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Basement Architecture of the Southern Caribbean Basin, Guajira Offshore, Colombia

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ABSTRACT

The distribution of the basement in the Guajira Offshore Basin in Colombia appears to be consistent with the evolution of the autochthonous South American Block as part of a continent-ocean transform fault of the late Jurassic rift system that created the proto-Caribbean Sea between the North and South American plates. Later, rotation, accretion of suspect terranes, and the collision-subduction with the Caribbean plate framed current architecture of the basement in the basin. In addition to the Mesoproterozoic crust found in the onshore Alta Guajira area, a set of terranes of diverse age including late Triassic metamorphic rocks, early Cretaceous meta-sediments, late Cretaceous granites and serpentines, Eocene plutonic intrusions, and a chain of undifferentiated-age suspect blocks, can also be identified in the offshore basin.

Although the current architecture of the basement in the Guajira Offshore Basin does not show a preferential tectonic arrangement, four different types of crustal-fabric can be identified: (1) a Pre-Cambrian autochthonous block that exhibits an abrupt thickness change across the margin over a distance of ca 80 km (49.7 mi), from ca 20 km (12.4 mi) near the coast line to less than ca 3 km (1.8 mi) near the so-called Tayrona Subbasin. This abrupt decrease in crustal thickness resembles modern-day transform margins involving continent-ocean transition; (2) two areas exhibit what appear to be systems of horsts and grabens, typical of block-tectonics settings. One area is identified north of the Chimare suture and the other is located further south in the Tayrona Subbasin. Even though their age is currently difficult to establish, they may correspond to stretched continental crust and proto-Caribbean remnants of the rift-system that separated North America from South America during Jurassic time; (3) the Chirrinche, Chinchorro, and Mochila paleohighs whose non-magnetic character separated these suspect terranes from the autochthonous basement further east; and 4) The South Caribbean deformed Belt (SCDB) and the Tayrona and Chimare Neogene Subbasins associated with transcurrent fault systems generated by the oblique convergence of the Caribbean and the South American plates. A simplified evolution model of the Guajira Offshore Basin, based on basement distribution, includes four main phases: opening of the proto-Caribbean seaway during late Jurassic;

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subduction of this oceanic crust under the continental South American plate and associated volcanism during the Cretaceous period; collision of the Caribbean Large Igneous Province (CLIP) with the continental block, effectively stopping the ongoing subduction process in the late Cretaceous–early Paleogene time; and the development of the still active SCDB mostly on Caribbean oceanic crust since middle Paleogene times. Our observations preclude the pervasive presence of the Great Arc of the Caribbean (GAC) in the Guajira Offshore Basin.

INTRODUCTION

The modern distribution of the basement in the Guajira Offshore Basin in Colombia is thought to be closely related to the dynamics of the convergence between the autochthonous South America and the Caribbean oceanic plate (Malfait and Dinkelman, 1972; Ladd, 1980; Lugo and Mann, 1995; Pindell et al., 2006; James, 2009; Pindell and Kennan, 2009). The Caribbean plate appears to be subducting at a low angle underneath the South American Block along the western margin of northern Colombia since the late Cretaceous–Paleogene time (Zuluaga and Stowell, 2012), forming the SCDB, an accretionary prism (?) located at the western outer edge of the Guajira Offshore Basin (Ladd et al., 1984, Figure 1). It is unclear though, if tectonic underplating has accommodated Caribbean crust in some of the thrust sheets forming the SCDB, as occurs further south in the San Jacinto–Sinu Belts where relicts of Caribbean (?) oceanic crust have been identified in some areas of the accretionary melange (Ceron-Abril, 2008). The main structural features appear to be a set of E–W right-lateral strike faults (Oca, Cuisa, and Carpintero faults, and the Chimare suture, Figure 1) that accommodate part of the displacement produced by the oblique convergence of the Caribbean and South American plates (Ceron-Abril, 2008; Vence, 2008; Zuluaga and Stowell, 2012). However, a set of mostly N–S right-lateral strike-slip faults can also be inferred as the tectonic boundary of the Tayrona Subbasin, and the limit between the South American autochthon and Chirrinche, Chinchorro, and Mochila suspect terranes in the lower Guajira offshore (Figure 2).

Based mostly on gravity data and two-dimensional (2-D) forward modeling, Ceron-Abril (2008) proposed a thinned, intensely intruded and metamorphosed continental crust underlying most of the Guajira Offshore Basin, with some fragments of the GAC, an island arc formed during the subduction of the proto-Caribbean crust underneath today's Caribbean plate (Burke, 1988), at the northern end of the basin. Ceron-Abril (2008) also argues that tectonic depocenters like the Tayrona Subbasin and the Chimare

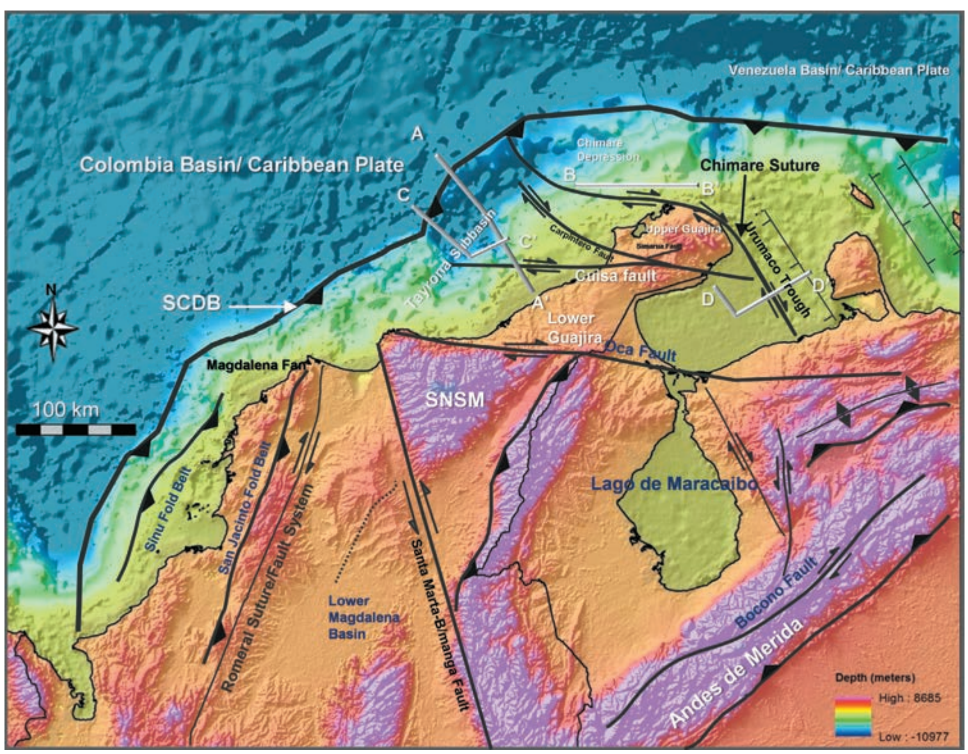

Figure 1. Guajira tectonic framework and topography/bathymetry. The Chimare suture, the northern limit of the autochthonous South American plate extends from the SCDB in the Guajira Offshore Basin in Colombia to the Gulf of Coquivacoa in Venezuela, forming the western boundary of the Urumaco trough. SCBD= South Caribbean deformed belt. 100 km (62.1 mi)

