomographic image (relative velocity changes) using JB one-dimensional model as final reference model. From Kissling and Spakman (1996).
developed by Spakman and Nolet (1988). Figure 3.15 shows the distribution of the earthquakes that contributed to the data set used in van der Hilst’s (1990) study. These earthquakes occurred between January 1964 and July 1987 and were recorded at the seismological stations shown in Figure 3.15. Van der Hilst (oral communication) points out that the distribution of the recording stations seriously impairs the result of the data in the Caribbean which impedes the extrapolation of subducted slabs at great depths.

The reference model of seismic velocities for the Caribbean tomographic images is shown on Figure 3.16, on which it is referred to as model VCAR (Velocities below the CARibbean). The model VCAR differs from the global Jeffreys-Bullen (JB) reference model (Figure 3.16) by the first order discontinuities at depths of 390 and 660 km (see van der Hilst and Spakman, 1989; and Chapter 2 of van der Hilst, 1990 for more information).

Van der Hilst (1990) divided the mantle under the Caribbean region into a larger number of blocks (Figure 3.17), which have constant horizontal dimensions of $1.25^\circ \times 1.25^\circ$ and vertical dimensions according to the layer thickness (from 33 km at the top to 225 km at the bottom; see Table 3.4). In each block a velocity perturbation relative to a reference model is searched out by solving the linear system of equations discussed in the previous section ($Ax=d$). Results of this tomographic investigation are presented by cross sections of the mantle structure below the Caribbean region.
Figure 3.15. The distribution of stations that reported the P-wave travel time residuals used in the study. (a) Stations located within the limits of the cell model (n = 936, nreg = 313,285), (b) Stations for which corrections were computed in the tomographic inversion (n = 1566, nreg = 353,559). These include the stations for which the station corrections of Dziewonski and Anderson [1983] are available (n = 706, nreg = 324,263) [from van der Hilst, 1990].
Figure 3.16. Reference models of seismic velocities and outlines of the layer boundaries of the cell model. From van der Hilst (1990).
**Figure 3.17.** The block model used to discretize the mantle below the Caribbean region and a large part of South America. The model consists of 15 layers of 3,250 blocks each (50 in longitudinal direction, 65 in latitudinal direction). From van der Hilst (1990).

<table>
<thead>
<tr>
<th>layer number</th>
<th>depth range [km]</th>
<th>mean velocity VCAR [km/sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 33</td>
<td>6.064</td>
</tr>
<tr>
<td>2</td>
<td>33 - 85</td>
<td>7.827</td>
</tr>
<tr>
<td>3</td>
<td>85 - 130</td>
<td>7.973</td>
</tr>
<tr>
<td>4</td>
<td>130 - 185</td>
<td>8.124</td>
</tr>
<tr>
<td>5</td>
<td>185 - 245</td>
<td>8.305</td>
</tr>
<tr>
<td>6</td>
<td>245 - 312.5</td>
<td>8.512</td>
</tr>
<tr>
<td>7</td>
<td>312.5 - 390</td>
<td>8.710</td>
</tr>
<tr>
<td>8</td>
<td>390 - 475</td>
<td>9.336</td>
</tr>
<tr>
<td>9</td>
<td>475 - 565</td>
<td>9.680</td>
</tr>
<tr>
<td>10</td>
<td>565 - 660</td>
<td>10.044</td>
</tr>
<tr>
<td>11</td>
<td>660 - 760</td>
<td>10.826</td>
</tr>
<tr>
<td>12</td>
<td>760 - 875</td>
<td>11.080</td>
</tr>
<tr>
<td>13</td>
<td>875 - 1000</td>
<td>11.322</td>
</tr>
<tr>
<td>14</td>
<td>1000 - 1150</td>
<td>11.542</td>
</tr>
<tr>
<td>15</td>
<td>1150 - 1325</td>
<td>11.792</td>
</tr>
</tbody>
</table>

**Table 3.4.** Layers of reference model VCAR. According to van der Hilst (1990).
3.6.4. Interpretation of Tomographic Images along the Southern Caribbean

The results of the tomographic investigation made by van der Hilst (1990) were used to determine the distribution of crust and upper mantle structures along the southern Caribbean. The location of the tomographic images can be seen in Figure 3.18.

The correlation of the Caribbean oceanic crust is suggested from cross section 6.9.a (Figure 3.19) in which is well illustrated the underplating of the southern part of the Caribbean plate below the South American continental crust. About the Atlantic oceanic crust, its correlation comes from the cross sections 6.8.b and 6.8.f (Figure 3.20), which can be considered characteristic for the subduction of the Atlantic oceanic crust below the Caribbean plate at the northern and southern part of the Lesser Antilles, respectively (van der Hilst, 1990).

Taking cross sections 6.9.a, 6.9.b, 6.8.b, and 6.8.f as control references, the interpretation of the Caribbean oceanic crust, the Atlantic oceanic crust, the South American continental crust, and the lithosphere attached to them have been made on north-south tomographic sections that cross the southern Caribbean (Figure 3.21). This north-south panel shows how the architecture of the crust and upper mantle changes along northern Venezuela.

In Section 6.7.a (Figure 3.21), located at the western side of northern Venezuela, a south-dipping subduction of the Caribbean oceanic crust is recognized below the South American continental crust. Also a high velocity zone associated with the Atlantic subducted slab is identified down to 600 km at the latitude 12°. Section 6.7.b illustrates a
Figure 3.18. Location map of tomographic sections. Meaning of the abbreviations: BFZ, Bocconó fault zone; BMFZ, Bucaramanga-Santa Marta fault zone; EPFZ, El Pilar fault zone; EYFZ, Eastern Venezuela Basin; J, Jamaica; LADB, Lesser Antilles deformed belt; MB, Maracaibo Basin; MT, Muertos trench; PRT, Puerto Rico trench; SGDB, Southern Caribbean deformed belt; SSFZ, San Sebastián fault zone; TN, Trinidad.
Figure 3.19. Interpretation of tomographic sections across the Western Venezuela
Tomographic Images from van der Hilst, 1990

Figure 3.20. Interpretation of tomographic sections across the Eastern Caribbean
Figure 3.21. Interpretation of north-south tomographic sections, Caribbean Plate
similar configuration but now the leading edge of the Caribbean plate is clearly distinguished at approximately the latitude 7.5° (200 km in the horizontal scale).

The tomographic Section 6.7.c (Figure 3.21) shows less convergence between the Caribbean plate and the South American (SA) continental crust than the one illustrated in the previous two sections (6.7.a and 6.7.b). The Atlantic subducted slab in Section 6.7.c is identified at a shallower level (in the upper 400 km).

In Section 6.7.d (Figure 3.21) the convergence between the Caribbean and the SA continental crust is much less than in the other sections located in the west. In Section 6.7.d the Atlantic oceanic crust is interpreted beneath the interaction of the Caribbean oceanic crust and the SA continental crust at a depth of 250 km. A high velocity structure between the Caribbean and Atlantic subducted slabs may suggest that they are attached to each other; however, correlations with Sections 6.9.b and 6.8.f indicate that the Atlantic subducted slab is moving at a lower level than the Caribbean subducted slab along northern Venezuela.

Sections 6.7.e and 6.7.f (Figure 3.21) show that the contact between the Caribbean and continental South America is more a strike-slip boundary than a convergent boundary. They also illustrate how the Atlantic oceanic slab is attached to continental South America. These two Sections 6.7.e and 6.7.f are located at the longitudes of the Paria Peninsula and eastern Trinidad, respectively. In these sections, the dominant subduction has an apparent dip to the north. This subduction is defined by the Atlantic subducted slab beneath the Caribbean-South America contact.
3.7. Implication of tomographic sections: Caribbean and Atlantic

Subductions along Northern Venezuela.

A contour map of the subducted slabs in the Caribbean region was made based on the interpretation of the tomographic sections. This map (Figure 3.22) shows two overlapping domains of subduction zones along the southern Caribbean: the Caribbean domain and the Atlantic domain. In Chapter 7 I will discuss how these two subduction domains may be linked to the diverse structural styles observed in the northeastern Venezuela offshore.

The Caribbean domain is limited to western and central Venezuela; in this domain the Caribbean oceanic slab is dipping towards the southeast. The map of subducting slabs (Figure 3.22) shows how the convergence between the Caribbean (CA) and continental South America (SA) plates decreases towards the east. At the longitude of Paria Peninsula, the CA-continental SA boundary is mostly strike-slip. The Atlantic domain is confined to northeastern Venezuela and Trinidad (i.e., roughly from longitude 63° to the east). In the Atlantic domain, the Atlantic oceanic slab is dipping towards the W-NW.

In summary, the plate tectonic architecture of northeastern Venezuela is defined by: (1) a strike-slip boundary that is superposed between the Caribbean and continental South America; and (2) the Atlantic subduction zone at a deeper level.

Velocity anomaly maps published by van der Hilst (1990) can also lend support to the previous conclusion. Figure 3.23 shows two velocity anomaly maps: one for a layer from 33 to 85 km of depth (layer 2; see Table 3.2), and the other for a layer from 245 to
**Figure 3.23.a.** Tectonic map of the Caribbean region as a reference frame for the velocity anomaly maps to be shown on the Figure 3.23.b. Meaning of the abbreviations: AvR, Aves Ridge; BbB, Barbados Basin; BBR, Barbados Ridge; BeR, Beata Ridge; Bmfz, Bucaramanga-Santa Marta Fault Zone; Bofz, Boconó Fault Zone; CaR, Carnegie Ridge; ChB, Chortis Block; CoB, Colombian Basin; CoR, Cocos Ridge; CP, Chiapas-Peten massif; CPT, Colombia-Peru trench; CsC, Cayman spreading center; CT, Curacao trench; CTr, Cayman Trough; EPfz, El Pilar fault zone; FBP, Florida-Bahama platform; GFr, Gulf of Fronseca; GrB, Grenada Basin; HE, Hess Escarpment; LADB, Lesser Antilles deformed belt; LAT, Lesser Antilles trench; MAT, Middle America trench; MAVP, Middle America volcanic province; MB, Maracaibo block; MPfz, Montagua-Polochic fault zone; MT, Muertos trench; NP, Nicoya peninsula; NPDB, Northern Panamá deformed belt; OFZ, Orozco fracture zone; PBFZ, Pedro Bank fracture zone; PFZ, Panamá fracture zone; PRT, Puerto Rico trench; SCDB, Southern Caribbean deformed belt; SwFZ, Swan fracture zone; ToB, Tobago Basin; TMVB, Trans Mexico volcanic belt; Yu, Yucatan; YuB, Yucatan basin; VeB, Venezuelan basin. From van der Hilst (1990).
Layer 2 (33 - 85 km)

Velocity anomalies. Phases: P, PP and pP

Layer 6 (245 - 312.5 km)

Velocity anomalies. Phases: P, PP and pP

Figure 3.23.b. Velocity anomaly maps for the layers 2 (33-85 km) and 6 (245-312.5 km). From van der Hilst (1990).
312 km of depth (layer 6). In the map for the layer 33 to 85 km, the velocity anomalies are sharply cut off on northeastern Venezuela, denoting the position of the strike-slip boundary system at this level of depth, the El Pilar fault system. In the map for the layer 245 to 312 km, an arcuate high-velocity structure below the Lesser Antilles continues into northeastern Venezuela and Trinidad. It could be evidence of how Atlantic oceanic subduction continues into continental South America.
CHAPTER 4

STRATIGRAPHY OF THE CARIACO AREA

4.1 Introduction

The Cariaco area is located offshore northeastern Venezuela, between La Orchila and La Blanquilla Islands to the north and the coast line from Cabo Codera to Araya Peninsula to the south (Figure 4.1).

In this study, the Cariaco area includes the Tuy-Cariaco Basin "sensu strictu" and the La Tortuga and the La Blanquilla Basins. The last two basins lie to the north of Tortuga Bank and Margarita Island. To the south, the Tuy-Cariaco Basin is composed of the following geologic elements: Northern Tuy-Cariaco sub-basin, Cubagua sub-basin, Cariaco trough, and the Ensenada de Barcelona shelf (Figure 4.1).

The Cariaco trough (Fosa de Cariaco) is the major geologic and geomorphic feature of the area. It has a maximum water depth of 1400 meters and is located between Tortuga Island to the north and the Ensenada de Barcelona shelf to the south.

This chapter provides stratigraphic data from wells drilled in the Cariaco area. These data have been integrated with the seismic profiles to constrain the timing of the different structural deformations. Based on it, a depositional and tectonic history of the Cariaco area will be proposed.
FIGURE 4.1. Bathymetric map showing the location of the different subbasins in the Cariaco area.
4.2. Stratigraphy

Cenozoic sedimentary rocks of variable thickness and facies overlie a Cretaceous igneous-metamorphic basement. This basement has been described in the previous chapter (section 3.3.2.) and is shown on Figure 4.2. The sedimentary section of the Cariaco area is best described in five units from bottom to top:

- Eocene
- Oligocene
- Miocene
- Pliocene
- Quaternary

All these units have been identified on seismic lines. In the Tuy-Cariaco Basin (e.g., Cubagua sub-basin), the Eocene and Oligocene units have been difficult to differentiate on seismic profiles; therefore they have been grouped into a single Paleogene unit. In most cases, the seismic data allow to divide the Miocene into Lower Miocene and Middle/Upper Miocene. In more favorable cases (e.g., in the La Tortuga Basin), the Middle Miocene can be distinguished from the Upper Miocene (see Panel-5).

Foldouts 1 to 5 are geological sections on which the stratigraphy of most of the wells drilled in the Cariaco area (Figure 4.3) are shown. Figure 4.4 illustrates the location of these sections. A summary of the stratigraphic data has been included in Table 4.1.
Figure 4.2 Distribution of basement, Cariaco area.
FIGURE 4.3. Location map of wells and stratigraphic columns used in the study of the Caríaco area.
FIGURE 4.4. Index map of geological sections in the Cariaco area (see Foldouts).
<table>
<thead>
<tr>
<th>GEOCHRONOLOGY</th>
<th>THICKNESS (M)</th>
<th>S</th>
<th>N</th>
<th>LITHOLOGY</th>
<th>PLANKTONIC FORAM BIOCHRONOZONES</th>
<th>CORRELATION w/ Keys, Margarita and surrounding area</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATERNARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RECENT</td>
<td>0.01</td>
<td>450/3650</td>
<td></td>
<td>Monotonous sequence of plastic clays with abundant shell debris.</td>
<td>N23/N22: Globorotalia truncatulinoides</td>
<td>CUMANA FM.</td>
</tr>
<tr>
<td>PLEISTOCENE</td>
<td>1.6</td>
<td>50/2150</td>
<td></td>
<td>Occasional thin sand intercalations.</td>
<td>N22/N18: Globorotalia truncatulinoides, P. obliquiloculata; G. margaritae.</td>
<td>CUBAGUA FM.</td>
</tr>
<tr>
<td>PLEISTOCENE</td>
<td>5.3</td>
<td>35/920</td>
<td></td>
<td>Clays and claystones with abundant shell debris and occasionally pyrite. Rare, thin, sandy intercalations.</td>
<td>N17-N14: Globorotalia acostaensis.</td>
<td></td>
</tr>
<tr>
<td>PLEISTOCENE</td>
<td>11.2</td>
<td>600/665</td>
<td></td>
<td>Lower conglomeratic/sandy interval is overlain by a shaly sequence with high glauconite content.</td>
<td>Poor planktonic foraminifera assemblages.</td>
<td></td>
</tr>
<tr>
<td>MIOCENE</td>
<td>16.6</td>
<td>300/1980</td>
<td></td>
<td>Claystone sequence with thin intervals of silts and fine grained sands.</td>
<td>N14-N8: G. stiakantes, G. tosiobita, G. tosiokibita; G. tosiokiba; G. peripheronodonta.</td>
<td>LAGUJA FM. OR MOTTLED CLAYS?</td>
</tr>
<tr>
<td>LATE</td>
<td>23.7</td>
<td>165/790</td>
<td></td>
<td>Silty shales with intercalations of fine grained sandstones at some intervals. Mottled shales and siltstones in Cubagua sub-basin.</td>
<td>NS-N4: G. peripheronodonta, Prasorbitaella glomerosa, Globigerinella insueca, C. starrhous; C. dissimilis, G. kugleri.</td>
<td></td>
</tr>
<tr>
<td>MIDDLE</td>
<td>36.6</td>
<td>40.0/1500</td>
<td></td>
<td>Brown calcareous shales. Mottled shales and siltstones in Cubagua sub-basin.</td>
<td>N9-N1: Globigerina angulifera, G. opima, opima and Globigerina ampliapertura.</td>
<td></td>
</tr>
<tr>
<td>LATE</td>
<td>57.8</td>
<td>&gt;325</td>
<td></td>
<td>Coarse sandstone and conglomeratic turbidites (in Cubagua sub-basin). Limestone with abundant large foraminifera and coralline algae (in North Toyo-Cadaco). Monotonous shale sequence with traces of sandstones and calcareous rocks (in the La Tonga and the La Sienilla Basins).</td>
<td>G. carabousaensis, Globigerinathela seminovulata, Truncorotalioides robi, G. lehneri.</td>
<td>LOS FRAILES FM.</td>
</tr>
<tr>
<td>EARLY</td>
<td></td>
<td>&gt;140</td>
<td></td>
<td>Volcanic to subvolcanic rocks of basic-intermediate composition (andesites/basalts/ diorites) which have been affected by a relatively low degree of metamorphism.</td>
<td></td>
<td>JUAN GRIEGO GROUP</td>
</tr>
<tr>
<td>PALEOCENE</td>
<td></td>
<td>144.0</td>
<td></td>
<td>Metamorphic rocks: quartzite, amphibolites, micaschists with quartz veins.</td>
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<tr>
<td>MASTRichtian</td>
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<tr>
<td>CAMpanian</td>
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<td>Santonian</td>
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<tr>
<td>CONAlictan</td>
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<tr>
<td>Turonian</td>
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<tr>
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<td>MASTRichtian</td>
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<tr>
<td>CRETAceous</td>
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<tr>
<td>ALBian</td>
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<td>Aptian</td>
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<td>Hauterivian</td>
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<tr>
<td>Valanginian</td>
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<td>Berriasian</td>
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<tr>
<td>JURASSIC</td>
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### SUMMARY OF CARIACO AREA

