Chronology of Cenozoic tectonic events in western Venezuela and the Leeward Antilles based on integration of offshore seismic reflection data and onland geology

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Abstract

Newly acquired, deep penetration BOLIVAR seismic reflection data from offshore western Venezuela (Bonaire basin) and around the Leeward Antilles islands are combined with existing geologic and geophysical data sets to examine the chronology of Late Cretaceous-Cenozoic tectonic events in this part of the South America-Caribbean plate boundary zone. These tectonic events have controlled the maturation and structural trapping of known hydrocarbons in the offshore Bonaire basin and the adjacent onland Falcón basin. We infer three tectonic phases that are constrained using these combined data sets: 1) Late Eocene – early Oligocene, north-south opening of the 3 to 6-km-thick Falcón-Bonaire basin occurred along east-west striking normal fault systems that have locally been inverted by later tectonic phases; these Paleogene normal faults rifted Late Cretaceous arc crust and Paleogene marine depositional sequences within the offshore Bonaire basin; 2) northwest-striking normal faults crosscut the older
normal faults of the Bonaire basin and Leeward Antilles and form deep, submarine rifts that contain up to 4 km of sedimentary fill and form deepwater channels between islands of the Leeward Antilles; offshore well data and age of onshore sediments in the Falcón basin indicate that this second phase of rifting occurred mainly during late Oligocene through early Miocene, and remains active to the present; 3) inversion of the subaerial Falcón basin commenced during the middle Miocene; this inversion phase is reflected in the present-day pattern of an east-northeast-trending fold-thrust belt that can be traced over 200 km along strike in the Falcón basin; a second offshore fold-thrust belt (La Vela) can be traced over a distance of 175 km along strike and parallel to northeast-trending Falcon basin coast; restoration of imbricate thrusts seen on seismic lines perpendicular to the La Vela fold-thrust belt indicates a minimum of 7 km of northeast-southwest-directed, thin-skinned shortening. Geochemical work indicates that source rocks for scattered occurrences of hydrocarbons in the Falcón basin and its coastal zone are Paleogene and Miocene marine shale. Reservoir rocks are Tertiary marine sandstone and shale deposited in Paleogene rifts formed during the first tectonic phase in late Eocene to early Oligocene time. Structural traps were formed during thrusting during the second tectonic phase in late Oligocene through early Miocene time.

**Introduction and significance**

The complex chronology of Cretaceous-Cenozoic tectonic events along the Caribbean/South American plate boundary zone has been interpreted by previous workers (Eva et al., 1989; Mann et al., 1990; Pindell and Barrett, 1990; Ave Lallemant, 1997; James, 2000) (Fig. 1). These previous interpretations have focused on the interpretation of tectonic events inferred from onland outcrops because availability of offshore geophysical data has been limited (Biju-Duval et al., 1982) and because the thickest, most complete, and least deformed sections of Cenozoic rocks are found in offshore basins. Previous outcrop interpretations have emphasized the importance of Cretaceous and early Cenozoic events based on metamorphic and igneous outcrops of this age (Muessig, 1984; McMahon, 2000). In this
paper we make use of offshore 2D seismic data and published well data that considerably expands the spatial and temporal scale of observations (Cretaceous through recent) and exploits the more complete geologic record preserved in less deformed sedimentary rocks in less deformed, offshore sedimentary basins.

Western Venezuela, particularly the offshore and coastal regions of Gulf of Venezuela, Falcón basin, Bonaire basin, and the Leeward Antilles (Fig. 2), is an area of current interest to explorationists who seek to define the north and northeast limits of the prolific Maracaibo Basin petroleum system (Fig. 1). Tectonic models in current use by both the oil industry and academic geologists can be classified into two main groups (Fig. 3): 1) Cenozoic pull-apart basins opening along east-west-striking, plate-margin-parallel, right-lateral strike-slip faults (Muessig, 1978; Muessig, 1984; Boesi and Goddard, 1991; Macellari, 1995) (Fig. 3A); and 2) extensional opening of an east-west trending back-arc basin in a subduction setting (Audemard, 1993; Audemard, 1998; Mann, 1999; Porras, 2000) (Fig. 3B) or as a backarc basin that formed behind a north-south-trending subduction zone and has been rotated clockwise by 90° into an east-west orientation (Skerlec and Hargraves, 1980) (Fig. 3B).

The pull-apart model first proposed by Muessig (1978) suggests the presence of a ~ 200-km-wide right-lateral fault stepover in late Eocene-Oligocene time, between the Oca fault to the south and the South Caribbean deformed belt to the north (Fig. 3A). This proposed strike-slip plate boundary zone encompasses both the present-day onshore Falcón and offshore Bonaire basins (Fig. 3A). Muessig (1984) proposes a diffuse pull-apart zone consisting of areas of stable basement highs (e.g. Guajira, Paraguana, Los Monjes, Leeward Antilles islands) and intervening, subsiding basins (e.g. Urumaco trough, Falcón basin, La Vela Bay, and Bonaire basin) (Fig. 3A). Major structural highs are linked to roughly northwest-striking normal faults (Fig. 3A). Pull-apart-related subsidence is inferred to be of late Eocene-Oligocene age based on the ages of the oldest Falcón basin marine sedimentary deposits and alkali basalt magmas that intruded into the Falcon basin during the early to middle Miocene (Muessig, 1984; McMahon, 2000).
A second tectonic model proposes that the Falcón, Bonaire, and Grenada basins were once a continuous Late Cretaceous-Eocene back-arc basin associated with the Great Arc of the Caribbean (Audemard, 1993; Audemard, 1998; Mann, 1999; Porras, 2000) (Fig. 3B). The large-scale continuity of the arc-related belts of the southeastern Caribbean apparent in the gravity data and the Paleocene-Eocene age for the undeformed Grenada basin in the Lesser Antilles lends support to the back-arc model (Mann, 1999) (Fig. 1B).

**Objectives**

In this paper we use a compilation of geologic studies and new offshore geological data to examine the geologic and tectonic relationships between the inverted Falcón basin and the offshore Bonaire basin and a group of smaller basins forming deep submarine passages between the Leeward Antilles islands. Geophysical data include BOLIVAR 2D seismic reflection data acquired in 2004 in the Bonaire basin and Leeward Antilles islands and the GULFREX 2D seismic reflection data acquired in 1974 by Gulf Oil Corporation. We use our data to constrain three Eocene-Recent tectonic phases and place these events into the larger context of Cenozoic Caribbean-South American plate interactions.

**Regional setting of the study area**

*Caribbean/northern South American neotectonics*

Northwestern Venezuela, the Leeward Antilles islands of Aruba, Bonaire and Curacao, and the Venezuelan basin are part of a 600-km-wide plate boundary of deformation formed by Cretaceous-Cenozoic tectonic interaction between the Caribbean and South American plates (Silver et al., 1975; Mann et al., 1990). Topographic-bathymetric data (Fig. 1A) and free-air gravity data (Fig. 1B) (Sandwell and Smith, 1997) illustrate the diffuse extent of the active deformation zone along with the distribution of six major tectonic and geologic provinces present within our study area (Fig. 1). The 1600-km-long, active plate margin of northern South America is characterized as a broad zone of “tectonic
transpression,” or combined interplate strike-slip and convergence (Fig. 1A) (Stephan, 1985; Babb and Mann, 1999; Audemard, 2001; Audemard et al., 2005; McClay et al., 2005).

The present-day tectonic setting in the southeastern Caribbean is controlled by the eastward motion of the Caribbean plate relative to South America at a rate of about 20 mm/yr as shown by GPS-based geodetic results (Trenkamp et al., 1995; Pérez et al., 2001; Trenkamp et al., 2002) (Fig. 1A). The Oca-Ancon fault zone is a right-lateral strike-slip fault system that cuts across the northwestern margin of South America and forms the westernmost strand of a sub-parallel zone of right-lateral strike-slip faults that includes the San Sebastian and El Pilar fault zones (Audemard, 2001) (Fig. 1). North of the Leeward Antilles, the Caribbean plate underthrusts the South America plate (Kellogg, 1984; van der Hilst and Mann, 1994; Taboada et al., 2000; Colmenares and Zoback, 2003). To the east, the Atlantic plate (North and South America) underthrusts the Caribbean plate at the Barbados accretionary prism (Westbrook et al., 1988) (Fig. 1).

In western Venezuela, north-south tectonic convergence further complicates deformation within the broad plate boundary zone between the Caribbean and South American plates. GPS results in Figure 1A show that the western Venezuela/Leeward Antilles region is moving eastward at a rate of about 13-17 mm/yr (Pérez, et al., 2001). In this region, the interplate deformation zone extends ~600 km from the South Caribbean deformed belt in the Caribbean Sea to the Merida Andes (Silver et al., 1975; Ladd et al., 1984; Audemard, 1993; Audemard, 1998; Audemard and Audemard, 2002) (Fig. 1A).