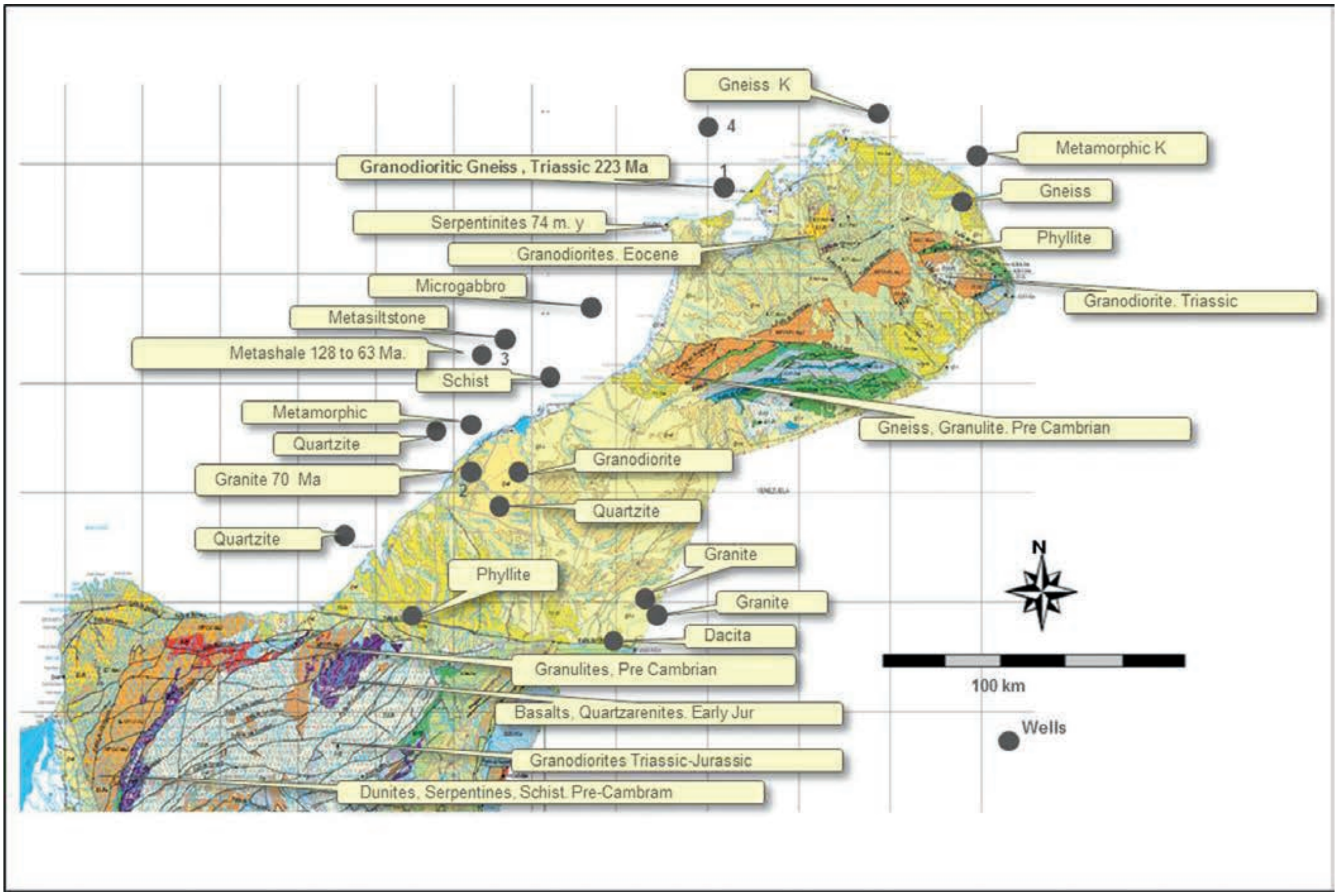

Figure 2. Geologic map of the Guajira Peninsula (modified from Ingeominas, 2011). Basement in the Guajira area shows a complex assemblage of igneous rocks (intrusive and extrusive) and diverse-grade metamorphic lithology, with a wide spectrum of ages from Pre-Cambrian to Eocene. Two wells offshore drilled crystalline basement rocks in the Guajira offshore: Well 1 tested a late Triassic Granodioritic gneiss, while Well 3 shows ambiguous age estimates, based on metamorphic rocks. The onshore Well 2 tested late Cretaceous granites of continental affinity. 100 km (62.1 mi)

depression are the result of transtensional releasing bends of the main strike-slip faults. According to this model, the boundary between the autochthonous South America and the allochthonous Caribbean terrane is located along the Simarua–Cuiza fault system in the Alta Guajira (Figure 1). Conversely, Vence (2008) focusing mostly on the seismic character and the domal shape of the basement in the Guajira Offshore Basin and partially on well data, argues that a 280-km (173.9 mi)-long belt of the GAC was accreted to the western continental margin of Colombia, including today's Guajira Offshore Basin, and extends further south to the Santa Marta massif. Additionally, Vence (2008) interpreted the GAC in Colombia as the continuation of the 1800-km (1118.4 mi)-long range that extends from the Aves ridge into the Guajira Offshore Basin. According to this model, the basement offshore is mostly arc-related material: metamorphic rocks of Cretaceous age and volcanic material of basaltic and andesitic affinity.

The origin of the Caribbean plate is still very controversial. However, its early history is linked to the breakup of Pangaea during the separation of the African plate and the South and North American plates during Jurassic time (Wilson, 1966; Ball et al., 1969; Burke et al., 1978; Pindell and Dewey, 1982; Burke, 1988; Pindell et al., 1988; Pindell and Kennan, 2009). The Caribbean evolution started with the opening of the proto-Caribbean seaway between North America (Yucatan Block) and South America as both blocks drifted apart during the late Jurassic–early Cretaceous time (Meschede and Frisch, 1998; Pindell and Kennan, 2009). Three main schools of thought have contrasting models about the evolution of the Caribbean from the middle Cretaceous epoch onward: (1) an *in-situ*, relatively simple model, arguing that the