<table>
<thead>
<tr>
<th>RELATION</th>
<th>DEPOSITIONAL ENVIRONMENTS</th>
<th>TECTONIC EVENT</th>
<th>COMMENTS</th>
<th>OIL &amp; GAS</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MANA FM.</td>
<td>Inner to outer nortic shelf. Very shallow, high-energy coastal environment in some places into Escambray de Barcelona.</td>
<td>TECTONIC</td>
<td>Increase the strike-slip activity; W-E Right-Lateral El Pilar Fault, NW-SE Right-Lateral Margarita Fault.</td>
<td>GAS</td>
<td>QUATERNARY</td>
</tr>
<tr>
<td>NEGUA FM.</td>
<td>La Tortuga and La Blanquilla Basins: Inner to middle nortic shelf. North Toy - Caracas sub-basin: lower bathyal to middle nortic. Cuba sub-basin: middle nortic to coastal environment. Escambray de Barcelona: upper bathyal to inner nortic.</td>
<td>TRANSTENSION</td>
<td>Predominantly orientation for normal faults: NW-SE</td>
<td>GAS</td>
<td>LATE MIocene</td>
</tr>
<tr>
<td>MUNICA FM. OR</td>
<td>La Tortuga and La Blanquilla Basins: upper bathyal to middle nortic. North Toy-Caracas sub-basin: from shallow marine to shelf influence to middle nortic. Cuba sub-basin: lower bathyal to outer nortic. Escambray de Barcelona: estuarine coastal plain and shallow water marine.</td>
<td>TRANSFORMATION</td>
<td>Reverse faults with orientation NS0°-60°E are dominant, Reactivation of older fault. Normal faults are more abundant towards the south.</td>
<td>GAS &amp; OIL</td>
<td>EARLY MIDDLE MIocene</td>
</tr>
<tr>
<td>SALTED CLAYS</td>
<td>La Tortuga and La Blanquilla Basins: upper bathyal to outer nortic. Cuba sub-basin: continental deposits. Probably shallow marine deposition in the present Caracas Trough.</td>
<td>EXTENSION</td>
<td>In Early Miocene, extensional activity probably related to a transform tectonic setting.</td>
<td>GAS &amp; OIL (In turbidites)</td>
<td>?</td>
</tr>
<tr>
<td>HURDÍN MUSGOLO Fm.</td>
<td>La Tortuga and La Blanquilla Basins: lower bathyal. Cuba sub-basin: continental deposits. Probably shallow marine deposition in the present Caracas Trough.</td>
<td>COMPRESSION</td>
<td>In Oligocene - Eocene, extensional deformation may also be associated to a retreating subduction zone.</td>
<td>OIL</td>
<td>Oligocene</td>
</tr>
<tr>
<td>OPORTO Fm.</td>
<td>La Tortuga and La Blanquilla Basins: lower bathyal. North Toy - Caracas sub-basin: shallow marine to reef environment. Cuba sub-basin: lower bathyal (Deep Marine).</td>
<td>EXTENSION</td>
<td>Oligocene compression in Cuba sub-basin may explain the contact between Eocene turbidites and Oligocene continental deposits.</td>
<td>EOCENE</td>
<td>PALEOC.</td>
</tr>
<tr>
<td>FRAILES FM.</td>
<td>Volcanic arc setting.</td>
<td>DEVELOPMENT OF VOLCANIC ARC</td>
<td>Radiometric ages between 65.4 and 78.3 ± 3.9 Ma indicate the time of metamorphism.</td>
<td>EARLY LATE CRETACEOUS</td>
<td>JURASSIC</td>
</tr>
<tr>
<td>PIN GRIEGO GROUP</td>
<td>Volcanic arc setting.</td>
<td>PASSIVE MARGIN</td>
<td>Fitig event, at the border of the Passive Margin, associated with mid-ocean ridge volcanism.</td>
<td>EARLY LATE CRETACEOUS</td>
<td>JURASSIC</td>
</tr>
</tbody>
</table>
4.2.1. Eocene

The Eocene has been penetrated in the northern Tuy-Cariaco sub-basin (i.e., between the La Tortuga high and the Cariaco trough), and in the La Tortuga and the La Blanquilla Basins. The Eocene may also be present in the Cubagua sub-basin.

In the La Tortuga and the La Blanquilla Basins, the Eocene is characterized by a thick monotonous deep marine (lower bathyal) shale sequence, with traces of sandstones and limestones (Haak, 1980; Talukdar and Bolivar, 1982). A well drilled in the La Tortuga Basin (i.e., to the northwest of Tortuga high, Figure 4.3) found 2951' of shales. The upper 2920' were dated as Late Eocene (Figure 4.5) and are conformably overlain by Oligocene shales.

In the northern Tuy-Cariaco sub-basin, the Eocene consists of an upper section of shallow water platform limestones (packstones and wackestones) with abundant algae, corals and larger foraminifera. Haak (1980) correlated this section with the limestones of Punta Mosquito in Margarita. The lower section is characterized by the intercalations of deep water shales with recrystallized limestones. Both the upper and lower sections are Middle Eocene age. The abrupt change from the bathyal environment of the lower section to a shallow marine reef environment of the upper section suggests an unconformity at this contact level. As will be discussed later this unconformity may be related to uplifts resulting from an early compressional event.

The top of the Middle Eocene platform limestones in the northern Tuy-Cariaco is unconformably overlain by Late/Middle? Miocene fluviomarine sediments [see Sections 1 and 2 (Foldouts 1 and 2)].
Figure 4.5. Sedimentary cycles of the La Tortuga Basin (well-1). Redrawn after Haak (1980).
In the Cubagua sub-basin (well-4, Figure 4.3), a possible Eocene age is represented by coarsely-grained clastic rocks deposited in a deep marine environment (Goddard, 1986). These sediments are barren of index fossils. An Eocene age was suggested by Evans (1982) based on lithostratigraphic similarities to the Punta Carnero Group in Margarita Island. On Section 3 (Foldout 3), a correlation between the Eocene? coarse-grained sandstones (also conglomeratic) of the Cubagua sub-basin and the Punta Carnero Group is suggested.

The Punta Carnero Group is exposed in the southern part of Margarita Island (González de Juana, 1947; González de Juana et al., 1980). It was divided into three formations: Las Bermúdez Formation, El Dátil Formation and Punta Mosquito Formation (González de Juana, 1968) [see Margarita column in Foldout 3]. These formations are described by Muñoz (1973) as intimately related facies within a flysch basin. The Las Bermúdez Formation consists of a shaly section containing lenses of limestones, sandstones and conglomerates and boulder-size particles of volcanic rocks, cherts, metamorphic rocks and quartz (Kugler, 1957; González de Juana et al., 1980). The El Dátil Formation is a monotonous brown-gray shale sequence with some very thin intercalations of sandstones and bioclastic limestones (Muñoz, 1973; González de Juana et al., 1980). The Punta Mosquito Formation represents a more clastic facies than the underlying El Dátil Formation. The lower section of the Punta Mosquito Formation consists of orbitoidal limestone beds intercalated with shales, some calcareous sandstones and conglomerates. The upper section of the Punta Mosquito is predominantly shale and siltstone with intercalations of calcareous sandstones and sporadic limestone beds.
(González de Juana et al., 1980). Bermúdez and Gamez (1966, p. 217) indicate the age of the Punta Mosquito Formation as Upper Middle Eocene.

4.2.2. Oligocene

In the La Tortuga and the La Blanquilla Basins (well-1, well-6 and well-7 on Foldouts 1 and 2), the Oligocene sections consist of monotonous shale sequences, deposited in a bathyal environment (Evans, 1983). Regarding well-6 (Foldout 2), it appears that the Oligocene (540' thick) is a fault sliver, structurally overlying the Lower Miocene.

In the Cubagua sub-basin, a thick sequence of continental deposits overlies the Eocene unit (well-3 on Foldouts 1 and 3). This Oligocene sequence is composed of mottled shales and sandstones. It has been correlated with the "Mottled Clays" of Cubagua-1 (Evans, 1982), located about 10 km to the northwest from well-3. As mentioned before, the Oligocene and Eocene sequences of the Cubagua sub-basin appear as a single seismic stratigraphic unit which in this study is defined as the Paleogene unit.

In the Cariaco trough, the seismic sections B19 and BD (Panel-1 and Panel-2) show the presence of the Oligocene. However, Figure 4.6 illustrates an isotime map which shows that the Paleogene sedimentation mostly occurred to the north of the Tortuga-Margarita basement high (i.e., in the La Tortuga and the La Blanquilla Basins). Between the Tortuga-Margarita high and the Cariaco trough, the occurrence of the Paleogene unit is irregular and more limited (Figure 4.6). It probably was deposited in
FIGURE 4.6. Isotime map of the Paleogene Unit (Cariaco area)
continental or shallow marine conditions. The Paleogene is absent to the south of the 
Cariaco trough (i.e., in Ensenada de Barcelona shelf).

4.2.3. Miocene

4.2.3.1. Early Miocene

In the La Tortuga and the La Blanquilla Basins, the Early Miocene consists of 
silty shales with intercalations of fine to very coarse-grained sandstones. The sandstones 
of the lower section of the Early Miocene have been interpreted as deep water turbidite 
deposits (Haak, 1980; Evans, 1983). This interval is overlain by shales deposited in upper 
bathyal to outer neritic conditions. The uppermost Lower Miocene section is a 
sandy/shaly sequence interpreted as a coastal offlap sequence [Haak, 1980 (Figure 4.5)].

In the northern Tuy-Cariaco sub-basin, where well-6 is located (Foldout 2), the 
Early Miocene sequence underlies the older Oligocene along a tectonic contact (Evans, 
1982). The sequence is characterized by shales with sandstone intercalations in the lower 
intervals while the upper part consists predominantly of shales.

Both the Oligocene and the Early Miocene in the Cubagua sub-basin are believed 
to be represented by mottled shales and sandstones deposited in continental conditions 
(e.g., Evans, 1983) [see Table 4.1 and Foldout 1].
4.2.3.2. Middle Miocene

Paleontologically, the Middle Miocene is only recognized in the La Tortuga and the La Blanquilla Basins (well-1 and well-7, Figure 4.3). This unit consists mainly of claystones with thin intervals of siltstones and fine-grained sandstones. Figure 4.5 shows the overall regressive nature of this sedimentary unit: the depositional environment changes from bathyal at the base of the sequence to middle neritic at the top (Haak, 1980). As can be seen from Section BJ (Figures 4.7 and 4.8), the Middle Miocene is unconformably overlain by the Late Miocene. The calibration of this unconformity is given by the stratigraphic column of well-1 (Foldout 1).

4.2.3.3. Late Miocene

In the La Tortuga and the La Blanquilla Basins, the Late Miocene consists of a claystone sequence with a few thin intercalations of fine-grained sandstones deposited in an upper bathyal to outer neritic environment (Haak, 1980; Evans, 1983). The Late Miocene sequence is discordantly overlain by the Pliocene (see the right side of Sections B6 and B7 in Panel-4). Towards the east of the La Blanquilla Basin, this unconformity is greater and in some cases the Late Miocene is absent (e.g., well-7 on Foldout 3 and also see also the right side of Section BI in Panel-3).

In the northern Tuy-Cariaco sub-basin, a fluviomarine sequence directly overlies the Eocene (see Foldouts 1 and 4). It consists mainly of sandstones and conglomerates. Since this sandy sequence is almost barren of microfossils, its age is speculative. Seismic interpretation of this study assigns this interval to the Late-Middle Miocene (Figure 4.9).
FIGURE 4.8. Example of seismic interpretation with well control in the La Tortuga Basin (Section BJ). See its location on Figure 4.7.
FIGURE 4.9. Example of seismic interpretation with well control in the northern Tuy-Cariaco sub-basin (Section B44). See its location on Figure 4.7.
The upper section of the Late Miocene consists of claystones and shales deposited in a middle/outer neritic environment (e.g., Evans, 1983).

In the area of Cubagua (e.g., well-4 [Foldout 5]), the Late Miocene is composed predominantly of claystones and clays deposited in a bathyal environment (e.g., Talukdar and Bolivar, 1982).

On the Ensenada de Barcelona shelf, the Late Miocene was found in well-10, well-11 and well-12 (Foldouts 2 and 3). It directly overlies the basement (Panel-7 and Panel-8). Towards the south (e.g., in well-10 and well-11), the Late Miocene consists of intercalations of silty shales and sandstones deposited in a deltaic complex (e.g., Haak and Pittelli, 1981). In well-11 (Foldout 3), a thick sandy interval of approximately 380' overlies the basement. On the north of Ensenada de Barcelona shelf, the Late Miocene is made of claystones and shales deposited in an inner to middle neritic environment (e.g., well-12 in Foldout 2).

### 4.2.4. Pliocene

In the La Tortuga and the La Blanquilla Basins, a thin Pliocene unit (Foldouts 2 and 4) consists of calcareous clays deposited in a middle to inner neritic environment (e.g., Talukdar and Bolivar, 1982). In these basins, most of the Pliocene has been eroded. Therefore, the Late Pliocene or Quaternary sequence discordantly overlies the Miocene units (see Sections BM and BI in Panel-3).

In the northern Tuy-Cariaco sub-basin, Cubagua sub-basin and the Ensenada de Barcelona shelf, the Pliocene unit consists of clays with thin intercalations of fine
sandstones and siltstones (e.g., Foldouts 3 and 4). In these basins, the depositional environments range from bathyal to inner neritic (e.g., Goddard, 1986).

4.2.5. Quaternary

In general, the Quaternary sequence consists of a monotonous section of clays with abundant shell debris deposited in a middle to inner neritic environment (e.g., Evans, 1983). In the northern Tuy-Cariaco sub-basin and on the Ensenada de Barcelona shelf, thin intercalations of sandstones are also present in this sequence.
CHAPTER 5

STRATIGRAPHY OF THE CARÚPANO AREA

5.1 Introduction

The Carúpano area is the most northeastern part of the Venezuelan continental shelf, north of the Paria Peninsula (Figure 5.1). It covers approximately 30,000 square kilometers.

Galaviss and Louder (1970) referred to the Carúpano area as the Margarita - Tobago shelf in their geomorphologic study of the continental margin of northern South America. The width of the shelf, defined by the 200 m isobath to the north and by the mountain-front coastline of the Araya-Paria Peninsula and the Trinidad Northern Range to the south, is from 80 to 100 km. The average inclination of the shelf varies from zero to 1 degree.

Between 1978 and 1982, PDVSA's exploration effort led to the drilling of 20 wells in the area (Figure 5.2). Gas was found in 14 of these wells. An economic-geological synthesis of this exploration program was prepared by Pereira et al. (1984). Detailed reports of the paleontology and biostratigraphy of the Carúpano area were made by Castro and Mederos (1984) and Furrer (1984). Much of the stratigraphy reviewed in this chapter is based on these studies.
FIGURE 5.1. Bathymetric map showing the location of the major structural features in Carúpano area.
FIGURE 5.2. Location map of wells drilled in the Carúpano area. Bigger circles correspond to the wells used in the stratigraphic correlations (Foldout 8, 9, 10 and 11).
To define the structural framework, the same methodology used in the Cariaco area was also applied in the Carúpano area; i.e., the stratigraphic information was integrated with the seismic interpretation (e.g., Figures 5.3 and 5.4).

5.2. Stratigraphy

In the Carúpano area, Upper Cretaceous and Tertiary sedimentary rocks unconformably overlie a Mesozoic igneous - metamorphic basement. This basement which has been related to a subduction setting (Talukdar, 1983) is described in Chapter 3 (Section 3.3.4.) and shown on Figure 5.5. Stratigraphic columns of wells used to construct generalized geological sections (Foldouts 7, 8, 9 and 10) reveal the approximate distribution of different types of basement. Figure 5.6 shows the location of the geological sections.

The sedimentary section will be described in ascending order. Foraminifera were used almost exclusively for age and environment interpretations. Appreciable numbers of planktonic foraminifera were found in Cretaceous through Recent sediments (Furrer, 1984). However, their distribution is relatively uneven; i.e., they are very scarce or totally absent in certain areas. It was particularly difficult to separate the Upper Miocene from the Lower Pliocene in the entire Carúpano area. Thus, for the present study it seems safer to group them together in one unit. In the Caracolito sub-basin, a similar situation occurs; there the Upper Eocene and Oligocene units are difficult to separate one from another on paleontological grounds. A summary of the stratigraphic data is presented in Table 5.1.
Figure 5.3. Example of seismic interpretation with well control. Section A23 illustrates NE-trending thrust faults with a southeast vergence. A Late Miocene - Early Pliocene folding is indicated by onlaps against the Caracolito Anticline. Abbreviations: EM, Early Miocene; EOC, Eocene; EP - LM, Early Pliocene-Late Miocene; L-M PLIOC, Late-Middle Pliocene; ME, Middle Eocene; MIOC, Miocene; MM B, Middle Miocene "B"; O-E, Oligocene-Eocene; OLIGOC, Oligocene. Location shown in Figure 5.11.
Figure 5.5. Distribution of Basement, Carúpano Basin. Based on Talukdar (1983) and Pereira et al. (1984).