North-south shortening has been attributed to north-south Cenozoic convergence between the North and South American plates (Pindell and Dewey, 1982; Colmenares and Zoback, 2003). Müller et al. (1999) outlines several stages of north-northwest directed interplate convergence at varying rates beginning in the early Eocene. A period of particularly fast convergence (~10 mm/yr) is suggested to have begun in the early Miocene and continues to the present-day (Kellogg, 1984). Pindell and Barrett (1990) suggest a total of 250 to 300 km of north-northwest directed convergence between North and
South America since the middle Eocene, whereas Müller et al. (1999) suggests a broader range of 200-400 km of north-south convergence since the early Eocene.

An important source of east-west plate convergence is created by Pliocene to recent subduction of the Nazca plate in western South America and the collision of the Panama arc with western Colombia (Mann and Burke, 1984; Kellogg, 1984; Trenkamp et al., 1995). Duque-Caro (1979) and Coates et al. (2004) use stratigraphic and paleontologic studies to infer that the collision between Panama and South America started at 10 Ma, whereas Audemard (1993; 1998), Audemard and Audemard (2002) and Audemard et al. (2005) propose a later suturing date around 5 Ma. Many authors have related the collision of the Panama arc to the northward extrusion or “escape” of continental fragments in a north to northeasterly direction (Pennington, 1981; Mann and Burke, 1984; Mann et al., 1990; van der Hilst and Mann, 1994; Audemard, 1993 and 1998); Trenkamp et al., 1995 and 2005).

**Subsurface geology of northwestern Venezuela**

The subsurface geology of northwestern Venezuela has three important components: basement geology, sedimentary sequences, and multiple fault families. Three basement provinces in northwestern Venezuela are distinguished primarily from published geologic and well data (Figs. 4A and 5). Next, a series of four seismic sequences is defined using all of the offshore seismic lines. These sequences are separated by unconformities and chronostratigraphically significant seismic reflections (Vail et al., 1977). Finally, two distinct fault patterns revealed by the offshore seismic data are interpreted from seismic lines and summarized on the basement structure map (Fig. 4B) and on a regional fence diagram (Fig. 6). The interaction between the three basement provinces, the three fault systems, and the four seismic sequences forms a basis for constraining our proposed series of three Cenozoic tectonic events that affected the region. Finally, the relationship between the three tectonic events and the distribution of known hydrocarbons in the different areas is discussed.
Three basement provinces of western Venezuela and the Leeward Antilles are identified based on well data compiled from González de Juana (1980), Curet (1992), and Macellari (1995), along with previous basement mapping efforts of Feo-Codecido et al. (1972) (Fig. 4A). Three wells drilled south and west of Aruba (Curet, 1992) reveal that basement in this area is composed of metamorphosed igneous rocks of the Cretaceous Caribbean arc (4A). Tholeiitic basalts and Andesitic volcanic rocks of oceanic affinity were penetrated in two of these wells and are similar to Cretaceous igneous outcrops of the Leeward Antilles islands (Jackson and Robinson, 1994) (Table 1A).

Well data from onshore Falcón and La Vela bay (Fig. 4A), reveal a different basement province associated with a Late Cretaceous intra-arc setting in this area. These wells, primarily in western and central Falcón (Fig. 4A) reveal Cretaceous metamorphosed igneous rocks that lack the oceanic affinity of the arc-related basement of the Leeward Antilles ridge (Macellari, 1995). González de Juana et al. (1980) reported that wells in La Vela bay penetrated basement consisting of gneiss, phyllite, and metamorphosed igneous rocks (Fig. 4A). Potassium argon dating yields ages of early to Late Cretaceous (Feo-Codecido et al., 1984). A third basement province of continental affinity is indicated by wells in the Guajira peninsula and northwestern Falcón basin (Fig. 4A). This basement province is related to the Paleozoic to Jurassic basement of the Maracaibo Basin as described from wells by Feo-Codecido (1984). Wells in this province (Fig. 4A) contain Paleozoic metamorphic rocks similar to those found in the basement of the Maracaibo Basin and are distinct from the two arc and intra-arc basement provinces defined above. A transition zone between the continental basement and the intra-arc basement is marked by the 40-km-wide Urumaco trough (Macellari, 1995). East of the Urumaco trough lies the Cretaceous metamorphic basement, while to the west is the Paleozoic continental basement province (Macellari, 1995) (Fig. 4A). Tertiary right-lateral strike-slip displacement along the Oca fault provides a possible explanation for the discontinuous arrangement of basement provinces in Figure 4A.
**Seismic sequences and age constraints**

Four seismic sequences are identified on the basis of lap relationships and reflection geometries in the offshore area (Vail et al., 1977) (Fig. 5). The sequences and the bounding surfaces are correlative throughout the region, although there is considerable variation in the character of individual sequences in each basin. These variations in seismic character within the different basins are summarized on Table 2.

Although there are few available offshore well ties in the region (Fig. 2), published stratigraphic information from the onshore La Vela oil field (González de Juana et al., 1980) was used to correlate the onshore stratigraphic units with the seismic data offshore (Fig. 5). Biju-Duval et al. (1982) made similar correlations using different offshore seismic data. In the Aruba basin, published well and seismic data from Curet (1992) provided additional constraints on the depositional setting and sedimentary thicknesses (Fig. 5). In our study, sparsely located well data is used to place age constraints on each of the four sequences. The sequences exhibit time-transgressive behavior as illustrated in Figure 5 and is described below.

**Cretaceous acoustic basement**

A strong regional reflector visible on all seismic lines marks the top of the acoustic basement (Fig. 6). This reflector separates the overlying sedimentary units, represented as coherent and continuous seismic strata, from underlying basement. Acoustic basement is generally chaotic in nature, with scattered continuous events possibly indicative of igneous sills or dikes, known from outcrop studies on Aruba (Jackson and Robinson, 1994) (Figs. 7, 8, 9 and 10). Throughout the region the basement exhibits superimposed faulting and folding (Fig. 4B).

**Late Eocene-Oligocene Sequence 1 (S1)**

This sequence unconformably overlies the acoustic basement (Figs. 9 and 10). Low frequency, variable amplitude reflectors onlap the acoustic basement reflector in each of the interpreted seismic sections (Figs. 7 to 11). Table 2 summarizes the varying reflection character of this sequence within the different offshore basins. This sequence is thickest (3000-4000 m) in the eastern part of the study area in
the Bonaire basin (Figs. 7 and 8). In the Aruba, West Curacao (Fig. 6), and Paraguana basins (Fig. 9), this unit is notably thinner (500-1000 m) than overlying sequences. Chaotic and shingled reflectors of the Bonaire basin (Fig. 7B-C) suggest erosion of sediments from the Leeward Antilles ridge and re-deposition in the central Bonaire basin (Fig. 4B). A different seismic character is found in the Aruba, Paraguana, and West Curacao basins, where parallel reflectors onlap basement (Fig. 9).

The age of Sequence 1 correlates with the earliest deposits of Eocene age in the Falcón basin (Wheeler, 1963; González de Juana et al., 1980). Sequence 1 spans the interval from late Eocene to late Oligocene based on published well data and onland-offshore correlations (Fig. 5). In the Falcón basin, these deposits are composed of deep-marine shale up to 4 km thick deposited during initial opening of the Falcón-Bonaire basin, as inferred from onshore well data (Fig. 5; Table 1B). In the Aruba basin, this sequence correlates with the upper Eocene-Oligocene unconformity-bounded lower sequence of Curet (1992) (Fig. 5). Well data from Curet (1992) show that this sequence is predominantly claystone and shale. Fossil paleobathymetric indicators from these wells reveal a deep marine depositional setting (Curet, 1992).

Throughout the region, sequence 1 is capped by a high amplitude reflector (Figs. 5, 8 and 9) that forms an angular unconformity in the western Bonaire (Fig. 7) and Paraguana basins (Fig. 9). In other locations, there is no observable unconformity due to poor data quality. This bounding surface is easily identified from a seismic character shift to high-frequency, highly reflective strata indicative of Sequence 2 (Figs 6, 8).

Early to middle Miocene sequence 2 (S2)

Sequence 2 comprises the thickest seismic unit in the offshore basins and rests unconformably on Sequence 1 (Figs. 5 and 9). Reflection character in Sequence 2 exhibits higher frequency and greater reflectivity than the underlying Sequence 1 (Fig. 5, Table 2). This sequence is dated to be early to middle Miocene based on its correlation with well data in Figure 5. In general, this was a period of major shale deposition throughout the Falcón and Aruba basins (Macellari, 1995) (Table 1B).
Offshore, parallel moderate frequency reflectors are apparent throughout Sequence 2 in the Paraguana (Fig. 9) and West Curacao basins (Fig. 8). These thick sedimentary packages are controlled by northwest-striking normal faults of Oligocene-Recent age (Figs. 4 and 6). In the Bonaire basin, wedge-shaped features are interspersed with parallel, low-amplitude reflectors (Figs. 7 and 8). Sequence 2 is notably thinner in the Bonaire basin (Figs. 7 and 8) than in the Paraguana (Fig. 9) and West Curacao basins (Fig. 11).