Caribbean plate (proto-Caribbean) formed between the diverging Americas along a left-lateral transtension system that separated South America and North America as part of the Jurassic Atlantic rift system (Ball et al., 1969; Aubouin et al., 1982; Donnelly, 1985; Meschede and Frisch, 1998; James, 2006; James, 2009); (2) a Pacific model that proposes the origin of the Caribbean oceanic crust in the Pacific realm with the participation of the Galapagos hot spot (Wilson, 1966; Malfait and Dinkelman, 1972; Burke et al., 1978; Pindell and Dewey, 1982; Burke, 1988; Pindell et al., 1988; Pindell and Kennan, 2009). This model implies that the Caribbean plate originated as part of normal Pacific oceanic crust, then drifted over the Galapagos hot spot during the middle Cretaceous time, thickened, and formed the so-called CLIP. Its continuous NNE drift originated the subduction of the proto-Caribbean crust of Atlantic affinity below the Caribbean plate and the creation of the GAC. This geodynamic framework is still active today: the Colombia and Venezuela Basins represent parts of the CLIP, an oceanic plateau, and the Lesser Antilles the eastern leading edge of the Caribbean–GAC converging margin (Ladd, 1980; Lugo and Mann, 1995; Pindell et al., 2006; Pindell and Kennan, 2009; James, 2009); and (3) The Mid American Model presented by Giunta and Oliveri (2009) and Giunta and Orioli (2011) that argues for an oceanic crust with middle ocean ridge (MOR) affinity formed at multiple spreading centers during the Jurassic–early Cretaceous time. According to this model, the formation of the CLIP took place during the middle Cretaceous time. Two converging phases involving intra-oceanic subduction and continent-ocean subduction occurred during the middle Cretaceous to early Paleocene period. These authors argue that the GAC originated as the thin oceanic crust of the proto-Caribbean plate subducted with a west-dipping direction below the thick Caribbean Plateau during the late Cretaceous time. Their model sets the location of this subduction system somewhere northeast of the Guajira Peninsula, implying that most of the Caribbean crust along the western margin of Colombia is part of the CLIP and was not affected by the island arc magmatism of the GAC. Coevally, the collision between the thickened oceanic crust of the Caribbean Plateau and the South American autochthon took place further south in the Guajira Offshore Basin area, effectively ceasing the subduction-related magmatism in the Guajira Block, and initiating the so-called flat-subduction, still active today. The Caribbean Plateau, a large igneous province of up to 20 km (12.4 mi) in thickness (Pindell, et al., 2006; James, 2009; Pindell and Kennan, 2009) exhibits a range of ages according to Kerr et al. (2003) at 124–112 Ma (Barremian–Aptian), 92–88 Ma (Turonian) and 78–59 Ma (Campanian–Danian). However, most authors accept a magmatic activity peak at around 90 Ma (Kerr et al., 2003).

Most authors appear to agree that before the converging phase that affected the Guajira Offshore Basin area, the northwestern corner of Colombia was a passive margin created during the opening of the proto-Caribbean Sea during the late Jurassic and most of the Cretaceous time (Martinez and Hernandez 1992; Lugo and Mann, 1995; Pindell et al., 2006; James, 2009; Kennan and Pindell, 2009). Given the lack of direct evidence in the Guajira Offshore Basin, the regional framework seems to offer a reasonable approach to a passive margin that was later deformed by either the arrival of the GAC and/or the initiation of the SCDB during the early Paleocene time. However, if it is assumed for example, that continental crust is underlying the lower Guajira Offshore Basin, and that the GAC is not present (Ceron-Abril, 2008), then it is necessary to reassess the interpretation of the Guajira Margin to see if it is consistent with a passive margin framework. An alternative approach would consider a shear model with a transition from continental to oceanic crust. According to Bird (2001) there are at least three main differences between shear margins and passive margins: (1) the transition from continental to oceanic crust is abrupt, with dramatic crustal thickness changes offshore from over 20 km (12.4 mi) to about 10 km (6.2 mi) or less over distances of up to 80 km (49.7 mi); (2) complex rift basins develop along the continental side of the margin with structures formed by a spectrum of normal, wrench, and strike-slip faults; and (3) marginal ridges form along the continental side of the margin. Harry et al. (2003) differentiated the nature of the early Paleozoic transform margin structure below the Mississippi coastal plain using gravity forward models and the crustal-thickness gradient along the stretching basement: passive rifted margins display a smooth thickness gradient, while transform margins have a steep crustal-thickness gradient seaward of the basement hinge zone. Lorenzo (1997) recognized the two-stage development of continent-ocean fracture zones across continental margins during rifting and drifting. During early drifting, the young oceanic block slides against the older continental block possibly inducing thermal uplift. After the passing of a ridge when the transform becomes inactive, mechanical coupling across the fracture zone is possible.

In this chapter a new interpretation of the basement distribution in the Guajira Offshore Basin, constrained by well information, more than 20,000 km (12,427.4 mi) of 2-D seismic data, and potential field models is presented. Most of the data are located in the inner parts of basin, close to the coastline in shallow waters (Figure 1), where crystalline basement has been drilled by several wells (Vence, 2008). In the outboard area, in deep and ultra-deep waters, however, there are no penetrations, and due to the poor quality of the seismic image it was difficult to interpret unambiguously the top of the crystalline basement. Therefore, the acoustic basement was mapped instead, and consequently it might not represent the true crystalline crust (Figure 3). Additionally, to constrain the basement interpretation along these poor-quality seismic lines, a proprietary basement-depth estimation technique was used combined with iterative 2-D gravity models to test multiple scenarios. Potential field data were also used to laterally extend basement trends and faults between seismic lines. All potential field data used in this analysis are from the GETECH Trident dataset or the GETECH SAMMP dataset. The integrated interpretation between seismic and potential field data also used a number of filtered gravity Bouguer maps (Figure 4), in addition to magnetic depth estimations. The crustal-thickness gradient, estimated from 2-D gravity models, was also plotted against a compilation of rift and transforms margins around the world, to identify the geodynamic origin of the basement in the basin, using the same approach of Harry et al. (2003).

This work tries to identify basement distribution in the Guajira Offshore Basin without bias toward any particular model of Caribbean plate evolution. Our observations may better fit one model than another, but given the localized area of study, albeit critical to understanding the Caribbean paradigm, do not solve the complicated tectonic puzzle that this province represents. We merely try to add information to the discussion about the evolution of the northwestern corner of Colombia and its heavy implications for hydrocarbon exploration.