**BASEMENT INFORMATION**

○ **CALCALKALINE BASALTIC ANDESITES**
  
  **Affinity:** Mature Island arc
  
  **Age:** Eocene-Oligocene (K-Ar whole-rock ages of 38.6±2.0 and 33.5±1.8 MA)
  
  **Comment:** Present hydrothermal alteration under submarine conditions

□ **SUBMARINE BASALTS**
  
  **Affinity:** Primitive Island arc
  
  **Age:** Late Cretaceous (K-Ar whole-rock ages between 87.0±9 and 102.2±10 MA)
  
  **Comment:** Massive and Pyroclastic rocks

△ **METABASALTS**
  
  **Affinity:** MORB
  
  **Age of metamorphism:** probably Late Cretaceous
  
  **Comments:** (1) Basalts affected by a low grade regional metamorphism of high P/T
  
  (2) Basalts might be part of the Jurassic ocean floor

**NOTE**

Black fill: Core sample
White fill: Cutting sample with the same material
FIGURE 5.6. Index map of geological sections in the Carúpano area (see Foldouts 7, 8, 9 and 10); F, foldout.
### TABLE 5.1: GEOLOGIC SUM

<table>
<thead>
<tr>
<th>GEOCHRONOLOGY</th>
<th>FORMATION NAME</th>
<th>THICKNESS (M)</th>
<th>LITHOLOGY</th>
<th>PLANISTIC FORAMINIFERA</th>
<th>CORRELATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATERNARY</td>
<td>RECENT</td>
<td>150/700</td>
<td>Molluscs and bryozoan bank debris, coral reef rubble, and skeletal limestone fragments. Also some shales, calcareous sandstone, pyrite nodules, glauconites and few reworked clay fragments.</td>
<td>Globorotalia truncatuloides, Pseudolaria finidii, Globorotalia hirsuta, Globorotalia fimbriata.</td>
<td>EL MANGLO</td>
</tr>
<tr>
<td></td>
<td>PLEISTOCENE</td>
<td>600/690</td>
<td>Coral reef, molluscs-bryozoan bank rubble, and calcareous intercalation of sandstone, shales, siltstone.</td>
<td>G. dutertrei, Pseudolaria obliquiloculata, Globigerina ruber, G. tasmanica, G. mcmickeni.</td>
<td>CUMAN</td>
</tr>
<tr>
<td></td>
<td>PLIOCENE</td>
<td>70/2070</td>
<td>In the southwestern part of the Caraparo area and the Los Testigos platform: Sandtone, calcareous sandstone, and molluscs-bryozoan bank bioclastics. In the rest of the Caraparo area: Shales, siltstones with pyrite nodules throughout.</td>
<td>G. margaretiae, Sphaeroenellopsis seminula, Sph. sp., Calcidiscus, G. hemprichii, G. acostaensis, G. eocrassata, Globigerina antiqua, Pseudolaria primula, G. pleistocenica, G. pseudoplicatula, G. kuhniensis.</td>
<td>CUBAGU</td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>23.7</td>
<td>Alternation of shales, siltstones, with coarse quartz sandstone, quartzite, microbreccias and metamorphic fragments.</td>
<td>Globigerina doroense, Globorotalia opima, operata.</td>
<td></td>
</tr>
<tr>
<td>OLIGOCENE</td>
<td>LATE</td>
<td>35.6</td>
<td>Calcilutites benthic associated.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MIDDLE</td>
<td>40.0</td>
<td>Alternation of shales, sandstones, calcarenites and bioclasts limestones.</td>
<td>Porticulosphera semi-involuta, Globigerina ampliaperture, Globorotalia ceratozona, pomeroni, Truncorotalia rohri, Globorotalia lehmanni, Globigerinites barri, Globorotalia densa, G. spinulosa, G. calcareo-inflata, Globorotalia aragonensis.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>52.0</td>
<td>Alternation of shales, sandstones, calcarenites and bioclasts limestones.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PALEOCENE</td>
<td>LATE</td>
<td>57.8</td>
<td>Metamorphic material are abundant at certain levels.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MIDDLE</td>
<td>60.4</td>
<td>Dark colored pelagic limestones and shales</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>97.5</td>
<td>Volcanic rocks (massive and pyroclastic breccias) in sequence with volcanoclastics and sedimentary rocks such as: pelagic limestone and shales, radiolarian chert, and calcareous sandstone.</td>
<td>Hedbergella, Heterohastis, Globotruncana and few Rotaliopsis cf. appendiculata.</td>
<td>WASHIEKEI (Foster, 1984)</td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>144.0</td>
<td>Alternation of metaquartz, arenites phylites, quartzite and rare quartz schists. Metabasites (essentially nonporphyritic) that underwent low grade of metamorphism.</td>
<td>The metamorph</td>
<td></td>
</tr>
<tr>
<td>JURASSIC</td>
<td>MIDDLE</td>
<td>≥1135</td>
<td>LEKNUXES COMPLEX</td>
<td>UNECONOMITIC OR FAULT?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>≥620</td>
<td>BOCAS COMPLEX</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

* Formational names proposed by Castro and Mederos (1985)
** Generalized lithologic column from the Pari Sub-basin (PS) at the south to the Los Testigos

---

** Formation names: **
- Maestrichtian
- Campanian
- Santonian
- Coniacian
- Turonian
- Lower Cenomanian
- Early Cenomanian
- Ablattan
- Aptian
- Barremian
- Hauterivian
- Valanginian
- Berriasian
- Jurassic
- Early Jurassic
- Late Jurassic
- Cretaceous
- Late Cretaceous
- Early Cretaceous

** Lithologic column names: **
- Los Testigos Complex
- Meullones Complex
- Bocas Complex
<table>
<thead>
<tr>
<th>DEPOSITIONAL ENvironments</th>
<th>TECTONIC EVENT</th>
<th>COMMENTS</th>
<th>OIL &amp; GAS</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner to middle platform type sedimentation</td>
<td>TECTONIC TRANSPRESSION, in the easternmost part of the Carupano area.</td>
<td>Exception for some NE-trending thrust faults in the Bocas High, the Carupano basin &quot;sensu strictu&quot; is characterized by normal faults trending NW-SE to W-E.</td>
<td>GAS</td>
<td>QUCKERN.</td>
</tr>
<tr>
<td>Inner to middle neritic shelf conditions (development of coral reef complexes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In the southeastern part of the Carupano area: very shallow-water conditions (i.e., inner neritic, Bank, Mesa, Keys and lagoonal areas). In the Los Testigos platform: middle to outer neritic. In the rest of the Carupano area: the depositional environment changes from bathyal at the base to outer-neritic at the top.</td>
<td>TECTONIC TRANSITION, within the basin and along the Carupano rift.</td>
<td>The transition in the southeastern part of the Carupano area is coeval with a mild compression on the Carapito anticline. It might imply a small c锁lomaccline rotation.</td>
<td>GAS</td>
<td>MIOCENE</td>
</tr>
<tr>
<td>Bathyal environment conditions (waterdepths of at least 1000 to 1500 feet) affected by turbidity currents.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On pre-Miocene positive areas (e.g., the Paso High, the Los Testigos Platform), the depositional environment is a shallow water carbonate platform. Between the Margarita-Los Testigos Platform and the Paso High, the Early Miocene was deposited in bathyal conditions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathyal with turbiditic deep water deposition</td>
<td>TECTONIC TRANSFORMATION, at an advanced stage of development</td>
<td>Inversion of the earlier extensional structures, as well as, NE-trending thrust faults are results of compressional forces related to the WNW-ESE oblique convergence between the Caribbean and South American plates.</td>
<td>GAS?</td>
<td>?</td>
</tr>
<tr>
<td>Island arc setting at an advanced stage of development</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep water conditions affected by turbidity currents.</td>
<td>EXTENSION, probably related to a tectorform drop.</td>
<td>Probably extensional activity related to a transform drop. Normal faults parallel to the Margarita-Los Testigos High (SW-NE trend at the present position).</td>
<td>GAS (in turbidites)</td>
<td>EOCENE</td>
</tr>
<tr>
<td>Submarine volcanic arc setting</td>
<td>DEVELOPMENT OF VOLCANIC ARC, Collision of volcanic arc vs. continental margin</td>
<td>Radiometric ages between 87 ± 9 and 102.2 ± 10 Ma (Abien to Santorini)</td>
<td></td>
<td>CREATACEOUS</td>
</tr>
<tr>
<td>Northwestern edge of South America Passive Margin</td>
<td>PASSIVE MARGIN</td>
<td>Rifting event, at the border of the Passive Margin, associated with mid-oceanic ridge volcanism</td>
<td></td>
<td>JURAS.</td>
</tr>
</tbody>
</table>

*Punta Moqueite Fm, El Dali Fm, Las Bermudez Fm.*
5.2.1. Cretaceous

5.2.1.1. Early Cretaceous

In the Carúpano area, Lower Cretaceous sedimentary rocks have been drilled only in the Bocas high to the north of the Paria Peninsula (well-21 in Figure 5.2). They are brownish skeletal limestones, containing green algae and mollusc fragments, that were deposited in a shallow water condition. As can be seen on Foldout 7 or Foldout 9 (well-21), these Lower Cretaceous carbonates are in an abnormal stratigraphical or structural relationship with the underlying Upper Cretaceous volcanic epiclastics and sedimentary beds.

A possible correlation between this Early Cretaceous sequence and the carbonates of the Barranquin - El Cantil sequences of Aptian - Early Albian age has been suggested by Furrer (1984).

5.2.1.2. Late Cretaceous

The sedimentary rocks of Late Cretaceous age include three facies: epiclastic and mixed pyroclastic-sedimentary facies, pelagic facies and clastic facies (Talukdar, 1983). The sandstones of the clastic facies are very coarse to very fine grained. Well-26 and well-28 (Foldout 8) represent examples of sites where this wide variety of Upper Cretaceous rocks of sedimentary and volcanic origin was penetrated.

The most common microfossils into the Upper Cretaceous sequence are Radiolaria; their presence points to deposition in water depths ranging from a few hundred to thousands of meters. (Castro and Mederos, 1985)
The whole Upper Cretaceous sequence of the Carúpano area has been correlated with the Washikemba Formation (see Chapter 3, Section 3.4.4) of Bonaire (Furrer, 1984).

To the north of the San Juan de las Galdonas High and the Patao High (Figure 5.1), Paleogene units unconformably overlay the Upper Cretaceous basement. On these highs and farther to the south, the Upper Cretaceous is unconformably overlain by the Miocene (see Figure 5.7 and see also Foldout 9). As mentioned before, a unique situation happens in well-21 (the Bocas High) where the Lower Cretaceous carbonates overlay the Upper Cretaceous (Foldout 9). This could be due to reverse faulting related to a major right-lateral strike-slip system that is inferred on the northern coast of the Araya-Paria Peninsula. Another option could be that these Lower Cretaceous rocks may have slid into a paleo-trough where the Upper Cretaceous sediments were laid down (Furrer, 1984)

5.2.2. Eocene

5.2.2.1. Early - Middle Eocene

The oldest Tertiary sedimentary rocks that have been paleontologically documented in offshore northeastern Venezuela are of Early to basal Middle Eocene age (e.g., Furrer, 1984). They were penetrated in the alignment that extends from the Tigrillo structure at the southwestern end to the Caracolito sub-basin on the northeast (Figure 5.1). Foldout 10 shows a geological section along this tectonic alignment, which illustrates that well-23, well-24 and well-29 penetrated this interval.
FIGURE 5.7 Section A1 shows how the basement is unconformably overlain by Paleogene units to the north of the Patao High; on and to the south of it, Miocene units discordantly overlay the basement. Note the push-up structure on the southern end of the section. Abbreviations: EOC, Eocene; MID, Middle; MIOC, Miocene; MM A, Middle Miocene "A"; OLIGOC, Oligocene; PLIOC, Pliocene. Location shown in Figure 5.11
The Lower to basal Middle Eocene consists of dark colored pelagic limestones and shales deposited in deep water conditions (Figure 5.8). Occasionally siltstone, sandstone and chert are found within this sequence in the Caracolito sub-basin (e.g., well-29). It is of interest that the Lower Eocene in well-24 (see Foldout 10) is overthrust by mostly volcanic rocks (basalts) and different types of schists; this Middle to Upper Eocene igneous-metamorphic occurrence is probably related to a mature island arc similar to the Los Testigos complex. Well-29 is located close to the axis of the Caracolito sub-basin (see Section A21 in Panel-12) and encountered by far the thickest Middle Eocene section in the offshore so far.

The upper intervals of the Middle Eocene are characterized by shale, siltstone, sandstone, bioclastic calcarenite and limestone with larger foraminifera and algae. Volcanoclastics are abundant at certain levels. Deep water sedimentation prevailed during the whole Middle Eocene (Figure 5.8). The abundant carbonates within the Middle Eocene, particularly in the Caracolito sub-basin, are probably calcareous turbidites with clasts derived from shallow water reefs and algal banks (Furrer, 1984) which at that time fringed the Los Testigos platform.

Castro and Mederos (1985) suggested a formal formational name for the entire Lower - Middle Eocene unit, i.e., the Tigrillo Formation which they correlated with the Punta Carnero Group in Margarita Island.
Figure 5.8. Stratigraphy of the Caracolito Sub-Basin, Carúpano Area, (well-29).
5.2.2.2. Late Eocene

A thin layer (210 feet) of Upper Eocene sedimentary rocks is suggested on well-23 (Tigrillo, see Foldout 10). But because of the bad preservation of planktonic foraminifera, no definite answer can be given. No paleontologic evidence supports the Late Eocene date suggested for well-29 in the Caracolito sub-basin (Foldout 10). Therefore in the Carúpano area, the Upper Eocene and the lower part of the Oligocene have been seismically combinated into a single unit (see Figure 5.3).

As mentioned in Chapter 3 (Section 3.3.4.) and shown on Foldout 7 (well-31), the Late Eocene of the Carúpano area is also characterized by the volcanics rocks (calc-alkaline basaltic andesites) that constitute the Los Testigos complex. K-Ar ages of 38.6 ± 2.0 Ma and 33.5 ± 1.8 Ma (Talukdar, 1983) suggest that volcanism continued during the Earliest Oligocene.

5.2.3. Oligocene

Like the Eocene, Oligocene sedimentary rocks were penetrated in well-23, well-24 and well-29 (Foldout 10). The Oligocene consists of alternating shale, siltstone with coarse quartz sandstone, quartzite and microbreccias with metamorphic fragments. The poor sorting and the different composition of the particles suggest continuous deposition of deep water turbidites during the Oligocene (Figure 5.8).

On seismic profiles (Panel-10, Panel-11 and Panel-12), a major unconformity has been identified within the Oligocene. The best expression of this unconformity occurs on the Caracolito sub-basin (see Section A21 in Panel-12 and see also A3 in Panel-10). This
unconformity suggests a deep water erosion following the inversion of the Eocene halfgraben.

The contact of the Oligocene with the overlying Lower Miocene is discordant in the west, gradually changing to concordant in the east (Panel-11). The Oligocene was named the Caracolito Formation by Castro and Mederos (1985).

Figure 5.9 is an isotime map of the Paleogene which shows continuous deepwater sedimentation from the southeastern part of Margarita Island to the Caracolito sub-basin. The greater thicknesses of the Paleogene occur toward the northeast where the tilting and extension of the basement has been more pronounced. In some areas located to the south of the Margarita-Los Testigos platform, the Lower?-Middle Eocene constitutes the thicker part of the Paleogene. Examples are shown on Section A6 (see Figure 5.10 and also Panel-10) situated to the southeast of Margarita Island and on Section A21 (Panel-12) that cross the Caracolito sub-basin. The Paleogene is absent on and to the south of the San Juan de las Galdonas High and the Patao High.

To the northwest of the Margarita-Los Testigos platform, Figure 5.9 suggests the continuation of the La Blanquilla Basin where a thick Paleogene fills another halfgraben system (see Foldout 13).
NORTH VENEZUELA
CARUPANO AREA

ISOTIME MAP
PALEogene UNIT

LEGEND

- STRIKE-SLIP (Arrows show direction on displacement)
- REVERSE FAULT (Triangle on upthrown side)
- NORMAL FAULT (Bars on downthrown side)
- INFERRED FAULT
- 1° CONTOUR LINE
- WELL LOCATION

SEISMIC CONTOUR INTERVAL
0.5 SEC. (TWT)

0.0
0.5
1.0
1.5
2.0
2.5
3.0

50 km

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FIGURE 5.9 Isotime map of Paleogene unit (Carúpano Area).
Figure 5.10.a. Section A6 shows a marked extensional deformation during the Middle Eocene. Note the angular unconformity between the Lower Middle Miocene unit (Middle Miocene "A") and the Late Miocene - Early Pliocene unit as a result of the Neogene tectonic inversion. Abbreviations: EM, Early Miocene; EOC, Eocene; ME, Middle Eocene; MIOC, Miocene; O-LE, Oligocene - Late Eocene; OLIG, Oligocene; PLIOC, Pliocene. Location shown in figure 5.11.
Figure 5.10.b. Reconstruction of N-S section in the SE Margarita sub-basin.
5.2.4. Miocene

5.2.4.1. Early Miocene

Except for the Bocas High, the San Juan de las Galdonas High and some areas of the Patao High, the Early Miocene was deposited over much of the Carúpano area (Panel-10 and Panel-11).

Cross-sections illustrating the different environmental conditions, in which the Early Miocene was deposited, are shown on Foldouts 7 and 9. To the north of the Patao High (see Foldout 9), i.e., within the Paleogene troughs, the Early Miocene is characterized by deep water sedimentation which consists of shale, siltstone, and sandstone with some pyrite. Metamorphic and pyroclastic fragments were also found in the Early Miocene of this area (e.g., well-24 in Foldout 10).

On the Patao High and the Los Testigos Platform (Foldouts 7 and 9 and see also Foldout 8), the Early Miocene is mostly represented by shallow water platform carbonates. Glaucolithic limestone and calcarenite are commonly found in wells drilled in these areas. Conglomerates with volcanic and metamorphic components are present in some cases (e.g., well-22 [Rio Caribe] in Foldout 8). On the Los Testigos Platform, the Early Miocene is also characterized by shale and siltstone (see well-31 in Foldout 7).

5.2.4.2. Middle Miocene

The Middle Miocene was deposited in a bathyal environment (water depths of at least 1000 to 1500 feet). According to Furrer (1984), the Middle Miocene was the time of
maximum water depths across the Carúpano Basin. The lithologies that characterize this period are mainly shale and siltstone with pyrite nodules. Sandstone, limestone fragments, quartz pebbles, metamorphic material and volcanoclastics are also characteristic for the Middle Miocene. These clastics were probably fed into a deep-water environment by turbidity currents.

The Middle Miocene is recognized in almost all the wells of the Carúpano area. Castro and Mederos (1985) grouped the Early Miocene and the Middle Miocene into a single unit, i.e., the Tres Puntas Formation.

5.2.5. Late Miocene / Early Pliocene

As mentioned previously, the Late Miocene has not been clearly documented in the Carúpano area, mainly because of the nature of its marker fossils. They are the planktonic foraminifera Globorotalia acostaensis and Globorotalia humerosa which are not limited to the Late Miocene but range up into the Early Pleistocene (Furrer, 1984). Therefore the Miocene-Pliocene boundary cannot be defined with certainty. It was decided to group the Late Miocene together with the Early Pliocene.

Except for Section AA in Panel-11 in which an internal unconformity within the Late Miocene - Early Pliocene could represent the top of the Miocene, there is no seismic evidence of a possible stratigraphic break within this unit.

Upper Miocene to Lower Pliocene sedimentary rocks have been found in all the wells drilled in the Carúpano area. In the southermost part of the Carúpano area (i.e., to
the north of the Paria and Araya Peninsulas), the lower section of the Late Miocene-Early Pliocene unit consists mostly of sandstone, calcareous sandstones, occasionally interbedded with siltstone and shale (see well-21 in Foldout 7). The upper section is characterized by calcareous sandstones, mollusc and bryozoan bioclastics, and with minor amounts of chalk, pyrite nodules and metamorphic clastic fragments. Both sections were deposited in very shallow water conditions, i.e., in inner neritic, littoral, inlets, bays and lagoonal areas.