A pronounced angular unconformity caps Sequence 2 in the Paraguana and West Curacao basins (Figs. 9 and 11). This unconformity correlates with the Middle-Miocene unconformity of Biju-Duval et al. (1982) in La Vela bay and the Bonaire basin. In the Aruba basin, Curet (1992) identifies a depositional hiatus at the middle-late Miocene corresponding to an unconformity in the seismic data. This unconformity also correlates with the angular unconformity capping Sequence 2 (Middle Miocene unconformity) (Fig. 5), suggesting that this unconformity is time-transgressive between the Bonaire basin and the Aruba basin.

Audeamard (1993; 1998; 2001) also widely reports an early-middle Miocene unconformity onshore. The west-to-east younging of this unconformity can be seen on the E-W oriented stratigraphic chart presented by Audemard (1993; 2001).

Middle-late Miocene Sequence 3 (S3)

Middle to late Miocene Sequence 3 reflectors lap out along the Middle Miocene unconformity north of the Bonaire basin (Figs. 7 and 8). Audemard (1993; 1998; 2001) proposes that this unconformity marks initial shortening and inversion of the onshore Falcon basin. If this inference is correct then the erosional products of this regional uplift and shortening event of the onland Falcon basin must certainly be reflected by an influx of erosional detritus into offshore sections and in the formation of the regional angular unconformity truncating sequence 2. In the Paraguana, Aruba, and West Curacao basins, strong, high frequency reflectors display northward-prograding, clinoformal geometries (Fig. 9 and 11). This seismic character is significantly different from the underlying reflection character of sequences 1 and 2,
which are almost exclusively sub-parallel (Figs. 9 and 11). These depositional patterns in addition to well data information (Fig. 5) suggest that the Middle Miocene unconformity capping Sequence 2 represents a major transition from deep water to a shallower-water depositional setting above the Middle Miocene unconformity. The age of this sequence is based on well data shown in Figure 5.

In the southwestern Bonaire basin, the La Vela fold-thrust belt deforms Sequence 3 sedimentary rocks, but the expression of the Middle Miocene unconformity is unclear due to its later deformation within the La Vela fold-thrust belt (Figs. 7 and 10). Sequence 3 strata in the Bonaire basin do not show evidence for progradation as seen in the Paraguana and West Curacao basins (Figs. 9 and 11). Instead, sequence 3 shows mainly parallel reflectors (Fig. 7). The variation in seismic character among basins suggests that the Middle Miocene unconformity is not uniformly represented in each basin and that this event did not affect the entire region simultaneously. Instead, Audemard (2001) has compiled stratigraphic data to indicate that the unconformity youngs from west to east. Eroded clastic sediments from the shortened and inverted Falcon basin did not travel far and were mainly deposited to the north of the Falcon basin area into La Vela bay. The time-transgressive character of the middle Miocene unconformity offshore suggests that it is related to the west-to-east progressing, post-middle Miocene inversion of the Falcon basin (Biju-Duval et al., 1982; Boesi and Goddard, 1991; Macellari, 1995; Audemard, 1993; Audemard, 2001).

Late Miocene-Pliocene sequence 4 (S4)

Refractor geometries in Sequence 4 resemble those in Sequence 3 (Fig. 5). In La Vela bay and the West Curacao basin, Sequence 4 is conformable with underlying late Miocene Sequence 3 (Figs. 9 and 11). Northward-prograding clinoforms in La Vela bay extend from the coastline to beyond the Paraguana basin (Fig. 9). The regressive character of this sequence is correlated with Pliocene-Pleistocene Coro and La Vela formations that are known from wells along the eastern coast of Falcón (Wheeler, 1963; Boesi and Goddard, 1991) (Fig. 5). A series of deep-sea channel systems and basin floor fans mark Sequence 4 in the West Curacao basin (Fig. 11). The northwest-southeast oriented profile of Figure 11 displays
several channel-like features and mound-shaped basin floor fans. Such features are absent in the north-south oriented profile shown of Figure 6, suggesting that the trend of these features is roughly north-south. This orientation implies a sediment source derived from the south for the West Curacao basin, consistent with the northward direction of sediment transport observed from clinoforms in La Vela Bay (Fig. 9). In the central and southern Bonaire basin, Sequence 4 onlaps the highly folded top of Sequence 3 (Figs. 7, 8 and 10). The unit drapes the underlying fold-thrust belt and is only slightly deformed (Fig. 10).

**Fault systems**

Offshore seismic reflection data reveal distinctive sets of parallel faults that define three Cenozoic fault families affecting the region (Fig. 4B). Normal faults are widespread across the study area and comprise the most common fault type. Reverse and thrust faults dominate the northern end of the study area within the South Caribbean deformed belt and along the eastern Falcón coastline (Figs. 2, 4B and 6).

**Family 1: Eocene-Oligocene east-west trending normal faults**

This fault set consists of sub-parallel normal faults striking roughly east-west within the offshore Bonaire basin (Figs. 4B and 6). Reflection data shows that these faults penetrate into acoustic basement and deform the oldest sedimentary layers of Paleogene age (Figs. 6 to 9). The lateral extent of these faults is shown on the structural map at the top of the acoustic basement (Fig. 4B). To the west, Family 1 faults extend into La Vela bay (Fig. 4B), but we see no evidence for these faults extending onshore (Audemard, 2001). Growth of sedimentary layers on the downthrown side of these normal faults indicates active faulting during deposition of the oldest Paleogene sedimentary units in the Bonaire basin (Figs. 7 and 8). With the exception of the Paraguana basin-bounding normal faults (Fig. 9), these normal faults are all truncated by the Middle Miocene unconformity (Figs. 7 and 8). The dip of these faults is difficult to constrain within non-reflective basement, but is estimated to be less than 45°. Near the coast, these faults are overthrust by Neogene thrust faults of the La Vela thrust-fold belt (Figs. 6 and 7). Some of the underlying normal faults demonstrate Neogene reactivation and inversion closer to the shoreline (Fig. 8).
This reactivation is probably related to transpressional movements along the Boconó-El Pilar-San Sebastian fault system (Fig. 8). The Paraguana basin-bounding normal faults appear to be a westward continuation of the east-west trending normal fault family seen offshore in the Bonaire basin. The Paraguana basin continues westward onshore into the Paraguana Peninsula where the basin has been mapped by Macellari (1995) (Figs. 4B and 9). Seafloor offset indicates that the northern bounding fault of the Paraguana basin remains active and may be subject to strike-slip reactivation as indicated by onshore evidence (Audemard, 1993; 1996; 2001).

Family 2: Oligocene-Recent northwest trending normal faults

A second group of Oligocene-Recent normal faults (Family 2) strike northwest and bound the basement highs of the Leeward Antilles islands (Fig. 4B). These faults extend from the basement through most of the sedimentary section visible on the reflection data. In a few locations on Figure 6 (East Curacao basin), seafloor offset is indicative of recent fault movements. These faults dip more steeply (50° to 60°) than the Eocene-Oligocene Family 1 normal faults (< 45°). Large grabens (up to 30 km wide), including the Aruba basin and the West Curacao basin, are controlled by these normal faults (Fig. 6). These fault bounded basins contain thick Oligocene to early Miocene sequences as observed in the seismic data (Fig. 6)

Family 3: Late Miocene-Recent west-northwest trending reverse faults – La Vela fold and thrust belt

A ~20-km wide and ~150-km long fold-thrust belt is interpreted offshore of eastern Falcón (Figs. 6, 7 and 10). These faults strike sub-parallel to the Eocene-Oligocene Family 1 normal faults (Fig. 6) and form a zone of imbricate thrust faulting that contrasts with the more isolated and steeply dipping normal faults (Figs. 6, 7 and 10). Family 3 reverse faults detach above or near the top of basement (Fig. 10), and so are not mapped in Figure 4B. A detachment surface is mapped on seismic reflection lines within Paleogene strata at a depth of 4.5 seconds two way travel time (TWT), or roughly 6 km, near the coast of Falcón (Figs. 6 and 10). The fold-thrust belt trends parallel to the coast of Falcón for 150 km and dies out
to the west in La Vela bay (Fig. 2). Vertical offset is apparent within 0.5 seconds TWT of the seafloor through late Miocene sediments (Figs. 2, 6 and 10).

**Tectonic controls on seismic sequences**

The evolution of western Venezuela and the Leeward Antilles reflects the changing nature of the Caribbean-South American plate interactions through the Cenozoic. The depositional and structural trends of the four seismic sequences are discussed below in the larger context of their tectonic controls.

Structural contour maps in TWT were constructed for the top of each seismic sequence. Isochron maps were constructed to illustrate the changing patterns of deposition and faulting within each sequence. These maps constrain a series of proposed three tectonic phases that affected the region.

**Basement faulting**

Structural mapping of acoustic basement reveals a highly faulted surface that exhibits a strong correlation to trends visible on regional gravity maps (Fig. 4). Eocene-Oligocene Family 1 normal faults strike roughly east-west through the Bonaire basin, while Family 2 normal faults of Oligocene-Recent, strike northwest-southeast along passages between the Leeward Antilles islands. South of the Leeward Antilles ridge, Family 2 normal faults appear to curve to the east and interact with more east-west striking Family 1 faults (Fig. 4B).