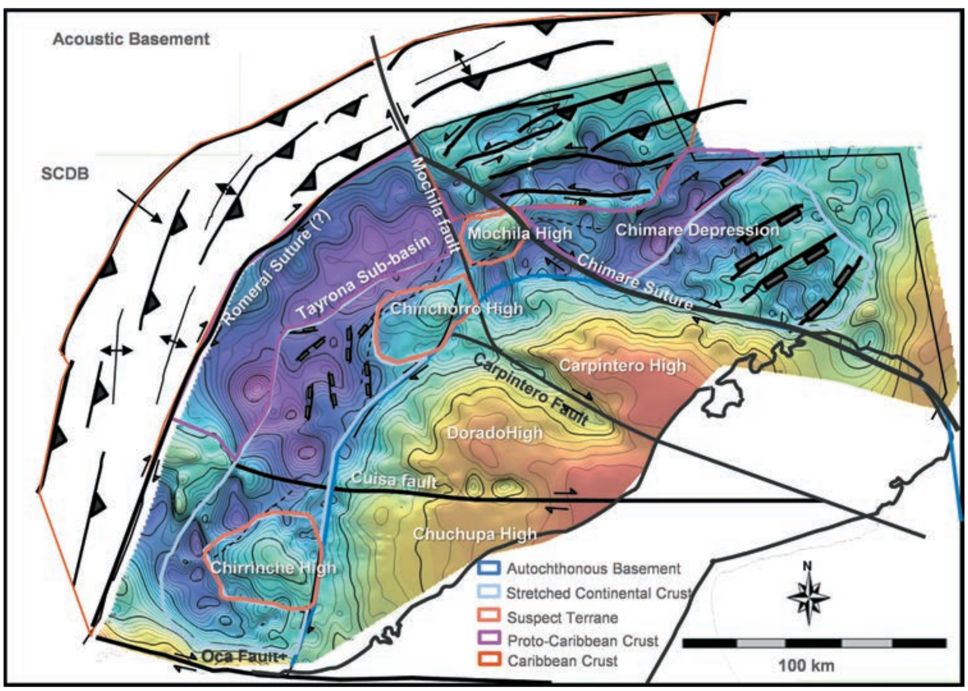

Figure 3. Acoustic basement showing three tectonic domains: (1) the main basement block formed by the Chuchupa, Dorado, and Carpintero highs, corresponding the autochthonous South American plate; (2) two areas of block tectonics with horst-and-graben systems: one in the north, contiguous to the Chimare depression, and one in the south contiguous to the Tayrona depression. These two systems could represent relicts of the Jurassic rift system that separated North and South American plates. Additionally, the deepest parts of the depressions could contain proto-Caribbean oceanic crust. Note how the Carpintero–Mochila right-lateral strike-slip fault system and the Chimare suture appear to have displaced the Chimare depression and contiguous horst-and-graben system westward, suggesting an earlier continuous Tayrona–Chimare depression system; and (3) the Chirrinche, Chinchorro, and Mochila paleohighs and their contrasting nature when compared to the main basement block. The Neogene Tayrona Subbasin is produced by a releasing bend (Mochila fault) of the suture between SCDB and the South American plate (Romeral ?). 100 km (62.1 mi)

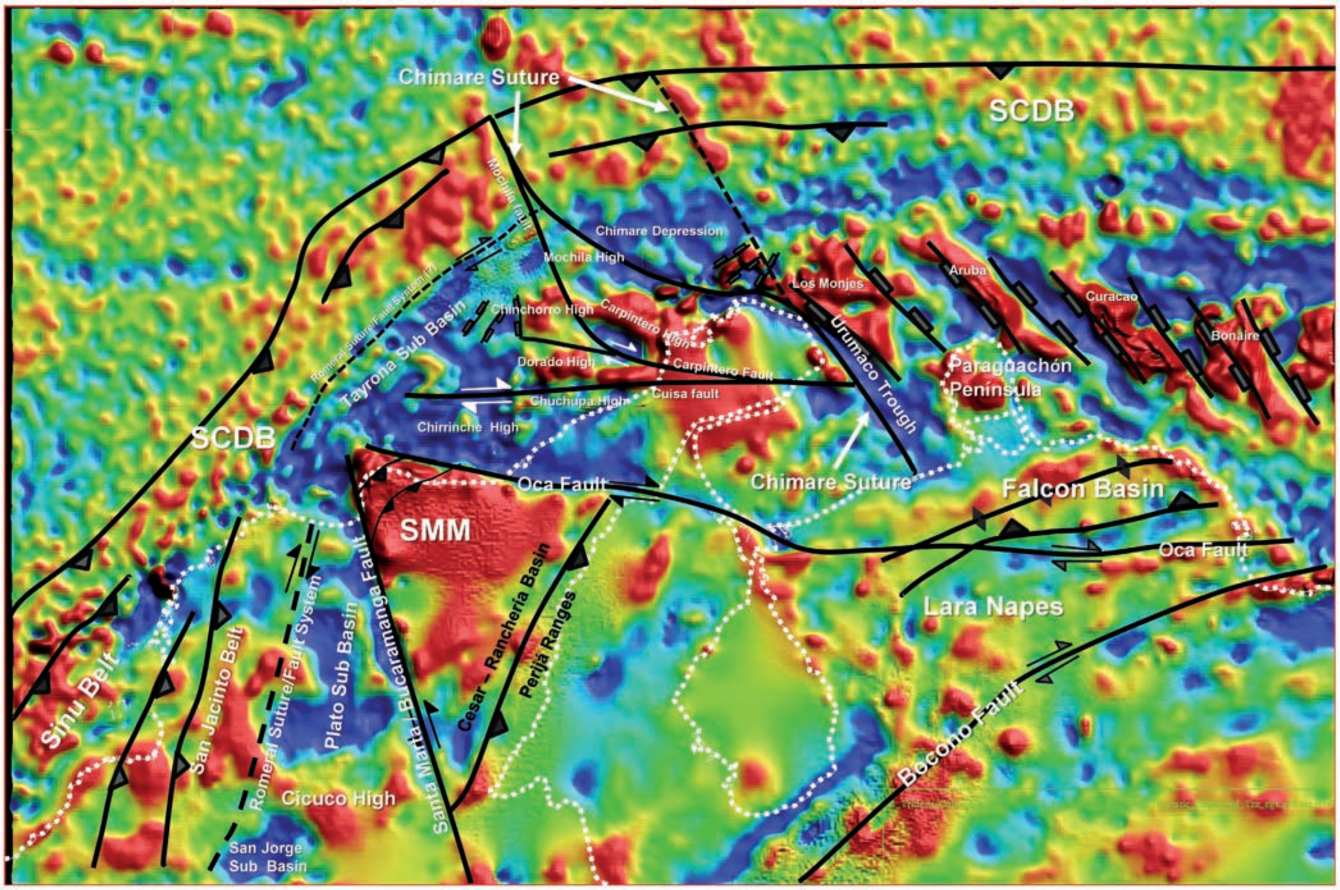

Figure 4. Bouguer-Free Air airborne anomaly map. Bandpass filter: 100 km (62.1 mi). The Aruba, Bonaire, Curacao Complex (ABC) anomaly in the east, shows a characteristic NNW–SSE fabric that corresponds to the Great Arc of the Caribbean. The Chimare suture, a conspicuous gravity minima stretching from the SCDB to the Gulf of Coquivacoa and Venezuela, is the western tectonic boundary of the ABC terrane, and marks a clear contrast with the fabric of the South American autochthon in Colombia toward the west. The Chuchupa, Dorado, and Carpintero basement highs are apparent in the map. Note the contrasting fabric of these blocks with that of the Chirrinche, Chinchorro, and Mochila suspect terranes. The Carpintero, Cuisa, and Oca faults are also apparent in the map.