In the Patao area (well-22, well-25, well-26 and well-28 in Foldout 8), the Late Miocene - Early Pliocene is composed predominantly of shale, siltstone with pyrite nodules throughout. It also contains a lesser degree of sandstones, with volcanoclastic, metamorphic and rare limestone fragments. Sandstone reservoirs with biogenic gas have been found in this unit. In this area, the deep-water deposition that characterized the Middle Miocene continued into the lower half of the Early Pliocene (Pereira et al., 1984). At the end of the Early Pliocene, a middle to outer neritic environment prevailed. Some of the gas-bearing sandstones were deposited in the context of turbiditic cycles (e.g., in the Mejillones Field [well-25]) and others were deposited in neritic shelf settings (e.g., in Patao and Dragón Fields [well-26 and well-28 respectively]).

From the Tigrillo structure to the Caracolito sub-basin (Foldout 10), the Late Miocene-Early Pliocene consists mainly of shale, siltstone with glauconite and pyrite nodules. Occasionally appreciable sand-bodies were found in well-23 (Tigrillo) and in the upper section of well-30 (Uquire). The depositional environment of the Late Miocene -
Early Pliocene is overall regressive and changes from bathyal at the base to outer/middle neritic at the top.

On the Los Testigos Platform (well-31 in Foldout 7), the Late Miocene-Early Pliocene consists of calcarenite, sandstone, glauconitic shale, with pyrite nodules and limestone fragments. In this area, the depositional environment is middle to outer neritic (Furrer, 1984).

Sections A3 and A4 in Panel-10 as well as Sections A21 and A22 in Panel-12 show how the Late Miocene-Early Miocene unit thins by onlap against the Caracolito Anticline. The greater thicknesses of the Late Miocene-Early Pliocene unit occurs in the Rio Caribe area (see Section A4 and Foldout 8) and in the Paria sub-basin (see Section AA in Panel-11 and see also Foldout 7).

5.2.6. Middle to Late Pliocene

In some wells, the Middle Pliocene has been separated from the Late Pliocene. In these cases, the Middle Pliocene has been defined to include sequences between the top occurrence of Globorotalia miocenica and the first downhole appearance of Globorotalia margaritae and/or Bolivina imporcata (Pereira et al., 1984). Except for well-30 (Uquire)[see Foldout 10], where the Middle Pliocene is mostly shale, siltstone and occasional sandstone, this interval is characterized by reef and bank rubble in the entire Carúpano area.
In general, the Middle-Late Pliocene consists of coral reef, mollusc-bryozoan bank rubble, and calcarenite, with intercalated sandstone (some with metasedimentary components), shale, siltstone and limestone pebbles. In the areas of Rio Caribe, Mejillones, Patao and Dragón (see Foldout 10), the top of the Pliocene is marked by a coral reef buildup.

Inner to middle neritic shelf conditions predominated over much of the Carúpano area during the Middle - Late Pliocene. The widespread development of coral reef complexes at the very end of the Pliocene suggests a wide and relatively flat inner to middle neritic shelf (Pereira et al., 1984).

5.2.7. Quaternary

The Quaternary is characterized by an inner to middle platform sedimentation which consists of mollusc and bryozoan bank debris, coral reef rubble, and skeletal limestone fragments (Furrer, 1984). There are also some shales, calcareous sandstones, pyrite nodules, glauconites and clastics with few metasedimentary fragments.
CHAPTER 6

STRUCTURE

6.1 Introduction

Twelve panels (Panel-1 to Panel-12) with line drawings of seismic profiles have been prepared to illustrate the different structural styles of the Cariaco and Carúpano areas. The vertical scale of the profiles is in time and their vertical exaggeration at the level of the basement is between 4X and 5X. A list of the seismic sections that were included in each panel is given in Tables 6.1.a, 6.1.b and 6.2. Figure 6.1 is the location map for all the sections.

Panels 1, 2, 3 and 4 show the regional structural framework of the Cariaco area. Local structural features in this area are shown from Panel-5 to Panel-9. The great variety of structural patterns in the Carúpano area are illustrated by Panel-10, Panel-11 and Panel-12.

The distribution of the structural features in the northeastern Venezuelan offshore (i.e., Cariaco and Carúpano area) [Figure 6.2] is documented by the structure contour map of the top of the acoustic basement, shown on Figures 6.3.a and 6.3.b (see also Foldout 11). Some of the faults were generated during the Paleogene and then reactivated; many others correspond to younger events (e.g., Neogene tectonism)[see Foldout 12].
<table>
<thead>
<tr>
<th>PANELS</th>
<th>LOCATION</th>
<th>SEISMIC SECTIONS</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| PANEL-1     | N-S REGIONAL TRANSECT           | B21, B19, B11, B9, B40 | - Eocene-Early Miocene extensional structures, especially in the La Tortuga and the La Blanquilla Basins.  
- Positive inversion during Middle Miocene.  
- Transtensional regime created the Cariaco trough on a preexistent Oligocene graben.  
- A more intense transtensional deformation during the Late Pliocene and Pleistocene. |
| PANEL-2     | E-W REGIONAL TRANSECT           | BL, BI (WEST), BJ, BH, BG2, BD | - Middle Miocene inversion of extensional lateral ramps.  
- Strike view of Cariaco trough. |
| PANEL-3     | E-W REGIONAL TRANSECT           | BM, BK, BI (EAST), BG1, BF, BE | - Middle/Late Miocene compression to the north of Margarita Island.  
- Strong erosion on Miocene folding in the Margarita platform.  
- Transtension in southern Cubagua accentuated since Late Miocene time. |
| PANEL-4     | SW-NE SECTIONS IN MARGARITA DEPRESSION/PLATFORM | B8, B7, B6 | - The right-lateral Margarita fault is responsible of the creation of the northern Tuy-Cariaco basin during Pliocene.  
- Middle/Late? Miocene folding in the La Tortuga and the La Blanquilla Basins. |
### TABLE 6.1.b. DESCRIPTION OF CARIAKO PANELS

<table>
<thead>
<tr>
<th>PANELS</th>
<th>LOCATION</th>
<th>SEISMIC SECTIONS</th>
<th>COMMENTS</th>
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<tbody>
<tr>
<td>PANEL-5</td>
<td>SE-NW SECTIONS TO THE NORTHWEST OF TORTUGA HIGH</td>
<td>B20, B18, B17</td>
<td>Note details of Middle Miocene Inversion to the northwest of Tortuga High (the La Tortuga and La Blanquilla Basins)</td>
</tr>
</tbody>
</table>
| PANEL-6  | SE-NW SECTIONS TO THE SOUTHEAST OF TORTUGA HIGH | B41, B42, B43, B44, B14 | - The Eocene-Early Miocene graben developed on the southeastern border of the Tortuga high  
- Middle Miocene inversion on some of the earlier extensional structures  
- Pliocene transtension at the south of Tortuga high |
| PANEL-7  | W-E SECTIONS IN THE ESENADA DE BARCELONA SHELF | BC, BB, BA       | - The Middle Miocene emplacement of the igneous-metamorphic terrane  
- Late Miocene-Pleistocene transtensional deformation |
| PANEL-8  | N-S SECTIONS IN THE ESENADA DE BARCELONA SHELF | B16, B15, B13, B12, B10 | - An approximate dip view of the Middle Miocene emplacement of the igneous-metamorphic terrane  
- The overprint of Middle Miocene (?) compressional features by a marked transtensional deformation developed during the Late Miocene-Pleistocene time. |
| PANEL-9  | N-S SECTIONS IN THE MARGARITA PLATFORM | B4, B3, B2, B1    | - An Eocene-Early Miocene extensional deformation to the north of Margarita Island  
- Middle-Late Miocene inversion of the former extensional structures |
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<tr>
<th>PANELS</th>
<th>LOCATION</th>
<th>SEISMIC SECTIONS</th>
<th>COMMENTS</th>
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</thead>
</table>
| PANEL-10      | N-S REGIONAL TRANSECT           | A7, A6, A5, A4, A3, A2, A1 | - Eocene-Early Miocene extensional structures in the La Orchila-La Biaquilla basin trend predominantly parallel to the Margarita-Los Testigos High. They were inverted during Middle Miocene.  
- To the south of the Margarita-Los Testigos High, the extensional phase is restricted to the Early(?)-Middle Eocene and the tectonic inversion occurred during the Late Eocene to the Middle Miocene.  
- To the southeast of the Margarita island, the Section A6 documents a huge post lower Middle Miocene erosion.  
- A push-up structure is shown on the southern end of the Section A1 |
| PANEL-11      | E-W REGIONAL TRANSECT           | AG, AF, AE, AD, AC, AB, AA | - Late Eocene-Early Miocene inversion of extensional lateral ramps in the Caracolito sub-basin.  
- In the central part of the Carupano basin, most of the reverse faulting activity occurred by the Early Miocene  
- Transrotational deformation might have enhanced the Tigrillo structure during the Late Miocene-Early Pliocene (Section AB).  
- Transtension has dominated the southern part of the Carupano area, especially since Late Miocene (Section AA). |
| PANEL-12      | DIP SECTIONS (SE - NW)           | A25, A24, A23, A22, A21 | - The Caracolito sub-basin is a former Early(?)-Middle Eocene graben trending parallel to the Margarita-Los Testigos High, that was mostly inverted during the Late Eocene to Early Miocene.  
- In the Carupano basin, NE-trending thrust faults were result of the Late Eocene-Middle Miocene transpression. |
|               | STRIKE SECTION (SW - NE)         | A31               | - Late Miocene-Early Pliocene folding activity is evidenced by onlap against the Caracolito anticline.  
- Transtension in southern Cubagua accentuated since Late Miocene time |
Figure 6.1. Location map of line drawings of seismic profiles prepared to illustrate the different structural styles in the Cariaco and Carúpano areas.
Figure 6.2. Index map of the major structural provinces, North
northeastern Venezuelan offshore. C.S., Cubagua Sub-basin.
Figure 6.3.a. Structural map of the top of the Cretaceous basement in the Cariaco area.
Figure 6.3.b. Structural map of the top of the Cretaceous basement in the Carúpano area.
A regional cross section illustrating the structural relations between the basement and the Cenozoic sedimentary cover through Margarita Island and its neighboring sedimentary basins is shown on Foldout 13. The internal structures of the basement of Margarita Island are based on Chevalier (1987).

Margarita Island is representative of crust underlying the Venezuelan offshore. Chevalier (1987) considered that the Mesozoic Margaritan crust consists of two units: Juan Griego Group (continental crust) and La Rinconada Group (oceanic crust). His interpretation is that they are separated from each other by a tectonic contact characterized by a mylonitic sole. From this point of view, he characterized the fault pattern of Margaritan crust by a series of frontal ramps that thrust and stack up many nappes. Guth (1991) questioned Chevalier's fault geometry and insisted on overall fold vergence on Paraguacho (i.e., in eastern Margarita) toward the NW. A discussion of Chevalier's (1987) or Guth's (1991) position is beyond the scope of the present study, as it would involve an exhaustive review of the evidence of the Mesozoic basement evolution of northern Venezuela. However, it is important to note that there is abundant evidence of a southward movement of the main thrust sheets in the central Caribbean mountains of Venezuela (e.g., Bell, 1972; Bellizia, 1986; Eva et al., 1989; Ostos, 1990), and that Margaritan crust has been related to the Cordillera de la Costa belt belonging to that system (e.g., Bellizia and Dengo, 1990). This observation together with the general agreement of the overall eastward migration of Margarita Island in terms of plate-tectonic reconstruction would favor a SE vergence. Chevalier's (1987) pattern of thrust-sheet like nappe is also in reasonable concordance with Stöckhert et al. (1995) work which
suggested that Margarita Island is an accretionary prism that underwent high-pressure metamorphism (500-600 °C, 10-14 kbar) in the deep level of a fore arc setting at 100-90 Ma; later, this accretionary terrane was emplaced at a shallow crustal level close to a transform plate margin. To conclude the basement surface itself was formed by widespread pre-Middle Eocene erosion.

As can be seen on the regional cross section (Foldout 13), Margarita Island is bounded to the north and south by Paleogene half-graben structures tilted away from the island. This type of deformation accentuated Margarita Island during the Paleogene as a central high with extensional rift flanks. Neogene transpression produced the tectonic inversion of these half-graben structures. North of the island (i.e., in the La Blanquilla Basin), the timing of the inversion is documented by Middle Miocene onlap against the Lower Miocene. This is shown on the seismic section A7 (Panel-10). To the south (e.g., in the southeast Margarita sub-basin [see Figure 6.2]), the timing of the tectonic inversion is Middle to basal Late Miocene. It is constrained by the shortest hiatus of a marked angular unconformity (see Figure 5.10); i.e., the sub-horizontal strata of the Upper Miocene-Lower Pliocene unit resting upon the eroded surface of the folded Middle Miocene rocks. As can be seen on the southern end of the regional cross section (Foldout 13), a second and milder inversion of the master fault of the former southeastern Margarita Paleogene half graben occurred during Middle Pliocene to Pleistocene time. Details of the different structural patterns that characterize the northeastern Venezuelan offshore, as well as their origin through time, will be discussed in this chapter.
6.2. Definition of structural provinces

Figure 6.2 shows the principal structural provinces of the Cariaco and Carúpano areas. This figure also shows all the major faults of the northern Venezuelan continental platform mapped at the level of the top of the Mesozoic igneous-metamorphic basement.

In the Cariaco area, the following structural provinces have been identified, from north to south: (1) Tortuga Basin, (2) Blanquilla Basin, (3) Tortuga High, (4) Northern Cariaco sub-basin, (5) Cubagua sub-basin, (6) Cariaco trough, and (7) Ensenada de Barcelona shelf.

The La Tortuga Basin is located between the La Tortuga high to the south and the La Orchila high to the north. Only a few seismic sections are available and much of the information is from the southern part of the basin (see Figure 6.1). The La Tortuga Basin is a Paleogene - Early Miocene extensional basin which before its offset by the NW-trending dextral strike-slip Margarita fault was continuous with the La Blanquilla and Grenada Basins (Figure 6.4). The basin was inverted during Middle-Late Miocene (see the northern end of Section B21 on Figure 6.5).

The La Blanquilla Basin is located to the northwest of the Margarita-Los Testigos platform (see Sections B6 and B7 in Panel-4 and Sections A5 and AG in Panel-10 and Panel-11, respectively). Its axis trends mostly SW-NE, pointing toward the Grenada Basin in the northeast (see Speed et al., 1993), suggesting that the La Blanquilla and Grenada Basins are closely related in their tectonic evolution. Toward the north, the basement of the La Blanquilla Basin is estimated to be deeper than 6.0 seconds two way
Figure 6.4. Isotime map of the Paleogene unit in the Caria
NORTH VENEZUELA

ISOTIME MAP
PALEOGENE UNIT

LEGEND

- STRIKE-SLIP (Arrows show direction on displacement)
- REVERSE FAULT (Triangle on upthrown side)
- NORMAL FAULT (Barbs on downthrown side)
- INFERRED FAULT
- CONTOUR LINE
- WELL LOCATION

SEISMIC CONTOUR INTERVAL
0.5 Sec. (TWT)

- 0.0
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0

50 km

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Cariaco and Carupano areas.
Figure 6.5 N-S seismic section (B21) across the Carriaco area. It shows the La Tortuga Paleogene transpressional basin inverted during Middle-Late Miocene. Note in the southern half the Late Neogene transpressional Carriaco trough. Abbreviations: E.MIOC, Early Miocene; EOCEN, Eocene; M-L MIOC, Middle-Late Miocene; OLG, Oligocene; PLEIST, Pleistocene; PLIOC, Pliocene; REC, Recent.
travel time. However, there are not enough seismic lines in this area to produce a reliable structural map.

The La Tortuga High is a shallow igneous-metamorphic basement high (see Panel-6) covered by horizontal Lower Pliocene sediments and Pleistocene coral reefs and clastic limestones (Galavíss and Louder, 1970). Its faulted north flank formed during Paleogene and Early Miocene. This flank is bounded to the north by a master fault of the Paleogene-Early Miocene Tortuga Basin half graben (Figures 6.2 and 6.3.a). The southern side of the La Tortuga High represents the updip flank of the Neogene transtensional Cariaco half graben.

The Northern Cariaco sub-basin is bounded to the north by the Margarita right-lateral strike-slip fault and to the south by the La Tortuga-Coche Neogene transtensional system (Figure 6.2). This sub-basin was mostly shaped during Pliocene and Pleistocene time as shown by a thick Plio-Pleistocene sequence of about 3500 m (approximately 3.0 seconds two way travel time) [Figure 6.6 and see also Panel-4].

The Cubagua sub-basin (C.S.) is located to the southwest of Cubagua Island. It is characterized by up to 1 km (about 0.7 seconds two way travel time) of Paleogene sedimentary rocks, which consist of Eocene deep water sequences (with turbidites) and Oligocene continental deposits. The change of depositional environment within the Paleogene might imply a combination of a sea level drop and local uplift (tectonic inversion) in the Oligocene. The Neogene to Quaternary sedimentation in this sub-basin has been mostly controlled by a transtensional regime (Figure 6.7).
FIGURE 6.6 SW-NE seismic section (B7) across the Cariaco area. Note the Late Neogene northern Tuy-Cariaco sub-basin and in the Cariaco trough. Abbreviations: E.MIOC, Early Miocene; MIOC, Middle-Late Miocene; PALEOG, Paleogene. In the index map, the solid line shows the location of the section and the dashed line illustrates the location of the foldout 2.
Sedimentary sequence expansion in the Early Miocene; M-L MIOC, location of the seismic
Figure 6.7 West-East line drawing (BE) across the Cubagua sub-basin. It shows a marked Late Neogene transtension associated with the La Tortuga-Coche fault system. Abbreviations: E.M., Early Miocene; M-L M., Middle - Late Miocene; PAL, Paleogene. The dashed line on the map shows the location of the section.
The Cariaco trough is a Neogene transtensional basin linked to the El Pilar right-lateral strike-slip fault, which offsets a foreland terranes/Villa de Cura-type igneous-metamorphic basement from the metamorphic Araya-Margarita. According to Figures 6.6 and 6.7, up to 3.5 seconds two way travel time (about 4100 m) of Plio-Pleistocene sedimentary rocks have been deposited in this trough, implying a relatively rapid average of sedimentation rate of almost 1 mm/yr during the last 5 My.

The Ensenada de Barcelona shelf represents the southern part of the Cariaco area close to the shoreline. It is a minor Neogene transtensional basin (Panel-7 and Panel-8). The pre-Neogene basement of the Ensenada de Barcelona consists of folds and imbricates of the Faja Piemontina and the Serranía del Interior, both of which are probably underlain by a Paleozoic basement monocline. The volcanic rocks that were encountered in wells appear as the continuation of the allochthonous Villa de Cura Klippe that overrode the Faja Piemontina.