Mapped structures in basement parallel regional trends seen on the gravity map (Fig. 4A). The Leeward Antilles ridge is an east–west trending basement high segmented by northwest trending basement lows. This basement high is equivalent to the Cretaceous arc-related basement province outlined in Figure 4A. Gravity data confirm that this trend extends westward and northward to the area north of the Guajira peninsula (Fig. 4A). The Bonaire basin basement low in Figure 4B corresponds to the Cretaceous intra-arc basement province defined in Figure 4A. Well data indicate that this intra-arc basement province extends westward into the onshore Falcón basin (Fig. 5).

**Sequence 1: Paleogene intra-arc deposition**
Paleogene Sequence 1 unconformably overlies a highly faulted, acoustic basement horizon (Figs. 5 and 6). Sedimentation patterns in Sequence 1 are equivalent to the oldest Falcón basin deposits of late Eocene-Oligocene age (Wheeler, 1963). Figure 12 illustrates the main depocenters proposed during Sequence 1. The first depocenter trends east-west, sub-parallel to the coast of Venezuela in the Bonaire basin (Fig. 12). This sedimentation is controlled by east-west trending normal faults (Family 1), some of which are inverted as a result of Neogene transpression most like caused by strike-slip motion along the Oca and Boconó-San Sebastian fault systems (Figs. 8 and 10). Thickness reach over 3 seconds TWT in the eastern Bonaire basin (equivalent to about 4500 m). The east-west trending Paleogene Bonaire depocenter is sourced from the South American continent. A likely point source is the proto-Maracaibo river system, which is believed to have also supplied Paleogene sediments to the Falcón basin (Escalona et al., 2004). Note that later, right-lateral displacement along the Oca fault has contributed to offset between the present-day Maracaibo, Falcón and Bonaire basins (Fig. 4A).

Onshore studies (Wheeler, 1963; Macellari, 1995) have defined the extent of Oligocene units in the Falcón basin (Fig. 12). The shale-rich Pecaya, El Paraiso, and Pedregoso Formations of Oligocene age form an east-west trend continuation of the Paleogene depocenter in the Bonaire basin (Fig. 12). Wedge-shaped and shingled reflection geometries indicate slump and gravity slide features at this level of the Bonaire basin. These features suggest Oligocene-Miocene tectonically-induced sedimentation possibly related to reactivation of the Family 1 faults (Fig. 7) and onset of inversion of the Falcon basin onland during the early Miocene (Fig. 5). A second Paleogene depocenter is apparent in the Los Roques basin (Fig. 12). The Los Roques basin formed as an isolated and elongate E-W basin between the high of the fold-thrust belt of the South Caribbean deformed belt to the north and the Leeward Antilles island arc to the south (Silver et al., 1975). We propose that the South Caribbean deformed belt is the product of subduction of the Caribbean slab and that this process has been ongoing since Paleogene time as suggested by previous workers (Pindell and Barrett, 1990; Müller et al., 1999).
The Paleogene sequence is capped by the unconformity surface mapped in Figure 13A. Northwest-striking normal faults (Family 2) are present between the Leeward Antilles islands. Westward-striking normal faults (Family 1) are present in eastern Bonaire. The reverse and thrust faults of the La Vela fold-thrust belt (Family 3) appear between the island of Curacao and the Falcón coast (Fig. 13A). The strike of these faults is nearly continuous with the underlying normal faults of Family 1. The lateral extent of the fold-thrust belt displays a strong correlation to the location of the Pecaya shale formation onshore (Fig. 12). These shale-rich Paleogene layers likely serve as the main detachment surface for the La Vela fold-thrust belt.

**Sequence 2: Late Oligocene-early Miocene east-west extension**

Isochron mapping of early Miocene Sequence 2 reveals major depocenters in the Bonaire basin and the West Curacao basin (Fig. 13B). Continued subsidence of the Falcón basin resulted in the deep marine Agua Salada Formation fringed by reef and continental facies (Wheeler, 1963; González de Juana et al., 1980; Macellari, 1995). The areal extent of these stratigraphic units is illustrated in Figure 13B. Offshore mapping indicates that the Bonaire and West Curacao basins experienced rapid (3-4 km) deposition during the early Miocene. The West Curacao basin deposits are closely controlled by northwest-striking normal faults (Family 2). In contrast, the Bonaire depocenter has migrated westward relative to the previous sequence. The structure map on top of Sequence 2 (Fig. 14A) illustrates Family 2 normal faults south of Curacao extending into the Bonaire basin where the faults cross-cut or reactivate the older Family 1 normal faults in the base of Sequence 2.

Early Miocene Sequence 2 deposits comprise the thickest (~3000 m) sedimentary sequence within the West Curacao basin. Thickness trends indicate extension along northwest-striking normal faults between the Leeward Antilles islands during the early Miocene (Fig. 13A). As seen from seismic facies and basin architecture (Figs. 11 and 13B), sediment is inferred to be sourced from the south and probably related to the proto-Maracaibo drainage system (Escalona et al., 2004). The Paraguana basin contains thick Sequence 2 deposits (Fig. 6 and 9).
Structural trends of the Middle Miocene unconformity

The top of Sequence 2 forms a regional unconformity throughout offshore western Venezuela and the Leeward Antilles (Fig. 14A). This unconformity, previously described by Biju-Duval et al. (1982), Audemard (1993; 2001) and Macellari (1995), is present onshore at the base of the Socorro formation. The Socorro formation correlates to the basal section of Sequence 3 (Fig. 5) and represents a shift in the tectonic setting from divergent opening of the basin to convergent closure or inversion of the basin during the middle Miocene (Audemard, 2001). Folding and inversion of the Falcón basin commenced at this time in western and southern Falcón, and progressed eastward and northward at least through the Pliocene, as indicated by intense folding and coastal exposures of vertical beds of the Pliocene La Vela Formation near the Guadalupe thrust (Audemard, 1993).

Structural mapping of the Middle Miocene unconformity offshore gives little indication that basin inversion is occurring onshore at this time. The top of Sequence 2 (Fig. 14A) essentially follows the present-day bathymetry (Figs. 1A and 2). Faulting styles are similar to those at top of Sequence 1 (Fig. 13A). Family 2 bounds the Leeward Antilles islands, and Family 1 bounds the Paraguana basin.

Sequence 2 is highly deformed within the La Vela fold-thrust belt, indicating significant thrusting during the middle Miocene. However, the inverted structures onshore are oriented roughly east-northeast, while the offshore thrusts are oriented parallel to the coast in a more west-northwest orientation (Fig. 14A). This orientation is nearly perpendicular to north-northeast trending folds of the Falcón fold-thrust belt.

Sequence 3 and 4: late Miocene-Pliocene depositional trends

The depositional trends of Sequence 3 and Sequence 4 (Figure 14B) indicate the beginning of present-day depositional patterns. Deposition continues in the West Curacao and Paraguana basins where clastic sedimentation is characterized by prograding clinoforms in La Vela bay (Fig. 9). The Aruba basin begins to experience significant deposition, while the West Curacao basin forms a less significant depocenter, possibly reflecting its eastward strike-slip displacement away from major sediment sources of
the proto-Maracaibo river (Escalona et al., 2004). Family 2 normal faults continue to control deposition between the islands. In the Bonaire basin, there is significant clastic deposition during Sequences 3 and 4 (Fig. 6). Onshore data show that the active Falcón basin decreases in size as late Miocene-Pliocene basin inversion progressed from west to east (Boesi and Goddard, 1991; Macellari, 1995). Significant late Miocene-Pliocene deposition is confined to the eastern and northern flanks of the Falcón basin (Fig. 14B) (Macellari, 1995; Audemard, 1996; Audemard, 2001). During Sequence 3 (late Miocene), ongoing uplift of the Falcón basin probably provided a clastic sediment source for the region (Boesi and Goddard, 1991; Macellari, 1995).

Discussion

Integration of onshore and offshore geology and relation to tectonic phases

In Figures 15A-D, a model depicting the three proposed tectonic phases for northwestern Venezuela and Leeward Antilles region is presented. This model integrates the established stratigraphic history of the onland Falcón basin with the tectonic sequences observed in the offshore reflection data.

Phase 1: Paleogene intra-arc extension

The onset of Caribbean/South American plate interactions in western Venezuela began in Paleogene time (Ostos, 1990; Pindell et al., 1998) (Fig. 15A). The earliest convergence took place along the northwestern corner of South America and progressed eastward throughout the Paleogene, reaching the Falcón basin by late Eocene time (Stephan, 1985; Audemard, 1991; Lugo and Mann, 1995; Mann et al., 2006; Escalona and Mann, 2006). The Siquisique ophiolite and the Lara metamorphic terranes were emplaced prior to the basin opening and formed the southern boundary of the incipient Falcón intra-arc basin (Stephan, 1977; Kellogg, 1984). The Burro Negro fault formed the western boundary of the Falcón basin (Roure et al., 1997; Escalona, and Mann, 2006) (Fig. 15A).