BASEMENT DISTRIBUTION IN THE GUAJIRA OFFSHORE BASIN

Figure 2 shows a geologic map of the Guajira (Gomez et al., 2011) highlighting the type and age of basement in the peninsula and nearby onshore and offshore exploration wells that publicly reported basement at total depth. Except for the SW–NE trend of the Grenvillian-age granulites at the center of the Alta Guajira, it is apparent from the map that no preferential tectonic arrangement exists in other areas where the basement has been found in the Guajira Basin, including the offshore province where it has been penetrated by wells. Rather, the basement in the Guajira shows a complex assemblage of igneous, volcanic, and diverse-grade metamorphic lithology, with a wide spectrum of ages from Precambrian to Eocene. It is interesting to mention the Cabo De La Vela ultramafic complex, identified by Weber et al. (2009) as a Pre-Campanian set of gabbros and serpentines related most likely to a back-arc spreading center. At a relatively short distance an offshore well named here 1 (Figure 2) drilled basement: a granodioritic gneiss dated as 223 $\pm$ 5 Ma, using radiometric methods. It is worth noting that this basement rock exhibits very low magnetic susceptibility values (ca 30 $\times$ 10^{-6} emu), atypical for granodiorites and gneisses that usually show values ranging from 400 emu to 2700 $\times$ 10^{-6} emu. Onshore Triassic granodiorites have been reported in the Serrania de Macuira area in the Alta Guajira, although it is not clear if both series represent the same genesis or thermal event. It also is interesting to note that the 70 Ma granite found in Well 2 (Figure 2) with strong continental affinity, which contrasts sharply with those considered of Caribbean–GAC affinity (Cardona, 2009). Metashales found in the offshore Well 3 (Figure 2) show ambiguous ages ranging from 128 Ma to 65 Ma. These are examples of diverse and contrasting basement types that do not allow us to interpret a single dominant tectonic event in the Guajira Basin. In the following sections a description of the four main basement provinces found in the Guajira Offshore Basin will be presented.

THE AUTOCHTHONOUS BLOCK

It is considered in this chapter that the main autochthonous basement block in the Guajira Offshore Basin is the extension of the Chuchupa, Dorado, and Carpintero highs into the deep water domain (Figures 3 and 4). The early–middle Cretaceous low-grade metamorphic belt and some late Cretaceous granites south of Chuchupa high, and the Pre-Campanian Cretaceous mafic and ultramafic bodies found in the Cabo De La Vela area, contrast in age with the late Triassic granodiorite found in Well 1, on top of the Carpintero high, although they appear to be located in the same block (Figure 2). Each one of these blocks has been displaced along major right-lateral strike-slip faults; evidence of this displacement is found in seismic lines (e.g., Figure 5), gravity anomalies (Figure 4), and basement distribution (Figure 3). The inner portion of the basin (Figure 3) exhibits the Chuchupa area basement block in the south, displaced by the offshore extent of the Cuisa fault. Further north, another major fault, called informally here the Carpintero fault, displaces basement and separates the Dorado block from the Carpintero block in the north (Figure 3). One common feature of the basement in these blocks is the dramatic deepening toward the western domain of the basin. In a relatively short horizontal distance (ca 80 km [49.7 mi]) the basement plunges from around 1000 mbsl to almost 5000 mbsl (Figures 3 and 5). Simple 2-D forward models of the Bouguer gravity anomaly constrained by density data from exploration wells show the geometry of the basement across the Guajira Offshore Basin (Figure 6). The model displays the subducting Caribbean plate under continental crust, at an average 17° angle, in the western offshore area. The model also shows that up to 7 km (4.3 mi) of sedimentary column was accumulated over the oceanic plate. Along the inboard area, the continental crust thickness decreases abruptly over a distance of ca 80 km (49.7 mi) from ca 23 km (14.2 mi) in the Dorado Block to ca 3 km (1.8 mi) in the inner Tayrona Subbasin (Figures 5 and 6). Harry et al. (2003) show how most continental margins around the world fall into two categories when the crustal-thickness-change gradient is measured across the margin (Figure 7). Typical passive margins show a gradual thickness change, while transform margins show an abrupt thickness adjustment (Figure 7). When the Guajira crustal-thickness gradient along the 2-D section is plotted against the compilation of Harry et al. (2003) it falls within the transform margin cluster (Figure 7). In order to validate our observations, an additional section showing the lower Guajira continental crust, modeled by Ceron-Abril (2008),

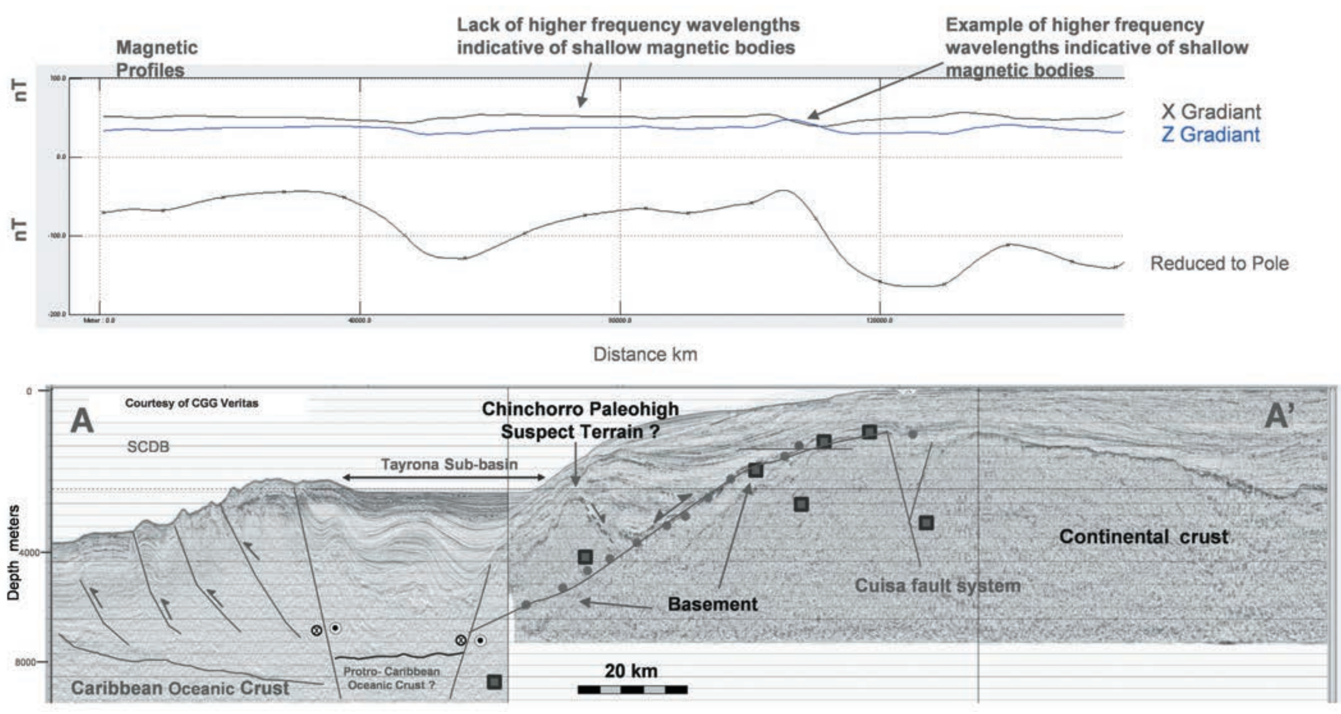

Figure 5. Composite seismic section showing the main basement tectonic blocks in the Guajira Offshore Basin and their corresponding magnetic anomaly. The top of the basement is calculated using proprietary spectral analysis techniques. The model shows the top of the "magnetic" basement extending underneath the Chinchorro suspect terrane. Note the nonmagnetic nature of this paleohigh. This section also shows the dramatic deepening of the crystalline basement in a short horizontal distance (location in Figure 1). 20 km (12.4 mi)