In the Carúpano area, the major structural elements have already been identified by Pereira (1985). Their names have been preserved in this study, i.e., from north to south: (1) the eastern prolongation of the La Blanquilla Basin, (2) the Margarita-Los Testigos platform, (3) the southeast Margarita sub-basin, (4) the Caracolito sub-basin, (5) the Araya sub-basin, (6) the Tigrillo structure, (7) the Patao High, (8) the San Juan de las Galdonas High, and (10) the Paría sub-basin (Figure 6.2).

As can be recognized on seismic sections (e.g., Section A5, Figure 6.8), the La Blanquilla Basin, discussed earlier among the structural elements of the Cariaco area, continues at the longitude of the Carúpano area (Figure 6.2).
CARUPANO AREA  
NORTH VENEZUELA

Figure 6.8 North-South line drawing (A5) showing the overall picture of the Carúpano area. Abbreviations: EOC., Eocene; E. M., Early Miocene; EP-LM, Early Pliocene - Late Miocene; L. MIOC, Late Miocene; MM, Middle Miocene; M. MIOC, Middle Miocene; MIOC, Miocene; O-E, Oligocene-Eocene; OLIG, Oligocene; E. PLIOC, Pliocene. See the section location on the map.
EASTERN PROLONGATION OF THE LA BLANQUILLA BASIN

LOCATION MAP
The Margarita - Los Testigos platform extends from Margarita Island to the Los Testigos archipelago. The shallow basement that underlies this structure extends northeastward into Grenada and the Lesser Antilles, as suggested by the distribution of magnetic anomalies (Foldout 11). Talwani (1966) and Lattimore et al. (1971) already described the Margarita - Los Testigos platform and the Lesser Antilles as part of the same gravity and magnetic belt.

The small southeast Margarita sub-basin is located to the south of the Los Frailes and Los Testigos Archipelago. It is a half-graben tilted to the south created during the Paleogene and then inverted in Middle-Lower Late(?) Miocene. During Paleogene, this sub-basin was probably continuous with the Caracolito sub-basin to the east; a later strike-slip and/or transfer fault might have produced a dextral offset between them.

The Caracolito sub-basin is located to the southeast of the Margarita-Los Testigos platform. It is the principal sub-basin developed in the Carúpano basin "sensu strictu" (i.e., between the Araya - Paria Peninsula and the Margarita - Los Testigos platform). More than 5600 m of Paleogene sedimentary rocks were penetrated by well-29 in this sub-basin without reaching the basement. Most of this is a thick Middle Eocene section (Section A21, Figure 6.9).

The Araya sub-basin is located to the southwest of the Carúpano area, close to the shoreline of the central part of the Araya-Paria Peninsula (Figure 6.2). Its evolution was controlled by extension during the Middle Eocene, which slowed down in Oligocene and Early Miocene (Figure 6.10).
Figur e 6.9 S-N/S60°E-N60°W Line drawings across the Carúpano area. Note the Paleogene expansion into the transtensional Caracolito subbasin in contrast with the Late Neogene expansion in the southern Carúpano area. The latter is linked to the Late Miocene-Present E-W strike-slip system identified as the Coche-North Coast fault system. On the map, the heavy solid line shows the location of the line drawing and the dashed line illustrates the location of foldout 8.
area. Note the contrast with the line drawing.
**CARUPANO AREA**

**NORTH VENEZUELA**

**Figure 6.10.** E-W line drawing (Section AA) crossing the Late Neogene transtensional system in the Southern Carupano area. Abbreviations: EP, Early Pliocene; LM, Late Miocene; MIOC, MM A, Middle Miocene "A"; OLIG, Oligocene.
The Tigrillo structure and the Patao High are located to the south of the Caracolito sub-basin. Both are associated with NE-trending thrusts with a southeast vergence.

The San Juan de las Galdonas High is situated to the south of the Tigrillo structure. Its northeastern boundary is a northwest-west trending dextral fault with a normal component (Figure 6.10). To the south, the San Juan de las Galdonas High is separated from the Araya-Paria Peninsula by a northwest-west striking normal fault probably related to a dextral slip motion (Figure 6.2).

In the southeastern part of the Carúpano basin, there is a small depression called the Paria sub-basin (not to be confused with the Gulf of Paria pull-apart basin). Its northern boundary is defined by the Patao High. To the south, it is bounded by the transpressional Paria-Bocas High (Section A3, Figure 6.9). Its maximum basement depth is about 4.6 seconds two-way travel time (Foldout 11). The oldest sedimentary rocks in this sub-basin are inferred to be Early Miocene (Figure 6.10).

6.3. Internal structure of the basement

The igneous and metamorphic basement that underlies the study area has already been summarized in Chapter 3. To understand the offshore basement encountered in wells and observed on various small islands, refer to the tectonic sketch map of Figure 3.2. It is not the purpose of this thesis to provide an in-depth summary of the structural geology of the Caribbean mountain system.
In the context of this study, the following points need to be emphasized: the Caribbean mountain system of northern Venezuela consists of an internal zone involving metamorphic nappes, an extensive Klippenbelt (the El Tinaco, Paracotos and Villa de Cura zones) which overrides an external zone of imbricates, and folds that involve Cretaceous passive margin sediments and the Paleogene Guárico flysch. Many authors assume that this external zone is underlain by a gently northeastward and northerly dipping Paleozoic and Precambrian basement.

Nappe-like structures have been illustrated and reported from Margarita Island (Chevalier, 1987) and the Araya Peninsula (Figures 6.11 and 6.12).

As noted in Chapter 3 (see sections 3.3.2. and 3.3.4.), the basement penetrated by offshore wells consists of metamorphic rocks and volcanic rocks with the following affinities: mid-oceanic ridge basalts (MORB), primitive island arc (PIA), and mature island arc. This type of basement has been correlated with the igneous-metamorphic terranes both in Margarita Island and the Caribbean mountain system. Thus, for the Cariaco and Carúpano basement, it is reasonable to expect internal structures similar to the ones interpreted in the basement of Margarita Island and the Caribbean mountain system.

6.4. Regional strike-slip faults

The eastward motion of the Caribbean plate with respect to both North America and South America (e.g., Pindell and Dewey, 1982; Burke et al., 1984; Stephan et al.,
Figure 6.11. Geologic map of Margarita Island (redrawn after Chevalier, 1987).
GEOLOGIC MAP OF ARAYA PENINSULA, VENEZUELA

Figure 6.12. Geologic map of Araya Peninsula (redrawn after Chevalier, 1987).
1990) is displayed by movement along complex strike-slip plate-boundary zones on both the northern and southern margins of the Caribbean (e.g., Rod, 1956; Burke et al., 1978; Robertson and Burke, 1989). Most Caribbean geologists have accepted the strike-slip nature of the boundary, but the age and magnitude of strike-slip motion are still subject to controversy.

The 1,100 km of total left-lateral offset across the Cayman trough in post-Eocene (?) time (Rosencrantz and Sclater, 1986; Pindell and Barret, 1990) represents a minimum estimate of the magnitude and timing of roughly east-west directed strike-slip motion between the Caribbean and North American plates. Assuming little relative displacement between South America and North America (Pindell et al., 1988), this amount could be indicative of the approximate strike-slip motion between the Caribbean plate and South America. Avé Lallemand (1997) recently reviewed strain partitioning in northern Venezuela, citing a minimum 1100 km continental margin parallel component (e.g., Mann et al., 1990) and a margin perpendicular component of about 200 km. However, to date the maximum right-lateral offset that has been documented in the southern Caribbean, has occurred along the Boconó-San Sebastian-El Pilar fault system and has not exceeded 100-125 km (Schubert, 1984). Vierbuchen (1984) suggested that gravimetric field distribution in northeastern Venezuela required right-lateral displacement along the El Pilar fault of at least 150-300 km. These observations mean that most of the hypothetical 1100 km of the eastward displacement in the southern Caribbean (if it was accumulated) may have taken place along other fault systems within the northern margin of South America. Many investigators think of the southern
Caribbean margin as a broad plate boundary zone where the major transcurrent movements are likely to occur in offshore faulting systems (e.g., Biju-Duval et al., 1982; Mann et al., 1990); in this context the El Pilar fault system may be one of the most important systems.

Significant evidence for a major strike-slip boundary along the southern Caribbean is the matching between the quartz-rich sediments of the Paleogene Scotland Group of Barbados with the Eocene Misoa delta, situated close to the present Gulf of Venezuela (Dickey, 1982). An alternative interpretation by Kasper and Larue (1986) suggesting that the Scotland Group sands were deposited close to their present location has been refuted by Eva et al. (1989), who noted that no conjugate Paleogene delta source has been recognized in northeastern South America.

The age of initiation of the right-lateral strike-slip motion in the southern Caribbean might be associated with the oldest strike-slip basin found in northern Venezuela: the Falcón basin, envisaged by Muessig (1978, 1984) to be a pull-apart basin formed during the Late Oligocene and Early Miocene.

6.4.1. El Pilar fault

In this study, the dextral E-W trending El Pilar fault and its associated Cariaco trough has been corroborated as the most remarkable structural feature of the Cariaco area (Panel-1). El Pilar fault marks the southern boundary of the Araya-Paria Peninsula. To the west, it extends into the Cariaco trench. Its western termination appears to overlap the San Sebastián fault, also known as the Morón fault (Schubert and Krause, 1984). To the
east, the termination of the El Pilar fault is not well defined. Speed (1985) argued that the El Pilar fault zone ends in Paria at a tip that is propagating east at about 1 cm/yr; seismicity data do not support continuity of the El Pilar fault through Trinidad. Robertson and Burke (1989), in contrast, suggested that the thrust, normal and strike-slip fault within Pleistocene deposits immediately south of the Northern Range in Trinidad indicated right-lateral strike-slip along the El Pilar fault. Evidence for right-lateral motion along the southern flank of the Northern Range was also found by Algar and Pindell (1993). However, they considered on the basis of the scale of the structures (no more than 5-10 km of right-lateral strike-slip motion) and the absence of seismicity of the region that the El Pilar fault in Trinidad is a right-lateral transtensive fault of minor significance in the South Caribbean plate boundary zone.

At the longitude of the Araya-Paria Peninsula, seismicity data show that the El Pilar fault zone is associated with frequent shallow earthquakes, many with right-lateral strike-slip on east-west planes (Russo et al., 1992). The last earthquake (Mw=6.8) occurred on July 09, 1997. Its epicenter was located at latitude 10.40°N and longitude 63.50°W (close to the town of Casanay), about 10 km depth (Figure 6.13). An east-west trending surface fault rupture related to this seismic event has been preliminarily mapped by Funvisis (Venezuelan Foundation for Seismological Research). This fault rupture of less than 3 to 4 m width extends for some 30 km between Muelle de Cariaco on the west and Las Varas (slightly east of Casanay) on the east. The coseismic right-lateral slip ranges from 0.40m to 0.08m. The focal mechanism of this earthquake given by the USGS National Earthquake Information Center is in reasonable agreement with the observations
Figure 6.13. Seismicity along northern Venezuela. The star corresponds to the epicenter (lat. 10.40°N, long. 63.50°W) of the July 09, 1997 earthquake (Depth 10 km, MW = 6.8).
mentioned above; it suggests a N86°E striking fault plane dipping 87°NW. Geometry of the El Pilar fault in the Cariaco area documented by seismic profiles (Panel-1) is consistent with the fault plane of the earthquake.

According to Schubert (1982), the El Pilar fault zone represents the southern margin of the Cariaco trough identified as a pull-apart basin formed by a right step in the San Sebastian/El Pilar fault zone. As can be seen on the basement map (Figure 6.3.a.), the Cariaco trough contains two small sub-basins; the deeper one on the east reaches more than 7.0 seconds two-way travel time of depth (i.e., more than 8.5 km using an average interval velocity of 2.45 km/sec for a sedimentary sequence mostly Middle Miocene to Recent). Taking the 4.0-sec contour line in the basement map as the external boundary of this depression (Figure 6.3.a.), the length of the Cariaco trough might be estimated in an order of 175 km. Accepting Aydin and Nur's (1982) proposal that the length of a pull-apart basin is approximately equal to the strike-slip offset, the right-lateral offset along the San Sebastian-El Pilar fault zone would be approximately 175 km. According to seismic interpretation, this lateral displacement might have been accumulated during Middle(?)-Late Miocene to Recent (i.e., for the last (?)16 My). It would imply a displacement rate of about 11 km/My, which would accommodate 52% of the Caribbean-South American E-W relative motion (assuming the 20 km/My total offset by Minster and Jordan, 1978, inferred from magnetic anomalies at the Cayman Spreading Center).

Transpressional zones have also been associated with the El Pilar fault. An example is the Los Cerros Caiguíre which is a Mio-Pleistocene restraining bend of the El Pilar fault that produced an uplift of more than 160 m near Cumana (Macsotay, 1987;
Beltran et al., 1996). Another small push-up structure occurs in the Cerro Las Minas on the Araya-Paria Peninsula where the trace of the El Pilar fault zone shifts 5 km to the north (Perez and Aggarwal, 1981; Vierbuchen, 1984).

6.4.2. Tortuga-Coche fault system and Margarita fault

These two fault zones are the other important strike-slip systems in the Cariaco area. Their interplay led to the formation of the Northern Tuy-Cariaco pull-apart sub-basin (Figure 6.2) in the Plio-Pleistocene. The Tortuga-Coche fault system is a transtensive fault zone (north side down) trending WNW-ESE in the west and then turning W-E to the east where the system may merge with the North Coast fault system (Figures 6.2 and 6.3.a). Many NW-striking small normal faults merge into the master faults of this system. Its major tectonic activity occurred in the Plio-Pleistocene (Figure 6.6; see also Figure 6.7). The amount of displacement is hard to constrain since it is accommodated in a great number of faults.

The Margarita fault is a NW-trending right-lateral strike-slip fault. At the latitude of southern Margarita Island, it is inferred that this fault changes its trend to W-E. The activity of this fault is well documented in the Plio-Pleistocene (Panel-4; see also Figure 6.6). However, Late Paleogene - Miocene activity along the Margarita fault cannot be ruled out. Paleogene half-grabens are offset by the Margarita fault, as it is shown on Figure 6.4, suggesting a displacement of about 50 km. Some of this displacement may have been preceded by a Paleogene transfer fault.
On the northern tip of Cubagua Island, air photos document the presence of an E-W left-lateral strike slip fault. It is located between and parallel to the right-lateral Margarita and La Tortuga-Coche fault systems (Figure 6.2; see also Foldout 5). This sinistral fault that has been called the Charagato fault is interpreted as the result of the different displacement rate between the two parallel master right-slip faults mentioned above. In this interplay, the sinistral nature of the Charagato fault implies that the greater right-lateral motion is taken up by the southern fault, i.e., the La Tortuga-Coche fault (Figures 6.14 and 6.15).

6.4.3. Southern Carúpano transtensional fault system and North Coast fault zone

The southern Carúpano transtensional system is located next to the northern Paria Peninsula shoreline. It consists of several NW-trending normal faults that merge into an E-W right-lateral strike-slip fault (Figure 6.16) which, in turn, connects with the North Coast fault zone to the east (Figure 6.2). The North Coast fault zone may well be the continuation of the Tortuga-Coche fault system. Figure 6.10 shows a strike section across the Southern Carúpano transtensional system. Fifteen (15) km of extension, at least, are documented at the level of basement in the seismic profile. This transtension mainly occurred during the Late Miocene to Pliocene (i.e., in a time span of roughly 10 My). A product of the Southern Carúpano transtension is the Paria sub-basin (Figures 6.2 and 6.10).
Figure 6.14. Structural interpretation of Charagato fault: a sinistral fault in a dextral strike-slip regime. The air photo is a reprint of a poster showed in the symposium of "Neotectonica, sismicidad y riesgo geologico en Venezuela y el Caribe", XXXIII Convencion Asovac, 1983, organized by FUNVISIS (Fundacion Venezolana de Investigaciones Sismologicas).
PULL APART BASIN GEOMETRY

1
D>>S,O
S/O>1
RHOMBIC GRABEN, SINGLE SUBSIDE CENTER

2
D>>S,O
S/O<1
NARROW, RECTANGULAR GRABEN, 2 SUBSIDENCE CENTERS

3
D<O,S
NO PULL-APART, ONLY TERMINAL EXTENSION FRACTURES

4
SERIES OF SUBPARALLEL FAULT-COALESCED BASINS

Figure 6.15. Geometry and locations of basins in oversteping domains of parallel faults (with minor modifications after Silvester, 1988). D=depth to basement; S=spacing between parallel or echelon fault strands; O=overstep.
Figure 6.16. Block diagram of Late Miocene-Recent transtensional systems in Eastern Venezuela offshore.
The North Coast fault zone, off the northern coast of Trinidad, has been defined by Robertson and Burke (1989) as a 7-15 km wide zone, that consists of two main faults associated with many secondary faults forming a pattern of branching (i.e., anastomosing faults with intervening wedge-shaped basins) [Figure 6.2]. According to them, this fault zone constitutes a recently active right-lateral strike-slip zone with 10 km of displacement in the last 1.6 My along one fault strand alone. This implies that about 30% (taking 20 km/My as a total offset [Minster and Jordan, 1978]) of the east-west right-lateral strike-slip displacement between the Caribbean and South America in the Trinidad region might have been accommodated along the North Coast fault zone (Algar and Pindell, 1993). As referred by Algar and Pindell, (1993), and mentioned previously, the El Pilar fault in Trinidad is considered as a minor transtensional fault having accommodated no more than about 5 km of right-lateral strike-slip and 1 km down to the south normal dip-slip.

6.4.4. Casanay-El Pilar-Arima fault and Warm Springs fault

The Casanay fault is a right-lateral transtensive (south side down) fault that branches from and rejoins to El Pilar fault on the southern part of the Paria Peninsula (Figures 6.3.b and 6.17). In the Trinidad region, the Casanay (or El Pilar) fault connects to the Arima fault which is traced along the southern flank of the Northern Range.

The Warm Springs fault, located in the center of the Gulf of Paria, is a NE-SW right-lateral transpressive fault dipping to the NE (Foldout 11). It has been active since Late Miocene (Flinch et al., in press). On its western termination, the Warm Springs fault is linked to a set of NW-SE normal faults.
Figure 6.17. Regional transect: Gulf of Paria - Carúpano. To the south of the CAFS (Casanay fault system), the northern part of Gulf of Paria underwent a Late Neogene transtension, farther to the south a coeval compressional event is documented in Pedernales. To the north of the Paria Peninsula, i.e., in the Carúpano area, the Bocas High evolves as a Late Neogene transpressional high linked to the North Coast Fault system (NCFS). Abbreviations: CAFS, Casanay fault system; EOC, Eocene; EP, Early Pliocene; LM, Late Miocene; ME, Middle Eocene; MIOC, Miocene; MM A, Middle Miocene "A"; M-L P, Middle-Late Pliocene; NCFS, North Coast fault system; PLEIST, Pleistocene; PLIOC, Pliocene; REC, Recent.
The Casanay-Arima and the Warm Springs faults represent the northern and the southern boundary, respectively, of a pull-apart system: the Gulf of Paria basin (Flinch et al., in press). This transtensional basin has been shaped since Late Miocene. The transtensional structures of the Gulf of Paria extend toward the west, affecting the Cretaceous folds and thrust of the "Serranía del Interior" in the Eastern Venezuelan Basin (Figure 6.16). To the east, the Gulf of Paria Basin continues into the Caroni Basin of northern Trinidad (Flinch et al., in press).