Oligocene marine transgression heralds the opening of the Falcón basin (Wheeler, 1963) and is correlated with Sequence 1 in our offshore data (Fig. 6). Initial opening of the east-west trending
depression led to progressively, lower-energy marine deposits in central Falcón, while the basin flanks accumulated higher-energy reef and shelfal deposits (Macellari, 1995). In the Bonaire basin, these earliest deposits are controlled by E-W striking normal faults (Family 1), observed on reflection profiles (Figs. 7, 8 and 10) and on a map of Oligocene sedimentary thickness (Fig. 12). Depositional styles inferred from seismic character in the Bonaire basin (Figs. 6 and 10; Table 2) indicate a pattern of deep-marine deposition initiating during the Oligocene and continuing through the early Miocene. Offshore well data published by Biju-Duval (1982) and Macellari (1995) reveal offshore units with semi-transparent seismic facies that correspond to the shale-rich units of onshore Falcón basin (Pecaya, El Paraiso formations; Fig. 5) (González de Juana et al., 1980).

Oligocene depositional environments in the Falcón and Bonaire basins indicate that deep-marine settings of the central basin progressively shallowed towards the flanks of the basin (Macellari, 1995) (Fig. 5). The Aruba and Curacao basins contain uniformly thin (~ 250 m) clastic deposits of Oligocene age, suggesting that fault segmentation of the Leeward Antilles ridge had not yet occurred and the fault-bounded basins between the islands were not yet active. Paleomagnetic data from the Leeward Antilles islands (Hargraves and Skerlec, 1982) suggest clockwise tectonic rotations of up to 90° since early Cretaceous time and are used to approximate a southwest-northeast orientation of the Leeward Antilles ridge during Paleogene time (Fig. 15A).

**Phase 2: Oligocene- early Miocene transtension**

By the end of Oligocene time, the Caribbean-South American plate boundary in western Venezuela changed from a convergent boundary to a transtensional one with a right-lateral strike-slip fault system established along the margin (Fig. 15B). Transtension along northwest-striking normal faults created rifts (Family 2) that segmented the Leeward Antilles ridge (Fig. 6). These basins (Aruba, West Curacao, East Curacao) accumulated thick, deep-water deposits derived from the South American craton. Localized extension between the islands resulted in deep-water passages connecting the incipient northwest-trending rift basins with the well-developed, east-west trending Falcón-Bonaire basin to the
southern. The two fault systems (Family 1, Family 2) were both active at this time to produce a large zone of regional subsidence (Fig. 15B).

Intra-arc rifting in the Falcón and Bonaire basins continued to be active throughout this Oligocene-early Miocene phase, but with reduced intensity. Basaltic stocks and sills in central Falcón intruded Oligocene marine sediments (Muessig, 1978). K-Ar and more recent 40Ar/39Ar dating by McMahon shows that magmatism was sporadic and ranged from 22.9 Ma (Muessig, 1984) to 15 Ma (MacMahon, 2000). This age interval represents the final stages of Phase 2 north-south intra-arc extension during the late Oligocene and middle Miocene. Phase 2 thus records the peak and subsequent waning of intra-arc extension. A maximum amount of crustal thinning, achieved in the late Oligocene-early Miocene as north-south intra-arc extension was at its peak, facilitated the intrusion of basalts in the central Falcón basin. By early Miocene, intra-arc rifting had diminished and the associated igneous activity in central Falcón had ceased.

Phase 3: Post-Middle-Miocene transpression

The final tectonic phase encompasses seismic offshore Sequences 3 and 4 (Fig. 15C-D). The onset of inversion of the Falcón basin occurred in the middle Miocene (Audemard, 2001). Falcón inversion has been attributed to three different mechanisms: 1) strain partitioning produced by the Andean orogeny (James, 2000); 2) a combination of North and South Americas convergence since at least the middle Eocene and complex oblique deformation between the Caribbean and South American plates resulting on transpression (Audemard, 2001; Audemard et al., 2005); and 3) Laramide-style basement reactivation and deformation related to shallow subduction of the Caribbean slab (Kellogg, 1984; van der Hilst and Mann, 1994; Taboada et al., 2000; Duerto et al., 2006).

A late Miocene-Pliocene date for the onset of movement on the Boconó fault (Schubert, 1980) constrains the movement of the Maracaibo block to within 5 Ma. The Middle Miocene event, recorded as an angular unconformity in the offshore seismic data, predates the movement of the Maracaibo block and the onset of the Andean orogeny (Biju-Duval et al., 1982; Kellogg, 1984; Kohn et al., 1984; Shagam et
A more plausible mechanism for the inversion of the Falcón basin is Laramide-style deformation (Dickinson et al., 1988) as a response to shallow underthrusting of the Caribbean plate. Kellogg (1984), van der Hilst and Mann (1994), Taboada et al. (2000), and Duerto et al. (2006) invoke a similar mechanism to account for the uplift of Mérida Andes and Sierra de Perija in western Venezuela, where pre-existing high-angle faults are reactivated by strong coupling between the shallowly subducted Caribbean slab and the base of the South American continental crust. Depth contours from tomographic data show that the shallowly-dipping Caribbean slab dips roughly south-southeast beneath South America (Fig. 1B), which is parallel to the trend of the Falcón fold-thrust belt (van der Hilst and Mann, 1994). Seismicity indicates that the southeast-dipping slab reaches depths of 60-75 km beneath the Falcón basin (Colmenares and Zoback, 2003). In general, the Caribbean slab has low seismicity, with the exception of the Bucaramanga nest in Colombia, southwest of the Merida Andes at a depth of ~180 km (Pennington, 1981; Malavé and Suárez, 1995; Taboada et al., 2000; Audemard et al., 2005). This orientation of the subducted slab is consistent with the northwest-southeast direction of maximum compressional stress in the Falcón fold-thrust belt (Audemard, 2001). However, geochemical analysis by McMahon (2000) of late Oligocene-middle Miocene basaltic intrusions of the Falcon basin does not provide enough evidence for slab melting caused by shallow subduction and coupling of the Caribbean slab. Instead, geochemical analysis supports melting at the asthenosphere-lithosphere boundary beneath the Falcon basin (McMahon, 2000).

As the inversion of Falcón progressed from southwest to northeast during the Late early – middle Miocene, the eastern Falcón basin and the rest of offshore northwestern Venezuela remained active sites of basinal deposition (Audemard, 2001) (Fig. 15C). Basin inversion is reflected by a shift in sedimentation styles from constant deepwater deposition characterized by parallel seismic facies (Figs. 8 and 9) to strongly prograding strata characterized by clinoforms, as seen in La Vela bay (Fig. 9). Because the inversion began in southwestern Falcón, the Middle Miocene unconformity is slightly younger in La Vela bay than in western Falcón and the Aruba basin, where the unconformity is earliest late Miocene.
(Curet, 1992) (Fig. 5). At the Leeward Antilles ridge, Phase 3 is recorded by Family 2 faulting segmenting the islands.

By the middle Miocene (Fig. 15C), Family 1 normal faults have formed the east-west trending Bonaire depocenter. Its present day setting (Fig. 15D) reflects eastward progression of the Falcón inversion. Regression of the shoreline has decreased the size of the active Bonaire basin and (late Eocene-Oligocene) Family 1 normal faults are overprinted by convergent tectonics. Gravitational instability induced by inversion and uplift of the Falcón basin results in thin-skinned “toe-thrust” style deformation in the La Vela fold-thrust belt (Fig. 5) as first proposed by Porras (2000). The La Vela fold-thrust belt remains localized and the detachment is closely controlled by shale near the top of Sequence 1, that we correlate to the Oligocene shale of the Pecaya Formation (Figs. 5 and 12). The areal extent of the shales of the Pecaya Formation corresponds closely to the lateral boundaries of the offshore La Vela fold-thrust belt (Fig. 12).

The present-day tectonic setting of the study area (Fig. 15D) is dominated by the shallowly-dipping subducting Caribbean slab, which extends 300-400 km to the south beneath northwestern Venezuela (van der Hilst and Mann, 1994). The South Caribbean deformed belt is a well-developed accretionary wedge, reflecting both the underthrusting of the Caribbean plate and the northward movement of the Maracaibo block. The eastward motion of the Caribbean plate continues at a rate of 20 mm/yr today (Pérez et al., 2001) (Fig. 1A).

**Tectonic phases in relation to existing models of the Falcón basin**

The three tectonic phases we propose for northwestern Venezuela and the Leeward Antilles contain elements of both the previous pull-apart model (Muessig, 1984; Macellari, 1995; Fig. 3A) and the previous intra-arc model (Audemard, 1993; Audemard, 1998; Porras, 2000; Fig 3B). The east-west-striking, Eocene-Oligocene Family 1 normal faults (Fig. 15A) support the intra-arc opening of the Falcón and Bonaire basins, while the northwest-striking, Oligocene-Recent Family 2 normal faults (Fig. 15B)
support the pull-apart model. However, Eocene-Oligocene Family 1 normal faults predate the Family 2 normal faults, as shown by the control of the Family 1 faults on the older (Eocene-Oligocene) basin fill of the Falcón and Bonaire basins (Figs. 7 and 8) than in the younger (Oligocene-Miocene) Aruba and West Curacao basins (Fig. 6). Cross-cutting relationships of these faults are difficult to constrain with 2-D seismic coverage, but Family 2 faults (Oligocene-Recent) demonstrate more recent activity than Family 1 faults (Eocene-Oligocene). Family 1 faults are no longer active (except for the Paraguana basin faults; Fig. 9) and are deformed by Family 3 (Pliocene-Recent) convergent tectonics in all areas (Figs. 4B and 6). These observations indicate that the initial late Eocene-Oligocene opening of Falcón-Bonaire basin was in an intra-arc setting following the collision of the Great Arc of the Caribbean and the South American continent. The two, east-west-oriented, right-lateral shear zones proposed in the pull-apart model (Fig. 3A) are not present at the time of the opening of the Falcón-Bonaire basin.