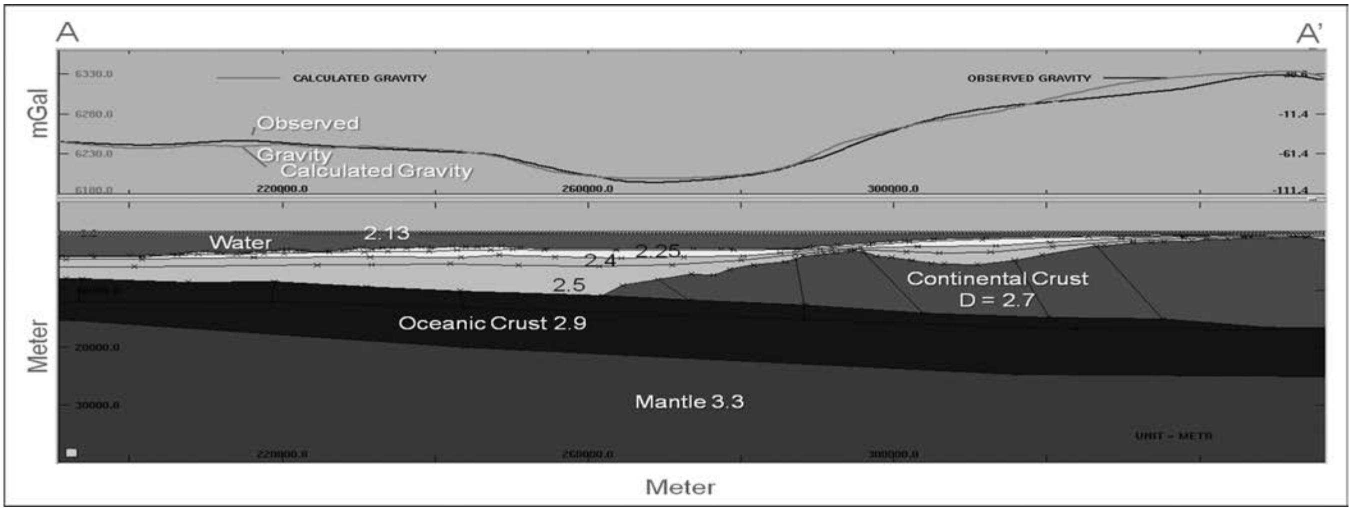

Figure 6. Two-dimensional forward model of the Bouguer anomaly. The results are consistent with a continental block forming the main autochthonous basement overlying the subducting Caribbean plate. Note the dramatic change in basement thickness from 20 km (12.4 mi) near the coastline to 2 km (1.2 mi) in the Tayrona Subbasin in ca 80 km (49.7 mi) (section A-A′ located in Figure 1).

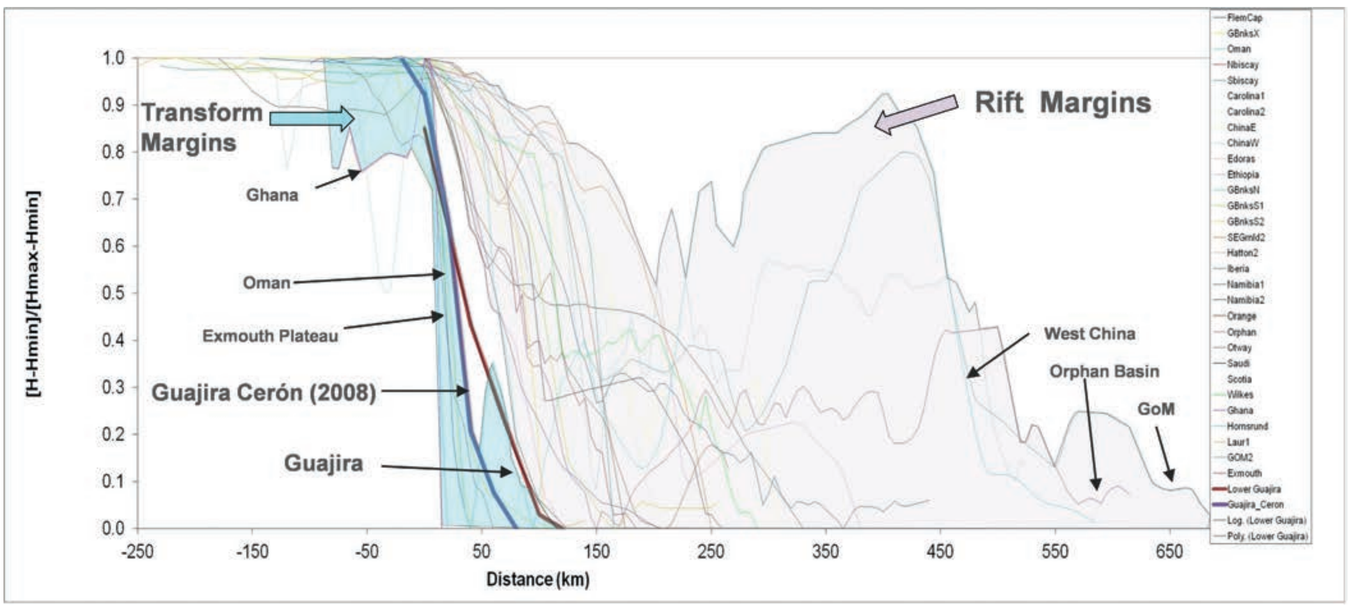

Figure 7. After Harry et al. (2003). This compilation shows the distribution of the crustal thickness as a function of horizontal distance along passive and transform margins. The Guajira offshore basement thickness-change gradient (based on 2-D forward models) falls within the transform margin cluster. It also includes the 2-D forward model developed by Ceron-Abril (2008). 50 km (31.1 mi)

was also considered: the continental crust thickness changes from 18 km (11.1 mi) to 1 km (0.6 mi) across the margin in ca 60 km (37.2 mi) of horizontal distance. When this gradient is plotted against the compilation of Harry et al. (2003), it also falls within the transform margin field with an even steeper gradient (Figure 7). The northern boundary of the autochthonous block is not clear. In this chapter we propose the Chimare suture (Figures 1, 3, and 4) as the boundary since it marks the northern end of the main basement blocks, considered here autochthonous, against the suture that appears as a clear gravity minima separating the basement block in the south from a block-tectonics domain (discussed in next section) in the north; it also is apparent in some of the seismic data. The southern boundary is clearly marked by the Oca fault where the lowlands of the lower Guajira terrane are in sharp contrast with the 5700 m (18,700.8 ft)-high Santa Marta massif (Figure 1).