6.5. Structural Evolution of the area

The major structural elements were defined in Section 6.2 (see Figure 6.2). Some basins have a clear Paleogene ancestry, such as the La Tortuga Basin, the La Blanquilla Basin and the southeastern Margarita and the Caracolito sub-basins. Others are marked by a Neogene tectonic history such as the Northern Tuy-Cariaco sub-basin, the Cariaco trough, the Ensenada de Barcelona shelf and the Paria sub-basin. Thus two tectonic domains are recognized, i.e., a Northern Paleogene extensional system and a Southern Neogene transtensional system. The isotime map of the Paleogene (Figure 6.4) should be interpreted in terms of Paleogene extensional faulting; i.e., a thick Paleogene isotime (e.g., in the Caracolito sub-basin) corresponds to Paleogene extension. By way of contrast, there is no Paleogene extension observed on and to the south of the Patao High, in the Carúpano area, nor is extension observed near the El Pilar fault in Cariaco area.
The areal distribution of the northern Paleogene extension and the southern Neogene transtension is also expressed on Tables 6.3, 6.4 and 6.5, which summarize the various structural regimes in the Cariaco and Carúpano areas. The vertical scale of these tables is roughly proportional to geologic time. The principal structural regimes are: an Eocene-Early Miocene rift regime (except for the Caracolito sub-basin and the Patao High where this phase ended in Oligocene); an Oligocene to Middle Miocene inversion regime; a Middle Miocene infill episode (limited to the Carúpano Basin sensu strictu and the Northern Tuy-Cariaco sub-basin); a Middle or Late Miocene to Present transtensional phase and a coeval transpressional(?) arch.

6.5.1. Eocene - Early Miocene Rift Regime

The inception of Paleogene extension was roughly during Early? To Middle Eocene (~50 Ma). The cessation of this extensional phase is not the same over the entire Carúpano area. In the Caracolito sub-basin and the Patao High, the rift phase ended in the Oligocene; while in the southeastern Margarita sub-basin, the Margarita-Los Testigos high and the La Blanquilla Basin extension ceased by the Early Miocene (~20 Ma).

The rifting in the Caracolito sub-basin is characterized by the expansion of the Paleogene units into a graben system (see Figure 6.9 and see also Panel-12 and Sections A3, A4 and A6 in Panel-10). A similar pattern is recognized in the southeastern Margarita sub-basin, but in this case the extension might have continued until Early Miocene (Figure 6.18). In the La Blanquilla Basin, the rift phase is characterized by a half-graben system tilted to the northwest. It is documented on Section A7 (Panel 10) where the
TABLE 6.3.  STRUCTURAL REGIMES, CARUPANO AREA.
TABLE 6.4. STRUCTURAL REGIMES, CARIACO AREA
<table>
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<th>EL PILAR FAULT</th>
<th>CARIACO TROUGH</th>
<th>LA TORTUGA HIGH</th>
<th>LA TORTUGA BASIN</th>
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TABLE 6.5. STRUCTURAL REGIMES, CARIACO AREA
Figure 6.18. Reconstruction of N-S section in the SE Margarita sub-basin.
Paleogene units thicken toward the normal master fault. In this case, like in the southeastern Margarita sub-basin, the extensional phase appears to continue into the Early Miocene (Table 6.3).

The rift phase in the Carúpano area probably began during Early Eocene. The presence of Lower Eocene sedimentary rocks, filling in half-grabens formed by extension, is documented by well-29 in the Caracolito sub-basin (see Foldout 7). According to Furrer (1984), this well, drilled on the central part of Section A21 (Figure 6.9), found Early Eocene planktonic foraminifera (e.g., Globorotalia aragonensis).

Figure 6.19 shows a map of the distribution of the Middle Eocene extensional faulting system in the Carúpano area. This map is characterized by NE-trending normal faults which are parallel or subparallel to the Margarita - Los Testigos platform. The rift regime led to the formation of half-graben systems on both sides of the Margarita-Los Testigos high (Foldout 13), making this high an extensional horst. The southern half-grabens are the southeastern Margarita and the Caracolito sub-basins. The northern half-graben is the La Blanquilla Basin. The axes of all these depressions trend parallel to the central high (i.e., to the Margarita - Los Testigos High).

In the Cariaco area, the rift regime occurred during Eocene to Early Miocene (Tables 6.4 and 6.5). This can be seen on seismic sections located in the western termination of the La Blanquilla Basin (e.g., section BM in Panel-3 and see also Panel-9) and on Sections across the La Tortuga Basin (e.g., B21 and B19 in Panel-1 and BL, BI, BJ and BH in Panel-2). On the northern end of Section B19 (Panel-1), this extensional phase is well illustrated by the expansion of the Paleogene units toward the northern
Figure 6.19. Distribution of Middle Eocene faulting system.
master fault of the La Tortuga High. As mentioned earlier, the La Tortuga and the La Blanquilla Basins are interpreted to have been a continuous basin before they were offset by the dextral NW-trending Margarita fault, which may have started as a transfer fault separating to segments of a Paleogene half-graben system.

A local mild Middle Eocene compression is suggested in the northern Tuy-Cariaco sub-basin. The bathyal Middle Eocene is in contact with an overlying shallow reeval environment upper section. This abrupt contact or unconformity may reflect an early transpressional event.

Much of the tectonic activity related to this rift regime in the Cariaco area occurred in the La Tortuga Basin. Most of the faults are downthrown to the north. Farther to the north into the La Tortuga Basin, there are some major faults dipping to the south (see Sections B21 and B40 in the Panel-1).

An approximate strike view of the Eocene-Early Miocene extension is shown on Panel-2 (see also Section BH on Figure 6.20). Extensional lateral ramps (later inverted during the Middle Miocene) are interpreted to the northwest of the La Tortuga High, as they can be seen on the left side of Sections BI and BH and on the right side of Section BJ. Of secondary importance is the extension identified to the southeast of the Tortuga High (i.e., in the northern Tuy-Cariaco sub-basin) and in the Cubagua sub-basin.

Section BG2 illustrates Late Eocene-Early Miocene normal faulting to the southeast of the Tortuga High. Panel-6 shows a dip view of this tectonic extension developing a sedimentary wedge on the southeastern border of the High.
Figure 6.20. E-W line drawing (Section BH) showing the contrast between the Pa of the La Tortuga extensional Basin and the Late Neogene expansion of the Northern transtensional sub-basin. In the map, the solid line shows the location of cross-section line illustrates the location of foldout 4. Abbreviations: E.M. = Early Miocene; MIOC = Oligocene.
The Paleogene expansion of the Northern Tuy-Cariaco Basin is section and the dashed lines represent Miocene; Oligocene (MIOC = Miocene; OLIG = Oligocene)
On Panel-3, Sections BG1, BF and BE document a Late Eocene-Early Miocene extension towards the western area of the Cubagua sub-basin. Similar extension is illustrated in the central part of Section B40 in the Panel-1. However, local Oligocene compression in the Cubagua sub-basin is not ruled out; it may explain the abrupt contact between the Eocene turbidites and the Oligocene continental deposits penetrated in well-4 (Foldout-1). The possible coexistence of extension and compression in the Oligocene may be related to overall strike-slip deformation.

Minor Oligocene(?)-Early Miocene extension is also suggested in the present Cariaco trough (Tables 6.4 and 6.5) as suggested by the seismic interpretation of Sections B19 in Panel-1 and BD in Panel-2, which indicate the possibility of thin units of Oligocene and Early Miocene.

Maps of the distribution of the Late Eocene-Oligocene and the Early Miocene faulting systems are shown on Figures 6.21 and 6.22. These illustrations reveal two general fault trends, i.e., (1) WNW-ESE to NW-SE, and (2) WSW-ENE.

The first fault trend is characterized by normal faults dipping to the north/northeast. They are probably the result of the right lateral wrenching on the old Margarita strike-slip fault.

Similar to the NE-trending Middle Eocene normal faults (Figure 6.19), the second set of WSW-ENE Late Eocene-Early Miocene normal faults are sub-parallel to the La Tortuga and the Margarita - Los Testigos basement highs. In the Cariaco area, they are mainly concentrated to the north of the basement highs; an exception is the normal fault that defines the southeastern boundary of the Tortuga High (Figure 6.20 and Panel-6).
Figure 6.21. Distribution of Late Eocene - Oligocene faulting system.
Most of the normal faults may be attributed to the effect of subduction rollback. The subduction rollback extension may be explained by the retreat of the plate boundary of the southeastern Caribbean, where the oceanic Atlantic crust was subducted westward.

6.5.2. Oligocene - Miocene Transpressive Inversion

The Oligocene to Early Miocene in the Carúpano Basin “sensu strictu” (e.g., in the Caracolito sub-basin and the Patao High) is characterized by the inversion of the earlier extensional structures (Table 6.3). The tectonic inversion is the result of compressional forces related to the WNW-ESE oblique convergence between the Caribbean and the South American plates.

As shown on Figures 6.21 and 6.22, during the Oligocene and Early Miocene, all the normal faults of Eocene age in the Caracolito sub-basin were inverted. This tectonic phase also produced the transpressional basement uplift of the Patao high associated with NE-trending southeast-verging reverse fault (see Sections A3 and A2 in Panel-10). Another structural element that was mostly developed during Oligocene and Early Miocene in the Carúpano area is the Tigrillo Structure (later reactivated by NW-SE Late Neogene strike-slip fault, Figure 6.23).

Sections presented in Panel-12, as well as Sections A2, A3, A4 and A5 in Panel-10, document the tectonic inversion and reverse faulting in the Caracolito sub-basin and surrounding areas during the Late Oligocene-Early Miocene structural regime. By the end of Early Miocene, most of the faults in or near the Caracolito sub-basin had become inactive.
FIGURE 6.23. Strike section (AB) from the Tigrillo structure to the Patao High. Abbreviations: E?-ME, Early? - Middle Eocene; E. MIOC, Early Miocene; LE-O, Late Eocene - Oligocene; M. MIOC, Middle Miocene.
In the southeastern Margarita sub-basin, the tectonic inversion took place later, but prior to the Pliocene. It is constrained by the angular unconformity shown on Section A6 (Figure 6.18) and Section AC in Panel-11, which documents a pronounced post-lower Middle Miocene and pre-upper Late Miocene erosion. This event is related to uplift resulting from the upper Middle to lower Late Miocene transpression.

To the northeast of the Margarita - Los Testigos platform (i.e., in the La Blanquilla Basin), the transpressive-inversion mainly occurs during the Middle Miocene. NE-trending reverse faults with a NW vergence were generated in the area during this regime (Figure 6.8 and Section AG in Panel-11). Middle Miocene NW-trending normal faults, dipping to the NE, are much less common (Figure 6.24). As mentioned earlier, before the Middle Miocene, the Tertiary tectonic history of the La Blanquilla Basin was characterized by extension. It is interesting to note the coexistence of extension to the north of the Margarita - Los Testigos volcanic arc and transpression to the south (e.g., in the Caracolito sub-basin), during the Oligocene to Early Miocene. Slab retreat of the Atlantic plate might represent an option to explain back arc extension within a zone of overall oblique convergence.

During the Middle Miocene, all the earlier extensional structures, occurring to the north of the Margarita - Los Testigos High, were inverted. Section A7 of Panel-10 shows an example of the Middle Miocene inversion. As can be seen on this section, a footwall shortcut thrust with a series of imbrications transfers the inversion displacement backwards onto the reactivated main extensional fault.
Figure 6.24. Distribution of Middle Miocene faulting system.
Middle Miocene tectonic inversion of ENE-trending normal faults are also shown on Panel-9, which includes sections located to the north of Margarita Island. Toward the western termination of the La Blanquilla Basin, in the Cariaco area, WSW-ENE folds with a décollement surface near the base of the Eocene are shown on Panel-4 (see Sections B6 and B7). These folds developed during Middle/Late Miocene. They are probably linked to the right lateral movement along the NW-trending Margarita fault. Evidence for a marked erosion of anticlinal structures, immediately to the north of Margarita Island, is presented on the eastern half of Section BI (Panel-3). Erosion occurred during Middle/Late Miocene and Early Pliocene.

Similar to the La Blanquilla Basin, the Middle Miocene in the La Tortuga Basin is characterized by WNW-oriented transpression. Panel-5 consists of sections located to the northwest of the Tortuga High (Table 6.2.b) and documents the Middle Miocene inversion of ENE-striking normal faults (see Figure 6.24). Other examples of Middle Miocene inversion are illustrated on the northern end of Sections B21 and B19 (Panel-1). Sections BL in Panel-2 and BM in Panel-3 also highlight structural inversions in the La Tortuga and the La Blanquilla Basins, respectively.

Few NW or W-trending normal faults, active during the Middle Miocene, are also identified in the La Tortuga Basin (see Section BJ in Panel-2). Some Middle(?)/Late Miocene inversions within or near the Cubagua sub-basin are illustrated in the central part of Section B40 (Panel-1) and on Sections BG1 and BF (Panel-2).

In the southernmost part of the Cariaco area, the emplacement of the igneous-metamorphic terrane on top of foreland is inferred to occur during Early to Middle
Miocene time. It would be coeval with the Early Miocene inception of the Maturín foredeep (DiCroce, 1995) and with the Middle Miocene deformation of the “La Serranía del Interior” of Eastern Venezuela (Chevalier et al., 1995). It would also agree with the definition of the Middle Miocene as the time during which the most intensive compressional features in the Cariaco area occurred. Panel-8, Section B13 suggests pre-upper Miocene age for the emplacement.

6.5.3. Middle Miocene infill episode-Subsidence

This event is characterized by a quiet tectonic period which in many places led to an almost uniform thickness of this unit. During the lower Middle Miocene, that is the Middle Miocene “A” in Panel-10, Panel-11 and Panel-12, the subsidence in the Caracolito sub-basin and the Patao High seem to prevail over uplift derived from transpression (Table 6.3). Much of the area was covered by sediments deposited in a bathyal environment. Bathymetric data from all the wells drilled in the Carúpano Basin indicate that the maximum water depths occurred during this time (Furrer, 1984). To explain the sudden deep-water encroachment on pre-Miocene positive areas (e.g., on the Patao High and the Los Testigos platform), a considerable increase in subsidence is required. A simple sea level rise, in the order of say 100 m which would be consistent with the world-wide relative sea level rise recorded toward the upper Early Miocene and particularly in the lower Middle Miocene (Haq et al., 1988), would not be adequate to explain the sudden deepening of the basin to bathyal depths.
Because of its high subsidence during the lower Middle Miocene, the Carúpano Basin might be classified as a forearc basin on a transform convergent margin. This lower Middle Miocene situation is illustrated in Figure 6.25, which has been adapted from Ingersoll and Graham, 1983. In this particular case, the accretionary basin, that is characterized by a rising imbrication stack, is located onshore Venezuela in the "Serranía del Interior"; the volcanic arc is represented by the Margarita - Los Testigos arc.

In the Cariaco area, a Middle-Late Miocene infill episode is recognized in the northern Tuy-Cariaco sub-basin (Table 6.5). As can be seen on Sections B6 and B7 in Panel-4 and on Sections BI and BH in Panel-2, the Middle-Late Miocene unit was deposited in relatively tectonic stable conditions in this sub-basin.

6.5.4. Late Miocene to Present transpressional(?) arch

Figure 6.8 shows Section A5, which documents a Late Miocene to Present transpressional(?) arch (see Table 6.3). This N-S seismic section illustrates the Margarita-Los Testigos High as the crest of the transpressional arch in the Carúpano area. The arch is defined by the geomorphologic expression of the base of the Late Miocene or the Middle-Late Pliocene units, dipping away from the central high. Notice also the convergence of the Late Miocene-Early Pliocene unit against the Caracolito anticline. This convergence and the onlapping relationship suggest a mild compression. A similar but less obvious relationship affects the Middle Pliocene to Present thickness intervals and the Margarita-Los Testigos High. A transpressional arch might be explained by an overall mild lithospheric N-S compression between the South American and North
Figure 6.25. Conceptual cross-section of Eastern Venezuela in lower Middle Miocene. Abbreviations: CRET, Cretaceous; EM, Early Miocene; EME, Early/Middle Eocene; E. MIOC, Early Miocene; EPF, El Pilar fault zone; M. MIOC, Middle Miocene; NCF, North Coast fault; PAL, Paleogene (Late Eocene/Oligocene in Carúpano Basin). This figure is inspired from Ingersoll and Graham (1983).
American plates combined with the Caribbean eastward migration. In the Cariaco area, this arch is also expressed on the seafloor as shown on Sections B6 and B7 in Panel-4.

Another explanation is that the arch is due to the Pliocene-Pleistocene transtension in the southernmost part of the Carúpano area combined with subsidence in the northern part (i.e., in the La Blanquilla Basin). A relative uplift is created in the central part, giving the impression of the crest of an arch. In this case the convergence of the Middle Pliocene-Present units towards the central basement high is an indirect consequence of the southern Pliocene-Pleistocene expansion and the northern subsidence.

6.5.5. Late Miocene to Present Transtension

The Late Miocene-Present transtension is concentrated in the southern part of the study area, near the northern Venezuelan shoreline (e.g., Cariaco trough, Ensenada de Barcelona shelf, Paria sub-basin) [see Tables 6.3, 6.4 and 6.5]. It is characterized by the predominance of dextral E-W strike-slip faults and WNW- trending normal faults (Figure 6.26). This structural pattern suggests a change of the dynamic conditions from a dominant WNW-ESE oriented transpression during Middle Miocene to a prevailing dextral E-W strike-slip component from Late Miocene on.

The most important strike-slip systems related to the Late Neogene - Present transtension were discussed previously in Section 6.4. They are: the El Pilar-San Sebastian fault system, the Margarita-Tortuga/Coque fault system, the Coche-North Coast fault system, and the El Pilar/Casanay-Warm Springs fault system. Besides the
transtensional deformation, the Coche-North Coast fault system also produces NE-trending transpressional features (e.g., the Bocas High) [see Figures 6.16 and 6.17].