The pull-apart zone developed later as the Caribbean plate continued to move eastward relative to South America, forming the northwest-trending Aruba, West Curacao, and East Curacao basins (Figs. 15B-C). A possible plate mechanism for the formation of broad and diffuse pull-apart zone is indicated by the GPS vectors in Figure 1A. Rates of plate movement in western Venezuela are slower by 2-5 mm (~10-20%) than rates of motion in eastern Venezuela and the Lesser Antilles arc (Fig. 1A) (Pérez et al., 2001). A stage of fast convergence between North and South America began around the end of the Oligocene (Müller, et al., 1999). This convergence and northward movement of the Maracaibo block may have impeded eastward Caribbean plate motion in the vicinity of western Venezuela and the Leeward Antilles ridge, accounting for slower rates of motion in this region. The differential in plate motion resulted in early Miocene rifting within the Leeward Antilles ridge along Family 2, northwest-striking normal faults as proposed previously by Pérez et al. (2001) and Escalona et al. (2003).

Ave Lallemant and Guth (1990) proposed an alternative explanation to explain the formation of Family 2 faults. Their arc parallel extension model proposes that extension is produced in areas of sharply
curved areas along the arc terranes that are subject to oblique subduction. However, Family 2 faults in the Falcon region occurs where the arc is straight and exhibits no major curves (Fig. 1)

**Petroleum system overview**

Hydrocarbon production in the Falcón basin dates back to the first well drilled in 1921 (Wheeler, 1963; James, 2000). Figure 16 shows the distribution of oil fields and oil seeps in the northern Maracaibo Basin and the Falcón basin. The Falcón basin has produced the least hydrocarbons of any onshore basin in Venezuela (Del Ollo et al., 1994; Ghosh et al., 1997; James, 2000). The low production in most of these fields is associated with Late Cretaceous and Cenozoic mature to overmature source rocks found in many parts of the basin (Del Ollo et al., 1994). Three petroleum provinces have been identified in the Falcón basin: 1) western Falcón (El Mene, Tiguaje, Hombre Pintado fields); 2) north-central Falcón, within the Urumaco trough (El Mamon field), and; 3) northeastern Falcón/La Vela Bay (La Vela, Cumarebo fields) (Fig. 16).

Known reservoirs in the Falcón basin are of Miocene age. As the basin inverted during late Miocene-Pliocene (Figs. 15C and D), sand-prone facies became more prominent along the flanks of the Falcón basin. These reservoirs produce in the Cumarebo and La Vela oil fields near Coro (Payne, 1951; González de Juana et al., 1980) (Fig. 2). Based on seismic sequences and the available well information, the best sandstone reservoirs seem to be associated with elastic deep water sedimentation during the middle Miocene (Macellari, 1995). Seismic facies suggest deep-water turbidite fan geometries in the northern Bonaire basin and west Curacao basin (Fig. 11). Late Eocene-early Miocene deep-water, laminated fine-grained sandstones show potential as reservoir rocks (Curet, 1992).

Traps offshore northwestern Venezuela may be structural or stratigraphic. Structural traps may exist: 1) beneath the Paleogene and Middle Miocene unconformities in much of the Bonaire basin; 2) against the basin flanks bounded by Family 1 faults; 3) along the La Vela fold-thrust belt in central-eastern offshore Falcón (Figs. 7 and 10); 4) and along the inverted high-angle structures observed in the
southeastern Bonaire basin (Fig. 8). Stratigraphic traps may occur in pinchouts overlain by Paleogene and Middle Miocene unconformities (Figs. 8 and 9), and in late Neogene, deep-water turbidite fans interpreted in the western Curacao basin (Fig. 11).

**Basement provinces and source rock implications**

The geologic model presented in this paper delineates basement provinces and structural and stratigraphic trends that closely control the petroleum systems of western Venezuela.

**Paleozoic basement province:** The western Falcon province is the northward continuation of the Maracaibo petroleum province, where a continuation of the Paleozoic continental basement province that contains Cretaceous (La Luna Formation) and Tertiary source rocks (Jarillal, Misoa y Cerro Misión Formations) has been identified (Boesi and Goddard, 1991; Ghosh et al., 1997) (Fig. 16). Alternative source rocks in the area include Tertiary rocks of the Pecaya and Agua Clara formations and their lateral equivalents (González de Juana et al., 1980). This province may also extend to the western Gulf of Venezuela region (Fig. 16).

**Cretaceous metamorphic basement province:** The Urumaco trough and northeastern Falcón/La Vela bay in central and eastern Falcon are structurally similar and contain equivalent source and reservoir rocks (Payne, 1951; Macellari, 1995). In this province, Cretaceous arc-related basement is not overlain by Cretaceous or early Tertiary clastic rocks. The Mamón field within the Urumaco trough and the La Vela and Cumarebo fields in northeastern Falcón are sourced by marine organic matter from Oligocene and Miocene shale-rich units, including the Pecaya, Socorro, and Caujarao formations (Boesi and Goddard, 1991; Ollo et al., 1994; Ghosh et al., 1997). The Urumaco trough and La Vela bay are graben features that form local zones of subsidence between structurally stable blocks (Fig. 16). In eastern Falcón, structural traps in the La Vela and Cumarebo fields are controlled by the Guadalupe thrust along the eastern Falcón coast and by northeast-trending folds of the Falcón fold-thrust belt (Fig. 2). Some stratigraphic traps of Miocene age exist where sand lenses of deltaic facies pinch-out into the thick shale units (Payne, 1951).
An average porosity of 21.7% for reservoirs containing light oil (47.5° API) in the Cumarebo oil field was reported by Payne (1951).

Offshore, the Cretaceous basement province extends beneath the Bonaire basin and the eastern Gulf of Venezuela (Fig. 4A). Source rocks in these offshore basins are a continuation of the late Eocene-Oligocene deep-water shale found in the inverted Falcón basin onshore (Cerro Misión, Pecaya and Agua Clara Formations) and have the potential to produce thermogenic hydrocarbons as observed in the Cumarebo field in northeastern Falcón (Payne, 1951).

**Cretaceous Caribbean arc basement:** The Cretaceous arc basement province is the least promising of all the basement provinces based on its known source rocks and degree of maturation (Curet, 1992). Geochemical analyses in the Aruba basin reveal low total organic carbon (TOC) and low geothermal gradient for upper Eocene-Oligocene rocks (Curet, 1992). Biogenic gas is present and is similar to gas from the Colombian part of the Guajira Peninsula (Katz and Williams, 2003). The main period of subsidence for reaching the oil window for the three basement provinces was during the Oligocene-early Miocene transtension of Phase 2 (Boesi and Goddard, 1991; Curet, 1992; Macellari, 1995). Main areas for source rock maturation are located along the axis of the Bonaire basin, which is controlled by east-west-striking normal faults of Family 1 (Fig. 13 A).

**Conclusions**

Integration of old and new seismic reflection data from offshore western Venezuela and the Leeward Antilles with onshore geologic data collected by previous workers over the past 50 years constrains three main tectonic phases of Cenozoic age. The first phase involves oblique convergence of the Great Arc of the Caribbean with South America in Paleogene time. The Falcón and Bonaire basins opened in an intra-arc setting in late Eocene-Oligocene time, accompanying or following this oblique collisional event. The origin and opening of the Falcón-Bonaire basin can be linked to a system of east-west striking normal faults which exhibit growth during the late Paleogene. These faults have been
affected by Miocene tectonic convergence, and are overprinted by the reverse faults of the La Vela fold thrust belt in the western Bonaire basin (Fig. 10). In the central Bonaire basin, these faults are visible in their original, undeformed state (Fig. 8).

The second tectonic phase during the early-middle Miocene, and still active locally, is characterized by rifting of the east-west trending Leeward Antilles ridge along northwest-striking normal faults (Fig. 15B). These faults are younger than the east-west-striking normal faults of Family 1, as indicated by younger sedimentary fill of the Aruba and West Curacao basins (Fig. 11).

The third tectonic phase (middle Miocene-present) is characterized by uplift and inversion of the Falcón basin progressing from west to east since middle Miocene time (Figs 15C-D). The Falcón fold-thrust belt is probably detached along the top of the Cretaceous basement. The La Vela fold-thrust belt offshore is a thin-skinned deformation, shortening to the north-northeast and parallels to the coastline (Fig. 10). We propose that this deformation is the result of gravity-induced structural instability related to the combined uplift and inversion of the Falcón basin.