BLOCK-TECTONICS DOMAINS

East of the Chimare depression area (Figures 1 and 3), there is a structural segment dominated by rift-tectonics: normal faulting that forms grabens and half-grabens in the basement (Figure 8a). These features can also be identified in the gravity map, where the horst-and-graben blocks coincide with gravity maxima and minima respectively (Figure 4). The synrift sedimentary succession, up to 3500 m (11,482.9 ft) thick, shows wedge-like geometries filling the accommodation created by the displacement and rotation of the blocks. In addition, a very continuous seismic event appears to be at the top of the synrift sequence and immediately above it; a sequence consistent with sag facies typical of these environments is also interpreted. Younger sequences seem to be affected by recent small-displacement normal faults at shallower levels. The oldest reliable age that we can correlate with some certainty is a mid-Paleocene reflector that can be extended to a nearby exploration well (Figure 8a). Below this reflector there is no certainty and any assigned age is speculative at best. This structural domain is separated from the Carpintero Block by the Chimare suture, a right-lateral strike-slip fault, with a strong vertical component, as suggested by a basement step identified in seismic data, and the east–west elongated gravity minima along the Guajira northern coastal border (Figure 4). This anomaly extends from the SCDB at the point where a strike-domain change exists, from a NE–SW to an E–W preferential orientation (Figure 4), into the Gulf of Coquivacoa and Venezuela, although it is not evident in the seismic data within the SCDB. In the Gulf of Venezuela the structural trend of the western limit of the Urumaco trough appears to coincide with the trace of the Chimare suture. In Venezuela this limit separates the western Guajira domain of South American affinity, from the

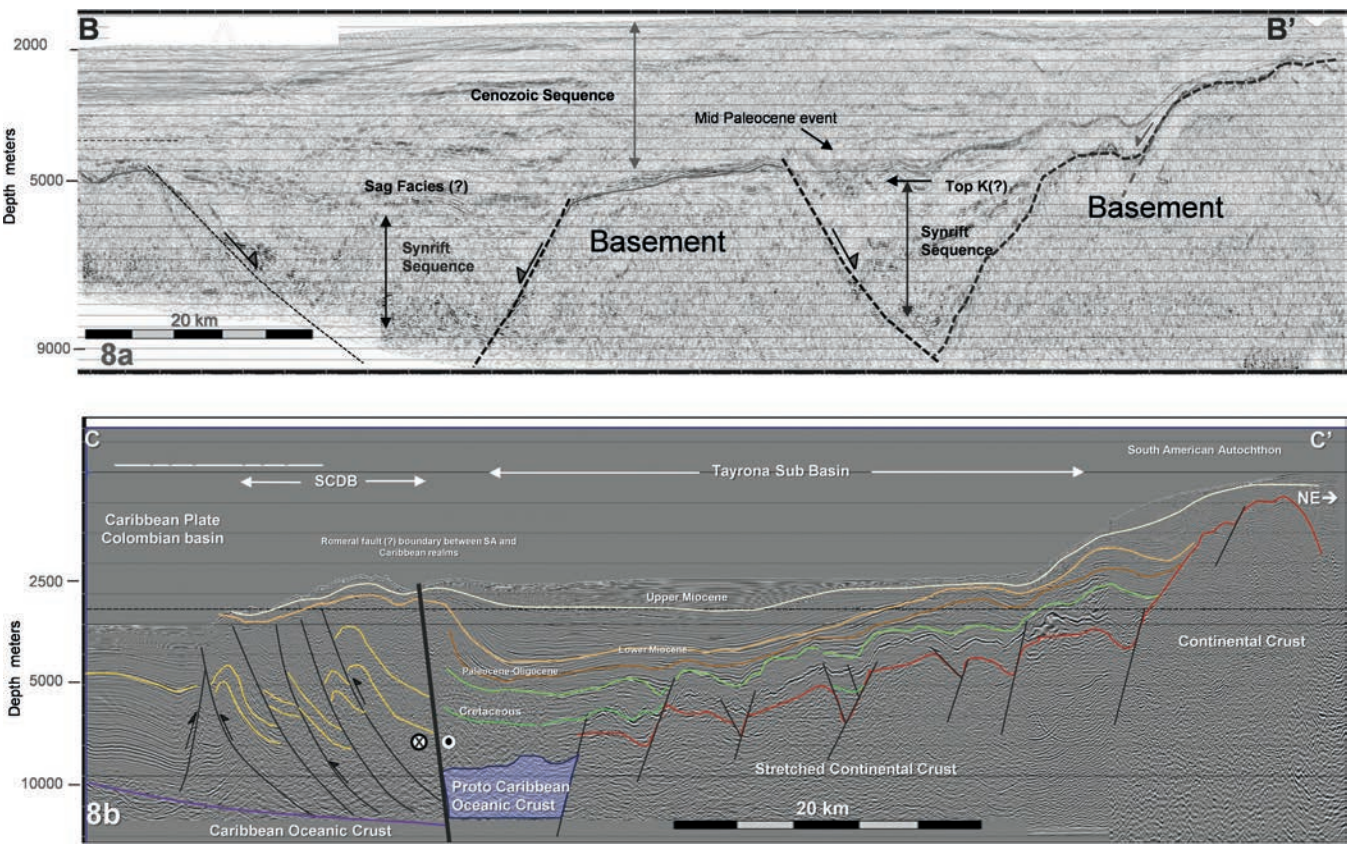

Figure 8. Cross sections showing two areas of block tectonics. (A) Northern Guajira rift-system area. The location of these grabens is also found in the gravity anomaly map (Figure 4). (B) Tayrona Subbasin (location in Figure 1). We speculate that these horst-and-graben systems correspond to stretched continental crust deformed during the opening of the proto-Caribbean Sea, when North and South American plates drifted apart in late Jurassic times. A relict of proto-Caribbean oceanic crust could also be present in the deepest parts of the basin. The boundary between the mostly autochthonous continental Tayrona Subbasin (South American plate) and the SCDB of oceanic affinity is a strike-slip fault that in some instances could be speculated as the continuation of the Romeral fault system. 20 km (12.4 mi)