The Late Miocene-Present dominant transtension, north of the northern Venezuela shoreline is coeval with the development of the Gulf of Paria pull-apart basin and with the frontal deformation in the Maturín sub-basin (Figure 6.26). The distribution of Late Miocene-Present transtensional systems shown on Figure 6.26 suggests a shift of the tectonic deformation, i.e., from a Northern Paleogene extensional system to a Southern Late Neogene transtensional system. As shown on the Paleogene isotime map (Figure 6.4), there is no transtension along the southern part of the northeastern Venezuelan offshore during the Paleogene. This observation, together with the distribution of the Late Miocene-Present faulting systems (Figure 6.26), lends support to the idea that the Southern Late Neogene transtensional system is independent and separated from the Northern Paleogene extensional system.

6.6. Summary

A summary of the structural regimes that occurred in the northeastern Venezuela offshore is illustrated on Table 6.3, 6.4, and 6.5. As can be seen on these tables, the Paleogene evolution of the area is dominated by an extensional deformation that is mostly limited to the northern part of the area (i.e., the La Tortuga and the La Blanquilla Basins and the southeastern Margarita and Caracolito sub-basins). Transpressional tectonic activity during the Oligocene to Early Miocene produced the inversion of NE-trending
normal faults in the Caracolito sub-basin, as well as the basement uplift in the Patao High. The timing of this tectonic inversion is slightly different in the southeastern Margarita sub-basin, the La Blanquilla and the La Tortuga Basins. In these depressions, the inversion occurred during Middle Miocene and perhaps lower Late Miocene.

In the Caracolito sub-basin, the Patao High and the northern Tuy-Cariaco sub-basin, the Middle Miocene is characterized by high subsidence. During the Late Miocene to Present, a transpressional(?) arch in the central and northern part of the northeastern Venezuela offshore is suggested to be coeval with a southern transtensional regime.

The presence of the Pliocene-Pleistocene northern Tuy-Cariaco sub-basin and the Middle Miocene-Present Cariaco trough suggests the Cariaco area as a region marked by a strong Late Neogene transtension. It contrasts with the evolution of the Carúpano area which overall was shaped by a Paleogene extension, except for the southern part where structural lows (e.g., the Paria sub-basin) are the product of the Late Neogene Coche-North Coast strike-slip fault system activity.
CHAPTER 7

DISCUSSION AND CONCLUSIONS

7.1. Introduction

All the transpressional, transtensional and strike-slip structural assemblages developed in the northeastern Venezuela offshore during the Tertiary appear to be controlled by the WNW-ESE oblique convergence between the Caribbean and South American plates. This implies that strain partitioning not only involved a N-S compressional component and an E-W strike-slip component but that strain partitioning also is responsible for Neogene SW-NE transtension. Paleogene NW-SE extension, which may be due to Atlantic slab retreat, results when the subduction rate is greater than the convergence rate.

Such a relationship between the subduction and the convergent vectors was anticipated by Dewey (1980) in his discussion of arc systems. In this perspective the Paleogene Margarita-Los Testigos- Aves/ Grenada arc might be an extensional arc where the overriding plate (Caribbean plate) advances more slowly than the retreat of the Atlantic subduction hinge.

As was pointed out by Royden (1993), in a retreating subduction boundary, the poor transmission of horizontal compressive stress across the plate boundary leads to regional extension within the overriding plate. An opposite situation applies to advancing
subduction boundaries, i.e., compression occurs when the rate of subduction is less than the rate of convergence; in this case the transmission of horizontal compressive stress is larger and the regional deformation is characterized by horizontal shortening (Figure 7.1). A similar argument can be made for widespread transtension on strike slip margins (e.g. Offshore Northeastern Venezuela) versus widespread transpression on strike slip margins (e.g., California, see Sylvester and Smith, 1976; Sylvester, 1984, 1988).

The slab retreat may be more common in west-dipping subduction zones (such as the Lesser Antilles), which are according to Doglioni (1993) and Shahabpour (1997), oppose the relative eastward-northeastward mantle counterflow that may result from a postulated westward drift of the lithosphere (Figure 7.2).

The two models proposed for the present-day motions between the Caribbean and adjacent plates may also lend some support to the idea of slab retreat (Figure 7.3). The Jordan (1975) model, based on the spreading rate and azimuth at the Cayman Spreading Center, predicts Caribbean-South America oblique convergence at about 2 cm/yr in a WNW - ESE direction. The Sykes et al. (1982) model, based on the configuration on the Lesser Antilles Wadati-Benioff zone, predicts South America-Caribbean motion at about 4 cm/yr in a WSW-ENE direction. Qualitatively speaking, it seems that Jordan's Caribbean-South American rate might be considered as an estimate of the Caribbean convergence rate and the Sykes et al.'s South America-Caribbean rate might be considered as a rough estimate of the Atlantic subduction beneath the Caribbean plate. Thus, from the vectorial comparison, the Sykes et al.'s subduction rate is greater than Jordan's convergence rate; consequently in the sense of Royden (1993), or Waschbusch
Figure 7.1. Schematic diagram illustrating deformation of upper plate rocks in response to the relative rates of convergence (vector AB) and subduction (vector AC). At advancing plate boundaries (left side) the rate of overall plate convergence is faster than the rate of subduction and the upper plate deforms regionally by horizontal shortening. At retreating plate boundaries (right side) the rate of overall plate convergence is slower than the rate of subduction and the upper plate deforms regionally by horizontal extension.
Figure 7.2. The main volcanic trails at the Earth’s surface have different source depths. The solid half arrows indicate the direction of migration of volcanism with time. Filled triangles represent the youngest volcanic products. Superficial hot spots such as some of those located along mid-oceanic ridges are not fixed because oceanic ridges are continuously moving with respect to one another, and thus the relative positions of the volcanic tracks are not reliable indicators of a fixed frame of reference. Other volcanic trails may be identified in a map view due to the propagation of a rift zone, without any implication for the motion of the lithosphere relative to the underlying mantle. If the hot spot reference frame is filtered, by removing such misleading tracks, the apparent westward drift of the lithosphere would increase by several centimeters per year. Light stipple, lithosphere; IA, island arc basalts; MORB, mid-ocean ridge basalts; OIB, ocean island basalts. From Dogliani (1993).
Figure 7.3. Alternative models for Caribbean Plate relative motions. The Jordan model, based on the spreading rate and azimuth at the Cayman Spreading Center, predicts approximately 2 cm/yr of NA-CA motion. The Sykes et al. model, based on the configuration of the Lesser Antilles Wadati-Benioff zone, predicts a NA-CA rate approximately twice as high and a more northerly azimuth. The predicted SA-CA motions also differ. The Jordan model predicts oblique convergence at about 2 cm/yr; the Sykes model predicts oblique extension at about 4 cm/yr. From Stein et al. (1988).
and Beaumont (1996), the Atlantic-Caribbean subduction zone may be defined as a retreating subduction boundary.

7.2. Discussion

To the north of the El Pilar fault, except for the isolated occurrence of the El Cantil Serranía-type limestones in well-21 (Foldouts 7 and 9), most of the Venezuelan platform appears to be underlain by a metamorphic sequence of gneisses and metasedimentary rocks that involve former passive margin sediments, meta-ophiolites and MORB-type volcanics of Jurassic to Early Cretaceous age, as well as Primitive island arc (PIA). This accretionary complex was assembled by mid-Cretaceous time (e.g., Stöckhert et al., 1995) and subjected to metamorphism until the Late Cretaceous. The reconstructed position of the accretionary complex and its associated island arc is shown on Figure 7.4.

Late Cretaceous - Paleogene calc-alkaline igneous rocks and their volcanic equivalents were emplaced in this accretionary complex. During the Paleogene, in the Los Testigos Archipelago, island arc volcanic activity continued until earliest Oligocene (Talukdar, 1983).

To the south of the El Pilar fault, the pre-Neogene basement of the Ensenada de Barcelona shelf consists of the continuation of the Villa de Cura klippe which probably is directly overlying the frontal folds and imbricates of the outer Faja Piemontina and the
Adapted from Stephan et al., 1990; Pindell and Barrett, 1990; and Pindell and Tabbutt, 1995

Figure 7.4. Plate tectonic reconstruction, Cretaceous [Maastrichtian (67 Ma)].
Serranía del Interior. Both in turn are likely to be underlain by the Paleozoic basement of the southern foreland.

The Lower Cretaceous Serranía-type El Cantil drilled in the Bocas High of the southern Carúpano area represents an unusual situation where Cretaceous Serranía-type carbonates occur isolated within an igneous-metamorphic terrain. These carbonates are clearly in an abnormal stratigraphical or structural relationship with the underlying Upper Cretaceous volcanic epiclastics and meta-sedimentary rocks. This could be due to reverse faulting associated with a major right-lateral strike-slip system as suggested by Figure 6.17, on which the Bocas High appears to be a transpressional high linked to the Late Neogene Coche-North Coast strike-slip fault system. Another alternative proposed by Furrer (1984) could be that these Lower Cretaceous carbonates may have slid into a paleo-trough filled with Upper Cretaceous rocks.

The evolution of the Paleogene extensional basins and their stratigraphy is illustrated by the reconstruction (Figure 7.5) and as an example by the stratigraphic summary of the Caracolito sub-basin (Figure 5.8) that suggests that the Carúpano area is characterized by bathyal sediments from the Eocene to the Middle Miocene. The Caracolito sub-basin is a Paleogene extensional graben system that was filled by deep water sediments, volcaniclastics and shallow water clasts transported by turbidity currents. Figure 7.6 by Cliff et al.(1995) serves as a conceptual representation of the early history of this sub-basin. The Lower(?)-Middle Eocene deep water sediments directly overlying the top of the igneous-metamorphic basement permit to visualize this surface as a peneplane that suddenly collapsed due to fore-arc and back arc extension.
Figure 7.5. Restored position of the Caracolito-Margarita-Blanquilla zone, Middle Eocene (~49 MA)

1: La Blanquilla basin
2: Southeastern Margarita and Caracolito sub-basins

Adapted from Stephan et al., 1990; Pindell and Barrett, 1990; and Pindell and Tabbutt, 1995
Figure 7.6. Diagram of Lau Basin by Cliff et al. (1995) serves as a conceptual representation of the early history of the Caracolito sub-basin showing the generation of volcanoclastic sediment by explosive eruption at nearby seamount volcanoes. The sediment is subsequently reworked as debris flows and turbidites and transported into the central part of the graben.
In the Cariaco area, the depositional environments are more diverse. In the Tortuga Paleogene extensional basin deep water sedimentation lasted until Early Miocene. From the Early Miocene to the Present, transgressive and regressive sedimentary cycles (Figure 4.5) confine the deposition within the upper bathyal to middle neritic domain. To the south of the Tortuga High, the Eocene-Middle Miocene sedimentary rocks consist mainly of shallow water sediments. The Cubagua sub-basin is an exception. In this sub-basin, deep water Eocene sedimentary rocks are overlain by the continental Oligocene-Lower Miocene sedimentary rocks. In some other cases in the Cariaco area, the Eocene to Middle Miocene could be absent (e.g., in the Ensenada de Barcelona shelf).

Accepting Pindell and Barrett's (1990) and Stephan's (1990) reconstructions of the Middle Eocene (Figure 7.5), the Eocene basins (i.e., the La Tortuga Basin, the La Blanquilla Basin and the Caracolito sub-basin) and Margarita Island were located offshore and to the north of the Golfo de Venezuela area. In other words the Eocene extensional basins are superimposed on a large transpressional Cretaceous/Eocene accretionary wedge which formed the internal main body of the more external Lara nappes (Stephan oral communication, 1997). These nappes were emplaced at the same time and to the northeast of the Misoa/Trujillo foredeep of the Maracaibo Basin.

Apparently near normal-arc extension during the Paleogene time is coeval with magmatic intrusion such as the Los Testigos complex (Figures 6.19 and 6.21). This extension occurs both in the fore arc (i.e., Caracolito sub-basin and toward the Tobago Basin) and in the back arc (i.e., La Blanquilla Basin and toward Grenada) regions and it
may be explained by the intiation of subduction rollback in the sense of Royden (1993). The distribution of the Middle Eocene normal faults parallel or sub-parallel to the Margarita - Los Testigos arc (Figure 6.19) constrains the inception of the retreating subduction boundary stage. According to Caribbean plate reconstructions (e.g., Burke, 1984; Pindell and Barret, 1990; Pindell, 1995), it seems that during Early Eocene or lower Middle Eocene the Caribbean plate underwent a no free face stage related to its collision with the Bahama platform. After this event, the ejection and southeastward escape of the proto-Lesser Antilles arc during Middle Eocene would lead to a retreating subduction boundary facing an unconstrained subducting Atlantic lithosphere.

In a tomographic image (van der Hilst, 1990), the Atlantic subduction below the southern Lesser Antilles is associated with a steeply dipping slab (see Section 6.8.f on Figure 3.21) suggesting the eastward retrograde motion of the subducted old Atlantic lithosphere.

During Late Eocene, the rifting regime becomes more accentuated. Most of the faults are near- parallel to the La Tortuga High and the Margarita - Los Testigos High, still implying a dominant near-normal arc extension. Of secondary importance are WNW-ESE normal faults which could be viewed as transfer faults that perhaps precede the formation of the younger NW-trending Margarita right-lateral fault.

Following this plate tectonic scenario, the Caribbean plate continues its migration toward the east and from here on is now characterized by a large strike component and a smaller dip-slip component (Figure 7.7). In this overall context from the Oligocene to Early Miocene, the NNW-SSE transtension of the Blanquilla Basin is coeval and parallel
**Figure 7.7.** Restored position of the Caracolito-Margarita-La Blanquilla zone, Late Eocene (~ 37 MA)

1: La Blanquilla Basin
2: Southeastern Margarita and Caracolito sub-basins

Adapted from Stephan et al., 1990; Pindell and Barrett, 1990; and Pindell and Tabbutt, 1995

- AR: Aves Ridge
- BR: Beata Ridge
- OB: Colombia Basin
- DR: Demerara Rise
- EVzB: Eastern Venezuelan Basin
- GB: Grenada Basin
- Gy: Guyana
- LA: Lesser Antilles
- Ma: Margarita Island
- MaB: Maracaibo Basin
- PaA: Panama Arc
- VB: Venezuela Basin
- VzCC: Venezuelan Coastal Cordillera
to the transpression of the Caracolito sub-basin. This situation is an example of coeval
distensive deformation behind a transpressional front which again might be explained by
the slab retreat mechanism, i.e., the rate of subduction exceeds the rate of convergence
producing a subduction rollback and consequently transtension in the distal part of the
convergent block. By the Early Miocene (Figure 7.8), the Caribbean arc system reaches
the Ensenada de Barcelona shelf producing the loading that causes the foredeep
unconformity (see DiCroce, 1995).

During the Middle Miocene, the Cariaco trough appears for the first time to be
linked to the El Pilar right-lateral strike-slip system (Figure 6.24). Transtensional activity
during this time is coeval with mild inversion on the northern part of the northeastern
Venezuela offshore (i.e., the La Tortuga and the La Blanquilla Basins) and the
southeastern Margarita sub-basin. It is also contemporaneous with a pronounced
subsidence event of the Carúpano Basin "sensu strictu" but, even more important, with
the inception of the deformation of the Serranía del Interior in the Eastern Venezuela
Basin. To the south of the El Pilar fault, the map of the distribution of Middle Miocene
faulting systems documents an unquestionable transpressional domain. To the north of
the El Pilar fault, the structural features are more complex but characterized by
considerable transtension.

From Middle Miocene on, the diversity of the structural styles is testimony of a
complex strain partitioning system. A prevailing strike-slip component may explain the
tectonic nature of the structures; i.e., most of the structures formed in response to EW-
trending dextral transform boundary within a general oblique convergent tectonic
Figure 7.8. Restored position of the major basins in Carúpano and Cariaco area, Early Miocene (20 MA)

Adapted from Stephan et al., 1990; Pindell and Barrett, 1990; and Pindell and Tabbutt, 1995
framework. The simultaneous coexistence of transpression and transtension is quite common. The regional picture is best described as follows: Transtensional features are mostly limited to the southern part of the Cariaco and Carúpano Basins (see Figure 6.26); a transpressional(?) arch is suggested in the central and northern part; and dominant NNW- SSE transpression in the Serranía and its foreland.

The Late Miocene plate tectonic reconstruction and the Present configuration of the Caribbean plate (Figures 7.9 and 7.10) illustrate the eastward migration of the Caribbean plate. The important point to retain from the Late Miocene reconstruction is that the Boconó-San Sebastian-El Pilar is an entirely a Middle Miocene- Plio/Pleistocene fault system. This fault system together with the Late Miocene-Pliocene Coche-North Coast fault system control the evolution of the Late Neogene transtensional basins on the southern part of the northeastern Venezuela offshore.

Overall it seems that the evolution of the study area involves:

(1) Paleogene arc- normal extension mainly limited to the northern part of the study area that is associated with a retreating subduction boundary.

(2) An Oligocene to Middle Miocene inversion phase that precedes the following stage.

(3) Neogene arc-subparallel extension is limited to the southern part of the study area and is linked to a complex strain partitioning mechanism which involves transpression in the Serranía del Interior and transtension enhanced by subduction rollback on the Northeastern Venezuela shelf and the Gulf of Paria.
Figure 7.9. Restored position of the major basins of the Caríaco and Carúpano areas, late Miocene (10 Ma). Adapted from Stephan et al., 1990; Pindell and Barrett, 1990; and Pindell and Tabbutt, 1995.
7.3. Conclusions

(1) The pre-Tertiary basement consists of a deeply subducted accretionary complex of a Cretaceous island arc system that formed far to the west of its present location. The internal structure of this basement consists of metamorphic nappes that involve passive margin sequences, as well as oceanic (ophiolitic) elements.

(2) The pre-Tertiary basement was uplifted prior to and deeply eroded and peneplaned during the Paleocene-Early Eocene.

(3) The Tertiary evolution of the northeastern Venezuela offshore is dominated by Paleogene extension and Neogene transtension. The Paleogene extensional structures are limited to an area that is farther north of and not directly tied to the El Pilar fault system.

(4) The Oligocene to Middle Miocene inversions are coeval and probably linked to the transtensional systems reported from the Falcón area (Audemard, 1991; Macellari, 1995). This relationship requires further study.

(5) The Margarita fault is a strike slip fault that may have been initiated as an Eocene transfer fault separating the Paleogene La Blanquilla and La Tortuga extensional systems.

(6) Eocene extension is limited to the La Tortuga and La Blanquilla Basins and the southeastern Margarita and Caracolito sub-basins. The first Oligocene inversion occurred in the Caracolito sub-basin.