Although hydrocarbon production in this region has been relatively minor compared to the adjacent Maracaibo province, continued offshore exploration is necessary to better define the geologic limits of a known petroleum system in the onshore Falcón basin and offshore La Vela basin (Fig. 16). The unexplored basins offshore of Falcón and the Leeward Antilles merit especially careful investigation. To our knowledge there is no previous history of seeps, shows or production in these areas. However, the distribution of marine Eocene source rocks present in the Falcón basin may extend offshore into the West Curacao and Bonaire basins and provide incentive for deep water exploration of this poorly studied region.

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**Figure captions**

Figure 1. Tectonic setting of the southeastern Caribbean displayed over satellite topography and bathymetry basemap from Sandwell and Smith (1997). T Six tectonic provinces are bounded by heavy dashed lines and related tectonic terranes are labeled: AR (Aves ridge), BAP (Barbados accretionary prism), BB (Bonaire basin), CM (Caribbean mountains), FB (Falcon basin), GB (Grenada basin), LA (Lesser Antilles arc), LWA (Leeward Antilles ridge), MA (Mérida Andes), MB (Maracaibo block), SCDB (South Caribbean deformed belt) and TB (Tobago basin). Black arrows represent GPS vectors compiled from Trenkamp et al. (2002) and Perez et al. (2001). Yellow box indicates area of Figure 2. B) Satellite free-air gravity map of southeastern Caribbean from Sandwell and Smith (1997). Black dashed
lines in the west are contours in depth to the top of the subducting Caribbean slab beneath northwestern South America (based on tomographic study by van der Hilst and Mann, 1994) and in the east are depth to the Benioff zone beneath the Lesser Antilles arc (Wadge and Shepherd, 1984). Faults traces include: BFZ (Boconó fault zone), EPFZ (El Pilar fault zone), OAFZ (Oca-Ancon fault zone), SSFZ (San Sebastián fault zone) and SMBZ (Santa Marta-Bucaramanga fault zone).

Figure 2. Geologic tectonic map of the study area showing tracks of seismic reflection lines collected during the BOLIVAR cruise in 2004 and the GULFREX cruise in 1974. Major fold and fault trends and ages of outcropping sedimentary units onshore are compiled from Muessig (1984) and Audemard (1991). Dashed lines indicate areal extent of on- and offshore basins. Abbreviations: AB (Aruba basin), CC (Cordillera de la Costa), ECB (East Curacao basin), PB (Paraguana basin) and WCB (West Curacao basin). Logs from wells on this map are shown on Figure 5 (DD- DiviDivi, LV- La Vela).

Figure 3. Comparison of A) Eocene-Oligocene pull-apart and B) Paleocene-Eocene back-arc models for the Falcón basin. A) Pull-apart model for Falcón and Bonaire region of northwestern Venezuela, illustrating the distribution of Eocene-Oligocene highs and sub-basins, modified from Muessig (1984). Northwest-striking normal faults control regional subsidence of deep-marine basins separated by emergent or shallow-water highs. Abbreviations: A (Aruba island), AB (Aruba basin), B (Bonaire island), BB (Bonaire basin), C (Curacao island), D (Dabajuro high), FB (Falcón basin), G (Guajira peninsula), LM (Los Monjes islands), LV (La Vela bay), P (Paraguana peninsula), U (Urumaco trough). B) Contrasting model for Paleocene-Eocene backarc basin opening model for the Falcón and Bonaire basins (modified from Porras, 2000). East-west striking normal faults time control the initial north-south basin opening during Eocene-Oligocene time, while the Leeward Antilles ridge remains a stable emergent or shallow-water high flanking the basin to the north.

Figure 4. A) Basement provinces of western Venezuela and the Leeward Antilles islands based on interpretation of satellite free-air gravity map from Sandwell and Smith (1997). Wells are labeled with depth to basement in meters and basement lithology (when available). Three basement provinces are distinguished: Cretaceous arc-related basement along the Leeward Antilles ridge, Cretaceous arc basement within Falcón and Bonaire basins, and Paleozoic continental basement south of the arc related basement. Well data was compiled from González de Juana (1980), Curet (1992), and Macellari (1995). B) Structural contour map showing depth to acoustic basement in two-way travel time constructed from data shown in Fig. 2 using ZMAP software, and major onshore structural trends compiled from Audemard (1991; 2001). Normal faults can be grouped into two sets: a set striking west to west-northwest within the Bonaire basin and formed during Eocene-Oligocene (Family 1); and a set striking northwest between the Leeward Antilles islands and formed in the Oligocene-Miocene (Family 2). Seismic lines discussed later in text are highlighted as bold black lines.

Figure 5. Lithologic formations of the Falcón basin correlated with offshore well and seismic data, and correlation of Aruba basin well data with seismic sequences. Falcón stratigraphic data and type log is modified from González de Juana (1980). Aruba basin well data compiled from Curet (1992). Inset map shows locations of the well and outcrop data.

Figure 6. Fence diagram constructed from BOLIVAR seismic reflection lines collected in 2004 (Fig. 2). Three fault families formed during successive tectonic phases 1 to 3 and four seismic sequences are described in detail in the text. Map abbreviations are given in the captions of Figures 1 and 2. Lower gravity values correlate with thick sedimentary packages, and higher gravity values correlate with basement highs overlain by thin sedimentary cover (e.g. Leeward Antilles ridge). Boxes locate interpreted seismic lines discussed later in text. Abbreviations: A (Aruba island), AB (Aruba basin), B (Bonaire
island), BB (Bonaire basin), C (Curacao island), ECB (East Curacao basin), FB (Falcon basin), PB (Paraguana basin), PP (Paraguana Peninsula), WCB (West Curacao basin).

Figure 7. A) Uninterpreted GULFREX seismic section from Bonaire basin. Location given in Figure 4B. B) Interpreted section with black arrows indicating fault motions. Eocene-Oligocene Family 1 normal faults control horst and graben structures that controlled deposition of seismic sequences 1 and 2. Thickening of Sequences 1 and 2 on downthrown side of Family 1 normal faults indicates deposition during an Eocene-Oligocene period of fault activity. Sequence 4 is not present on this section. C) Detailed chaotic zone suggestive of fault-related debris flows.

Figure 8. A) Uninterpreted GULFREX seismic section from the central Bonaire basin. Location given in Figure 4B. B) Interpreted seismic section. Black dotted lines with arrows indicate northward prograding clinoforms. Red arrows indicate onlap relationship. Middle Miocene unconformity (red-dashed line) is onlapped by reflections of Miocene Sequence 3 strata. Family 1 normal faults are inverted near the shoreline to the south. To the north, family 1 normal faults are not inverted in the western Bonaire basin (cf. Fig. 7).

Figure 9. A) Uninterpreted GULFREX seismic section east of the Paraguana peninsula. Location given in Figure 4B. B) Interpreted seismic section. Black half-arrows indicate fault motion and red arrows indicate onlap surfaces. Parallel reflectors of Eocene to early Miocene Sequences 1 and 2 exhibit signs of later middle Miocene inversion. Above the Middle Miocene unconformity (red dashed line), Miocene-Pliocene sequences 3 and 4 prograde northward. Semi-continuous reflectors in the Aruba basement high may indicate igneous sills or dikes within the Cretaceous arc rocks of the Great Arc of the Caribbean.

Figure 10. A) Uninterpreted GULFREX seismic profile from the western Bonaire basin. Location given in Figure 4B. B) Interpreted seismic section. Neogene age, offshore La Vela fold-thrust belt overthrusts relatively undeformed Cretaceous basement. Eocene-Oligocene Family 1 normal faults are deformed by younger Miocene folds and thrusts. Basal thrust occurs within Paleogene Sequence 1 that is equivalent to onshore shale-rich units studied in outcrops by previous workers (see Figure 7). Deformation is greatest within Sequences 2 and 3. Thrust deformation is less prominent within Pliocene-Pleistocene Sequence 4.

Figure 11. A) Uninterpreted GULFREX seismic section from the West Curacao basin. Location given in Figure 4B. B) Interpreted seismic section. Black arrows indicate direction of northward prograding clinoforms of middle to late Miocene age. Middle Miocene unconformity (red-dashed line) is onlapped by reflections of sequences 3 and 4. Channel systems and apparent basin floor fans in Sequence 4 are described in the text.

Figure 12. Isochron map of Paleogene Sequence 1 illustrating the primary Paleogene depocenters located in the Bonaire basin and offshore Falcón, and in the Los Roques basin north of Leeward Antilles ridge. Onland paleogeography is compiled from Wheeler (1963) and Macellari (1995) and shows that Oligocene age, shale-rich units occupy the central part of the Falcón basin.

Figure 13. A) Structural map in TWT to top of Paleogene Sequence 1, showing Family 1 and Family 2 fault systems of Eocene to early Miocene age. Family 3 reverse faults of the La Vela fold-thrust belt parallel the eastern coast of Falcón. B) Isochron map of Sequence 2 illustrates widespread late Oligocene-early Miocene marine clastic deposition in the West Curacao and eastern Falcón basins. Onland paleogeography is compiled from Wheeler (1963) and Macellari (1995).