(7) The San Sebastian/El Pilar fault system is exclusively Neogene with major transtension occurring during the Late Miocene to Recent.
(8) On a reconstruction the Paleogene extensional system was located to the north of the present-day Maracaibo Basin. It was emplaced on the eroded and peneplaned top of an uplifted Cretaceous accretionary wedge, which was still active in the area of the Lara nappes and responsible for the Guárico flysch foredeep and the Misoa/Trujillo foredeep of the Maracaibo Basin.

(9) By Early Miocene the leading edge of the now transpressional system had migrated to a position north of the Ensenada de Barcelona. This relative to South America eastward migration is responsible for the major inversions that began during the Oligocene and lasted into the Middle Miocene.

(10) The Middle Miocene to Recent Boconó-El Pilar-Casanay-Warm Springs transtensional system formed later and acted independently from the earlier Paleogene extensional system. It is responsible for the large Neogene transtensional basins of the area: the Cariaco trough, the Northern Tuy-Cariaco and the Paria sub-basins, and the Gulf of Paria transtensional Basin.

(11) This latest phase is characterized by strain-partitioning into strike slip faults, an overall transtensional northern domain and transpressional southern domain that is responsible for the décollement tectonics and/or inversions of the Serranía del Interior and its associated Monagas foreland structures.

(12) Part of the latest (Middle Miocene to Recent) phase is the formation of a large arch that corresponds to the Margarita-Testigos-Grenada zone which perhaps was subject to mild lithospheric compression during the Plio-Pleistocene.
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UMI
PANEL-1
Cariaco Area
NORTH VENEZUELA
Regional Transects
(S-N Sections)

LOCATION MAP

LEGEND
LEGEND

SYMBOLS

KEY WELL

CROSS POINT WITH THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS
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PANEL-2
Cariaco Area
NORTH VENEZUELA
Regional Transects
(W-E Sections)
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PANEL-3
Cariaco Area
NORTH VENEZUELA
Regional Transects
(W-E Sections)

LEGEND

SYMBOLS

KEY WELL

B CROSS POINT WITH THE SECTION B

NORMAL FAULT
THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS

LOCATION MAP
NOTE TO USERS

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PANEL-4
Cariaco Area
NORTH VENEZUELA
Margarita Depression/Platform
(SW-NE Sections)
LOCATION MAP

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS

LA BLANQUILLA HIGH

RAUL YSACCIS (1997)
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UMI
PANEL-5
Cariaco Area
NORTH VENEZUELA
Northwestern Tortuga
(SE-NW Sections)

LEGEND

SYMBOLS

KEYWELL

CROSS POINT WITH THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS

LOCATION MAP
Caria northwest (SE-NW)

B18

B17

5 KM
Cariaco Area
NORTH VENEZUELA
Northwestern Tortuga
(SE-NW Sections)

LEGEND

SYMBOLS

KEYWELL

CROSS POINT WITH
THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-
METAMORPHIC ROCKS

LOCATION MAP

RAUL YSACCIS (1997)
NOTE TO USERS

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PANEL-6
Cariaco Area
NORTH VENEZUELA
Southeastern Tortuga
(SE-NW Sections)

LEGEND

SYMBOLS

KEYWELL

B CROSS POINT WITH THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS
NOTE TO USERS

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UMI
PANEL-7
Cariaco Area
NORTH VENEZUELA

Ensenada de Barcelona Shelf (W-E Sections)
PANEL-7
Cariaco Area
NORTH VENEZUELA
Ensenada de Barcelona Shelf
(W-E Sections)

LOCATION MAP

RAUL YSACCIS (1997)
NOTE TO USERS

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UMI
PANEL-8
Cariaco Area
NORTH VENEZUELA
Ensenada de Barcelona Shelf
(S-N Sections)

LEGEND

SYMBOLS

KEYWELL

CROSS POINT WITH THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS
NOTE TO USERS

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UMI
PANEL-9
Cariaco Area
NORTH VENEZUELA
Margarita Platform
(S-N Sections)

LEGEND

SYMBOLS

KEYWELL

CROSS POINT WITH THE SECTION B

NORMAL FAULT

REVERSE FAULT

CRETACEOUS IGNEOUS-METAMORPHIC ROCKS
NOTE TO USERS

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PANEL-10
Carupano Area
NORTH VENEZUELA
Regional Transects
(S-N Sections)

EASTERN PROLONGATION OF
THE LA BLANQUILLA BASIN
ABBREVIATIONS

L-M PLIOC.: LATE - MIDDLE
EP-LM: EARLY PLIOCENE
MM B: MIDDLE MIocene
MM A: MIDDLE MIocene
EM: EARLY MIocene
OLIGOC.: OLIGOCENE
O - E: OLIGOCENE (?) - EOC
ME: MIDDLE EOCENE
NOTE TO USERS

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UMI
PANEL-11
Carupano Area
NORTH VENEZUELA
Regional Transects
(W-E Sections)
NOTE TO USERS

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TRIKE SECTION (SW-NE)

A31

CARACOLITO SUB-BASIN

RECENT-PLEISTOC.

L-M PLIOCENE

EP - LM

MIDDLE MIocene "A"

MIDDLE MIocene "B"

OLIGOCENE

EUROC - ECC

MIDDLE ECC

OLIGOCENE

EP - LM

MIDDLE MIocene "A"

RECENT-PLEISTOC.

TIME (SEC)

0.0

1.0

2.0

3.0

4.0

5.0

N60°E

10 KM

PANEL-12

Carupano Area

NORTH VENEZUELA

LEGEND

SYMBOLS

KEY WELL

CROSS POINT WITH
ABBREVIATIONS

L-M PLIOC.: LATE - MIDDLE
EP-LM: EARLY PLIOCENE - MIDDLE PLIOCENE
MMB: MIDDLE MIocene "b"
MMA: MIDDLE MIocene "a"
EM: EARLY MIocene
OLIGOC.: OLIGOCene
O-E: OLIGOCene (?) - EOC
ME: MIDDLE EOCene
SYMBOLS

KEY WELL

CROSS POINT WITH
THE SECTION A

NORMAL FAULT

REVERSE FAULT

REVERSE FAULT

RIGHT-LATERAL
STRIKE-SLIP FAULT

LOS TESTIGOS COMPLEX
(Late Eocene - Early Oligocene)

MESOZOIC IGNEOUS-
METAMORPHIC ROCKS

LOCATION MAP
LOCATION MAP
NOTE TO USERS

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UMI
FOLDOUT 2. SECTION 2 (based on well and seismic data)
NOTE TO USERS

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UMI
ENSENADA DE BARCELONA SHELF

39.5 km

WELL-10

SEA LEVEL

WELL-11

RECENT - PLEISTOCENE

PLIOCENE

LATE MIocene

CRETACEOUS

TD = 4677'

T.D. = 9136'

NO SAMPLES

DEPTH (FEET)

AGE

DEPOSITIONAL ENVIRONMENT

LITHOLOGY

GAMMA RAY

NO SAMPLES
GENERALIZED SW - NW TRENDE FROM ENSENADA DE BARCELONA

99 km

CARIACO TROUGH

SEA WATER

RECENT - PLEISTOCENE

PLEISTOCENE

LATE MIocene

EL PILAR
CUBAGUA SUB-BASIN

WELL-4

DEEP (FEET)

AGE

DEPOSITIONAL ENVIRONMENT

LITHOLOGY

GAMMA RAY

NO SAMPLES

RECENT-PLEISTOCENE

PLIOCENE

LATE MIocene

? MIDDLE MIocene

EARLY MIocene

OLIGOCENE

EOCENE

PROBABLY CONTINUATION OF
FOLDOUT 3. SECTION 3 (based on well and seismic data)
MARLS
SHALES
CLAYSTONES
SILTSTONES
FINE SANDSTONES
SANDSTONES
CONGLOMERATES
VOLCANIC ROCKS
METAMORPHIC ROCKS
IGNEOUS INTRUSIONS

LOCATION MAP

VOLC. = VOLCANIC ROCKS

KAGGERATION = 16.5 X

Raul Ysaccis
July 1997.
NOTE TO USERS

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UMI
FOLDOUT 5. SECTION 5  (based on stratigraphic and geologic data)
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UMI
THE GEOLOGICAL SECTION FROM THE BASIN TO MARGARITA ISLAND

NORTHERN TUY-CARIACO
SUB-BASIN

51.25 km

WELL-5

DEPTH (FEET)

AGE DEPOSITIONAL ENVIRONMENT LITHOLOGY GAMMA RAY

PLIOCENE

OUTER TO MIDDLE SEDIMENTARY

NO SAMPLES

RECENT - PLEISTOCENE

PLIOCENE

SEA WATER

NO SAMPLES

MARGARITA

STRIKE-SLIP FAULT

UJA HIGH
FROM THE LA TORTUGA RID

MACANAO PENINSULA

E

LEGEND

- MICROFOSSILS
- MACROFOSSILS
- LIMESTONES
- MARLS
- SHALES
- CLAYSTONES
- Siltstones
- Very-fine Sandstones
- Sandstones
- Conglomerates
- Volcanic Rocks
- Metamorphic Rocks

STRIKE-SLIP FAULT

CRETACEOUS BASEMENT
NOTE TO USERS

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UMI
FOLDOUT 6
NORTH VENEZUELA

ISOTIME MAP
PALEOGENE UNIT

LEGEND

\[\text{\textbackslash strike-slip} \text{ (Arrows show direction on displacement)}\]

\[\text{\textbackslash reverse-fault} \text{ (Triangle on upthrown side)}\]

\[\text{\textbackslash normal-fault} \text{ (Barbs on downthrown side)}\]

\[\text{\textbackslash inferred-fault} \]

\[-1.0\]

\[\text{\textbackslash contour-line} \]

\[\bullet\]

WELL LOCATION
NORMAL FAULT (Barbs on downthrown side)

INFERRED FAULT

CONTOUR LINE

WELL LOCATION

SEISMIC CONTOUR INTERVAL
0.5 Sec. (TWT)

0.0
0.5
1.0
1.5
2.0
2.5
3.0

50 km

RAUL YSACCIS, 1997
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ABBREVIATIONS
AGE
E.C. = EARLY CRETACEOUS
E.M. = EARLY MIOCENE
E.O. = EARLY OLIGOCENE
E.P. = EARLY PLIOCENE
L.E. = LATE EOCENE
L.M. = LATE MIOCENE
ENVIRONMENT
I. NER. = INNER NERITIC
O-M NER. = OUTER TO MIDDLE NERITIC
M-L BAT. = MIDDLE TO LOWER BATHYAL
PRIM. = PRIMITIVE
UP. BAT./O. NER. = UPPER BATHYAL TO OUTER NERITIC

VERTICAL SCALE IN FEET
VERTICAL EXAGGERATION ≈ 12.5 X
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UMI
ABBREVIATIONS

AGES
E.M. = EARLY MIocene
E-M EOC. = EARLY TO BASAL MIDDLE EOCENE
E. PLIOC. = EARLY PLIOCENE
L.M. = LATE MIocene
MIOC. = MIocene
M. PLIOC. = MIDDLE PLIOCENE
U. MID-LAT EOC. = UPPER MIDDLE TO LATE EOCENE

ENVIRONMENT
I. NER. = INNER NERITIC
O-M NER. = OUTER TO MIDDLE NERITIC
PLATFORM = PLATFORM
PRIM. = PRIMITIVE

FOLDOUT 8. SECTION 7 (based on well and seismic d
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UMI
### Section in the Eastern Part of [Relevant Location]

<table>
<thead>
<tr>
<th>Depth (Feet)</th>
<th>TD = 8700'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

#### Stratigraphic Section

- **Middle Miocene**
- **Late Miocene**
- **Early Pliocene**
- **Middle Pliocene**
- **Late Pliocene**
- **Pleistocene - Recent**
- **Middle Neritic to Inner Neritic Shelf**
- **Depositional Environments**
- **Lithology**

**Patao**

**Well-26**

**Well-27**

**Well-30**

**Uquire**

- 4.75 km
- 27.13 km

---

**Note:** The diagram depicts a section with various geological layers and their respective depths and environments.
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UMI
VERTICAL EXAGGERATION ≈ 12:1

VERTICAL SCALE IN FEET
AND CALCARENITE
FINE SANDSTONES
SANDSTONES
CONGLOMERATES
VOLCANIC ROCKS (MATURE ISLAND ARC)
VOLCANIC ROCKS (PRIMITIVE ISLAND ARC)
METAMORPHIC ROCKS
VOLCANIC ROCKS (MORB)

LOCATION MAP

Raul Ysaccis, 1997
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UMI
NORTHEASTERN VENEZUELA TECTONIC MAP

LEGEND

- Trace of Subduction (teeth on upper plate)
- Highly Folded Sediments

A. TECTONIC SYSTEM OF VENEZUELAN OFFSHORE AND COASTAL CORDILLO

- Strike-Slip (Arrows show direction on displacement)
- Reverse Fault (Triangle on upthrown side)
- Normal Fault (Barbs on downthrown side)
- Fault
- Inferred Fault
- Anticline
- Contour Line of Cretaceous Basement
- Well Location

B. TECTONIC SYSTEM OF "SERRANIA DEL INTERIOR" AND SOUTHERN TRINIDAD

- Tear Fault (Arrows show direction on displacement)
- Reverse Fault (Triangle on upthrown side)
- Normal Fault (Barbs on downthrown side)
- Fault
- Anticline
- Syncline
- Cretaceous Sedimentary Rocks

C. TRANSTENSIONAL SYSTEM OF GULF OF PARIA (NORTHERN AREA) AND NORTHERN TRINIDAD

- Strike-Slip (Arrows show direction on displacement)
- Normal Fault (Barbs on downthrown side)
B.- TECTONIC SYSTEM OF "SERRANIA DEL INTERIOR" AND SOUTHERN TRINIDAD

- TEAR FAULT (Arrows show direction on displacement)
- REVERSE FAULT (Triangle on upthrown side)
- NORMAL FAULT (Bars on downthrown side)
- FAULT
- ANTICLINE
- SYNCLINE
- CRETACEOUS SEDIMENTARY ROCKS

C.- TRANSTENSIONAL SYSTEM OF GULF OF PARIA (NORTHERN AREA) AND NORTHERN TRINIDAD

- STRIKE-SLIP (Arrows show direction on displacement)
- NORMAL FAULT (Bars on downthrown side)
- SYNCLINE

D.- NEOGENE GROWTH FAULT SYSTEM (OFFSHORE OF SOUTHEASTERN TRINIDAD)

- GROWTH FAULT

MAGNETIC ANOMALY

REFERENCES
- STRUCTURE OF "SERRANIA DEL INTERIOR" AND COASTAL CORDILLERA ADAPTED FROM BELLADA AND PARENTEL (1976).
- STRUCTURE OF GULF OF PARIA ACCORDING TO PUNCH ET AL. (1996)
- DEFORMATION FRONT IN MATURE SUB-BASIN IS TRACED AFTER DIORGE (1990)
- STRUCTURAL INTERPRETATION OF THE VENEZUELAN OFFSHORE BASED ON THIS STUDY.

50 KM

RAUL YSACCIS
MAY 1997
NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

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UMI
NORTHEASTERN VENEZUELA
TECTONIC MAP

LEGEND

TRACE OF SUBDUCTION
(teeth on upper plate)

A.- TECTONIC SYSTEM OF VENEZUELAN OFFSHORE
AND COASTAL CORDILLERA

STRIKE-SLIP (Arrows show
direction on displacement)

REVERSE FAULT (Triangle
on upthrown side)

NORMAL FAULT (Barbs on
downthrown side)

FAULT

INFERRED FAULT

ANTICLINE

SEISMIC LINE

WELL LOCATION

B.- TECTONIC SYSTEM OF "SERRANIA DEL INTERIOR"
AND SOUTHERN TRINIDAD

TEAR FAULT (Arrows show
direction on displacement)

REVERSE FAULT (Triangle
on upthrown side)

NORMAL FAULT (Barbs on
downthrown side)

FAULT

ANTICLINE

SYNCLINE

C.- TRANSTENSIONAL SYSTEM OF GULF OF PARIA
(NORTHERN AREA) AND NORTHERN TRINIDAD

STRIKE-SLIP (Arrows show
direction on displacement)

NORMAL FAULT (Barbs on
downthrown side)

SYNCLINE
DISTRIBUTION OF FAULTING SYSTEMS
C.- TRANSTENSIONAL SYSTEM OF GULF OF PARIA (NORTHERN AREA) AND NORTHERN TRINIDAD

- STRIKE-SLIP (Arrows show direction of displacement)
- NORMAL FAULT (Barbs on downthrown side)
- SYNCLINE

D.- NEogene GROWTH FAULT SYSTEM (OFFSHORE OF SOUTHERN TRINIDAD)

- GROWTH FAULT

REFERENCES

- STRUCTURE OF "SERRANIA DEL INTERIOR" AND COASTAL CORDILLERA ADAPTED FROM BELLIZIA AND PIMENTEL (1976).
- STRUCTURE OF GULF OF PARIA ACCORDING TO FLINCH ET AL. (1996)
- DEFORMATION FRONT IN MATURIN SUB-BASIN IS TRACED AFTER DIOCESE (1995)
- STRUCTURAL INTERPRETATION OF THE VENEZUELAN OFFSHORE BASED ON THIS STUDY.

50 KM

RAUL YSACCIS, 1997
MIDDLE EOCENE
MIDDLE MIocene
LATE EOCENE - OLIGOCENE
NOTE TO USERS

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UMI
**ABBREVIATIONS**

- **E.M.** = **EARLY MIocene**
- **EOC.** = **EOCene**
- **L.M.-E.P.** = **LATE MIocene - EARLY PLIOcene**
- **MIOC.** = **MIocene**
- **M.M.** = **MIDDLE MIocene**
- **M.P.-R.** = **MIDDLE PLIOcene TO RECENT**
- **O.-L.E.** = **OLIGOCene - LATE EOCene**
- **OLIG.** = **OLIGOCene**
- **PLIOC.** = **PLIOcene**
REGIONAL CROSS SEC

MARGARITA SUB-BASIN

MARGARITA ISL

FIELD DATA (After Chevalier, 1)

ACOUSTIC BASEMENT
(MESOZOIC IGNEOUS - METAMORPHIC ROCKS)

RELATIVE AUTOCHTHON
(TRIASSIC ? - EARLY CRETACEOUS)
MARGARITA ISLAND

SECTION - A7

MID-OLIGOCENE - EOCENE

MIDDLE PLIocene - RECENT

MESOZOIC IGNEOUS - METAMORPHIC BASEMENT

LITHOSERIES

SANDSTONES

CLAY LITEST

EARLY CRETAceous?)

LOCATION