Figure 14. A) Structural map in TWT of Middle Miocene unconformity (top of early Miocene sequence 2). Map illustrates the major fault trends of Miocene-Recent fault families 2 and 3. Oligocene-early
Miocene Family 2 normal faults separating the Leeward Antilles islands and middle Miocene-Pliocene Family 3 reverse faults off the eastern coast of Falcón control the structural trends of this surface. B) Isochron map of Sequences 3 and 4 illustrates late Miocene-present day depocenters, located in the Bonaire and Aruba basins. Onland paleogeography is compiled from Wheeler (1963) and Macellari (1995). Shoreline regression due to uplift of Falcón confined deposition to the eastern and northern Falcón basin. Northern and central Falcón basin dominated by transitional to continental shelf facies.

Figure 15. Schematic paleotectonic reconstructions of southern Caribbean and northern Venezuela illustrating the three Cenozoic tectonic phases affecting the region. The Lesser Antilles arc is in green, the Aves-Leeward Antilles ridge in red, and zones of subsidence are in a stippled pattern. Inset cross-sections correspond to red lines on reconstruction maps. A) Oligocene tectonic reconstruction shows events of tectonic Phase 1. B) Early Miocene tectonic reconstruction shows events of tectonic Phase 2. C) Middle to late Miocene age reconstruction equivalent to tectonic Phase 3. D) In the present-day, the Bonaire depocenter is constricted as the shoreline regresses due to tectonic uplift and the La Vela fold-thrust belt offshore juxtaposes the onshore Falcón anticlinorium.

Figure 16. Topographic/bathymetric map of northwestern South America showing three main basement provinces that control the petroleum systems in the Falcon basin and adjacent offshore basins.

Tables.
Table 1. A) Description of stratigraphic units of the Leeward Antilles islands compiled from Beets (1972); de Buisonje (1974) and Jackson and Robinson (1994). B) Description of stratigraphic units of northeastern Falcón/La Vela bay from Wheeler (1963), and Macellari (1995).
Table 2. Seismic reflection character for seismic sequences defined in this paper for the offshore basins.
A. Eocene-Oligocene pull-apart model (Muessig, 1978; Macellari, 1995)

- Caribbean plate
- South Caribbean deformed belt
- Gulf of Venezuela
- South American plate
- Oca – El Pilar fault zone

B. Late Eocene-Oligocene back-arc model (Audemard, 1993; Audemard, 1998; Mann, 1999; Porras, 2000)
A. SW

B. La Vela fold-thrust Belt

Family 3 reverse faults

Basal Detachment

Inverted Family 1 normal faults

Onlap terminations

Fault and sense of displacement

Inverted fault

4 km

V.E. 3:1

CRET. PALEOCENE

OLIGOECENE

EOCENE

BASEMENT

PLIOCENE - PLEISTOCENE

LATE

MIDDLE

EARLY

S1

S2

S3
Table 1.
A) Description of stratigraphic units of the Leeward Antilles Islands.

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation and island</th>
<th>Lithology</th>
<th>Depositional environment</th>
<th>Seismic sequence (this paper)</th>
<th>Tectonic phase (this paper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Terraced limestone (A, C, B)</td>
<td>Fine-grained sandstone, subordinate siltstone, claystone, limestone</td>
<td>Shallow marine, reefal</td>
<td>4</td>
<td>Phase 3: Post mid-Miocene inversion</td>
</tr>
<tr>
<td>Late Miocene-Early Pleistocene</td>
<td>Seroe Domi (A, C, B)</td>
<td>Detrital limestone and conglomerate</td>
<td>Submarine talus fans</td>
<td>3</td>
<td>Phase 3: Post mid-Miocene inversion</td>
</tr>
<tr>
<td>Eocene-Oligocene</td>
<td>Butucu (A) Mainsjie, Seroe di Cueba (C) Montagne (B)</td>
<td>Fossiliferous limestone</td>
<td>Shallow marine</td>
<td>1, 2</td>
<td>Phase 1: Paleogene back-arc opening</td>
</tr>
<tr>
<td>Paleocene</td>
<td>Midden Curacao (C) Soebi Blanco (B)</td>
<td>Conglomerate, turbidites</td>
<td>Deep marine, submarine fan</td>
<td>1</td>
<td>Phase 1: Paleogene back-arc opening</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Tonalite pluton (A) Knip Group (C) Rincon Fm. (B)</td>
<td>Silica-rich-turbidites, slump breccia, limestone lenses</td>
<td>Deep marine</td>
<td>Acoustic basement</td>
<td>Great Arc of the Caribbean</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>Aruba Lava Fm. (A) Curacao Lava Fm (C) Washikemba Fm. (B)</td>
<td>Tholeiitic basalt, diabase and porphyritic lava</td>
<td>Oceanic plateau volcanism</td>
<td>Acoustic basement</td>
<td>Great Arc of the Caribbean</td>
</tr>
</tbody>
</table>

Stratigraphic data compiled from Beets (1972), de Buisonje (1974), and Jackson and Robinson (1994).
Key to island abbreviations: Aruba (A), Curacao (C), Bonaire (B).
### B) Description of stratigraphic units of onland northeastern Falcon and offshore La Vela bay

<table>
<thead>
<tr>
<th>Age</th>
<th>Formations</th>
<th>Thickness</th>
<th>Lithology</th>
<th>Depositional environment</th>
<th>Seismic sequences (Macellari, 1995)</th>
<th>Seismic sequence (this paper)</th>
<th>Tectonic phase (this paper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliocene-Pleistocene</td>
<td>Coro, La Vela</td>
<td>120-145 m</td>
<td>Fine-grained sandstone and minor siltstone, claystone and limestone</td>
<td>Marine shelf</td>
<td>Cycle A</td>
<td>4</td>
<td>Phase 3: Post mid-Miocene fault and basin inversion</td>
</tr>
<tr>
<td>Upper Miocene</td>
<td>Cuajarao</td>
<td>260-580 m</td>
<td>Glaucotic calcarenite with interbedded conglomeratic sandstone</td>
<td>Marine; shallowing upward to shelf setting</td>
<td>Cycle B</td>
<td>3</td>
<td>Phase 3: Post mid-Miocene fault and basin inversion</td>
</tr>
<tr>
<td>Early-Middle Miocene</td>
<td>Socorro</td>
<td>850-1740 m</td>
<td>Claystone with intercalations of calcarenite and fine grained sandstone</td>
<td>Deep marine</td>
<td>Cycle B</td>
<td>2</td>
<td>Phase 2: Early Miocene rift opening</td>
</tr>
<tr>
<td>Early Miocene</td>
<td>Cerro Pelado, Agua Clara/Agua Salada</td>
<td>500-1800 m</td>
<td>Monotonous shale and clay, intercalated sands and limestone</td>
<td>Marine</td>
<td>Cycle C</td>
<td>2</td>
<td>Phase 2: Early Miocene rift opening</td>
</tr>
<tr>
<td>Oligocene</td>
<td>Pecaya, El Paraiso, Pedrogoso</td>
<td>1500-3000 m</td>
<td>Shale, interbedded sandstone and limestone</td>
<td>Marine</td>
<td>Cycle D-C</td>
<td>1</td>
<td>Phase 1 (cont.): Paleogene back-arc opening</td>
</tr>
<tr>
<td>Late Eocene</td>
<td>Cerro Mision, Agua Negra</td>
<td>400-2400 m</td>
<td>Conglomerate, limestone, sandstone, shale</td>
<td>Lacustrine-marine</td>
<td>Cycle D</td>
<td>1</td>
<td>Phase 1: Paleogene back-arc opening</td>
</tr>
</tbody>
</table>

Table 2. Source and reservoir characteristics of petroleum provinces in the onland Falcon Compiled from Payne (1951), Boesi and Goddard (1991), and James (2000).

<table>
<thead>
<tr>
<th>Fields (date of discovery)</th>
<th>Source Rocks</th>
<th>Reservoir</th>
<th>API</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Falcon</td>
<td>El Mene (1921), Hombre Pintado (1927), Media (1929), Tiguaje (1953)</td>
<td>Eocene marine shale of Jarillal and Misoa Fms, Oligocene sandstone of Agua Clara Fm.</td>
<td>32°</td>
</tr>
<tr>
<td>Urumaco trough</td>
<td>Mamon (1926)</td>
<td>Oligo-Miocene marine shale of Agua Clara, Cerro Pelado Fms.</td>
<td>Miocene sandstone lenses of Caujarao and Socorro Fms.</td>
</tr>
<tr>
<td>Northeastern Falcon/La Vela Bay</td>
<td>La Vela (1972), Cumarebo (1931)</td>
<td>Oligo-Miocene marine shale of Agua Clara, Cerro Pelado Fms.</td>
<td>Miocene sandstone lenses of Caujarao and Socorro Fms.</td>
</tr>
</tbody>
</table>