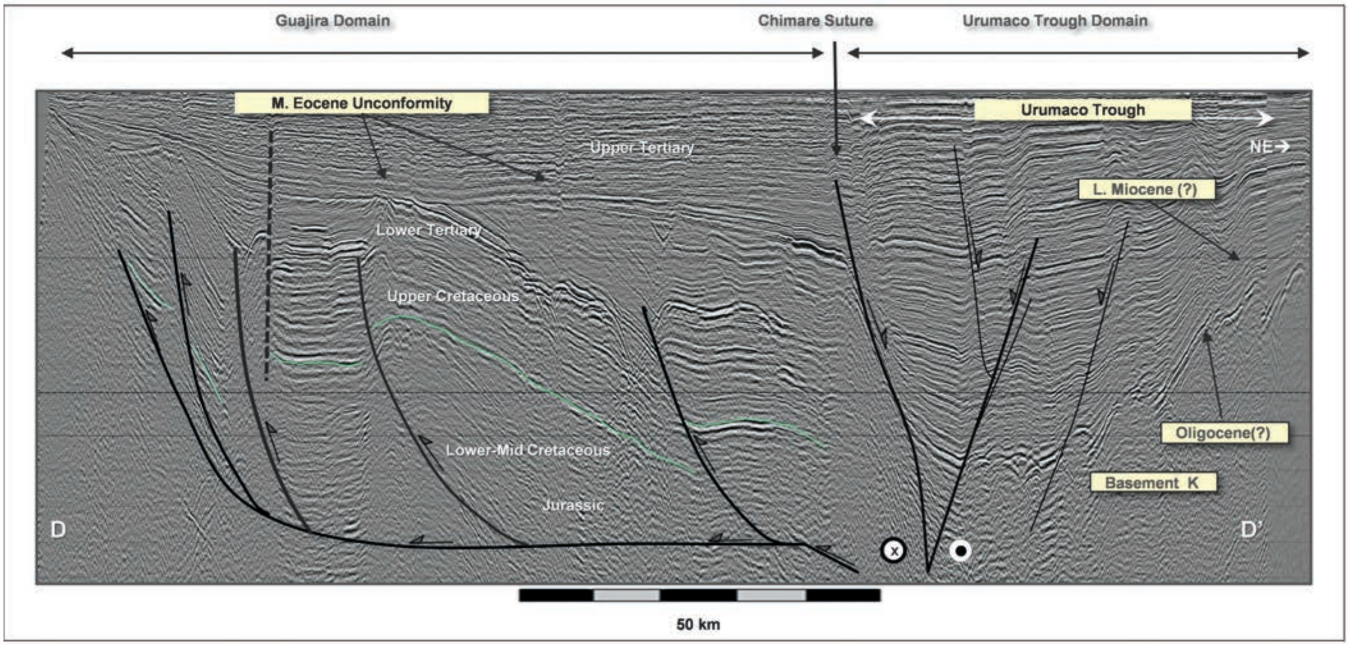

Figure 9. Seismic section showing the Chimare suture (location in Figure 1). There is a conspicuous contrast between the eastern Urumaco trough domain and the western Guajira domain. The trough exhibits a thick Neogene sedimentary sequence, and Oligocene sediments overlaying Cretaceous metamorphic rocks. The Guajira domain exhibits a thin Neogene sedimentary column on top of the regional middle Eocene unconformity, overlying a thick Mesozoic sedimentary sequence that includes Jurassic, Cretaceous, and Paleogene sequences. Also note the contrasting structural styles between both domains (discussion in text). The Chimare suture is an important tectonic boundary that separates the Caribbean realm to the east, from the South American Block to the west (after Malave and Contreras, 2012) (location in Figure 1). Courtesy of PDVSA–Intervep. 50 km (31.1 mi)

eastern "Caribbean domain" (Figure 9). The Chimare depression could represent the deepest part of the Jurassic rift system, where relicts of proto-Caribbean crust may even exist. The depression was later affected by more recent strike-slip faulting at the western edge of this subbasin (Figure 2).

A second area that exhibits block tectonics can be identified in the southeastern end of the Tayrona Subbasin and can be distinguished in both gravity and seismic data (Figures 4 and 8B). The gravity anomaly map shows narrow semicircular gravity minima. There is a similar anomaly further north near the Mochila high. Seismic data shows stretched continental basement affected by normal faulting that deepens toward the west and ends in the suture or boundary against the SCDB. The proto-Caribbean remnant shown in Figure 8B comes from the character and depth of the basement in that region, but its nature is merely interpretative. The synrift sequence can reach up to 3000 m (9842.5 ft) in thickness, although no sag facies are easily discernible in the seismic data. The northern extend appears to be limited to the southern flank of the Chinchorro paleohigh, but the relationship between these two blocks is not evident within the dataset; the most likely scenario would be a faulted/transcurrent contact. The main fault within the blocks appears to be dipping to the west, with abundant small-slip antithetic faulting. On the gravity map, the faults are apparent as bounding basement blocks (Figure 4). In both cases, the interpretation of basement blocks and bounding faults in seismic data coincide with those interpreted in the gravity anomaly map. The age of this domain is uncertain; however, the strong reflector that tops the graben and the synrift sequence can be correlated with a similarly strong event in the northern rift of the Chimare depression area.

SUSPECT TERRANES

A conspicuous set of features, easily recognizable in both seismic and in potential field data, is a succession of relatively small basement paleohighs, here informally called Chirrinche, Chinchorro, and Mochila highs (Figures 3 and 4). The gravity anomaly shows a NNE maxima trend, in clear contrast with the contiguous E–W trend of the Chuchupa, Dorado, and Carpintero basement blocks in the area (Figure 4). Additionally, the amplitude of the gravity anomaly caused by these highs is characteristically smaller than that of the main basement blocks (Figure 4). Seismically they do not appear to be a continuation of the basement block from the east (Figure 5). The geometry of these blocks does not resemble that of block tectonics (Figure 3), rather it appears to be in a faulted contact (perhaps a right-lateral strike-slip fault with a reverse component?) with the main basement block toward the east (Figures 3 and 5). Magnetic analysis also confirms that the nature of these suspect blocks can be differentiated from the contiguous basement block for its non-magnetic character (Figure 5): carbonates or metashales appear as the best candidates for the lithology of these terranes, although this is a speculation only based on density estimates (ca 2.4–2.7 g/cc). Additionally, given the low magnetic susceptibility of the granodioritic gneiss found in Well 1 (Figure 1), it is also possible that this terrane could be part of the same Carpintero Block in the north displaced by the Mochila–Carpintero fault system (Figures 3 and 4). Densities in the models, however, are lower than those found in the well. The top of the crystalline basement would require then to either go underneath this block or abruptly end against the strike-slip fault (Figure 5). The northern limit of the Tayrona Subbasin appears to be the Mochila fault (Figures 3 and 4), which exhibits a strong normal component. The age of these suspect terranes is uncertain, although reflector geometries and onlap relationships constrain the age of collision/accretion of these block to pre–mid-Paleocene. Structurally the Chirrinche and Chinchorro paleohighs are in direct contact with the main basement block along what appear to be strike-slip faults (Figures 3, 4, and 5); however the Mochila paleohigh is contiguous to the SCDB and separated from the main basement block by what is interpreted as an extension of the Chimare depression (Figures 3 and 4).

TRANSCURRENT BASINS

The Neogene Tayrona Subbasin and the Chimare depression appear to have developed along the main Mesozoic rifted and stretched crust. The evolution of these basins appears to be related to the transcurrent fault systems developed during the collision of the CLIP with the South American autochthon. Within the western domain, inboard of the SCDB (Figure 3) two structural segments can be distinguished: the southern Tayrona Subbasin and the northern inner part of a deformed belt (Figure 3). These two areas are separated by a NW–SE right-lateral strike-slip fault, informally called the Mochila fault (Figure 3). This fault also seems to be a critical part of the transcurrent system that created the Neogene Tayrona Subbasin. This depression is a NE–SW mostly Miocene depocenter that appears to be aligned along the SCDB and ends in the south, against the Santa Marta massif (Figure 3). Ceron-Abril (2008) interpreted this feature as the product of a release-bend of the Oca fault. In this chapter the Tayrona Subbasin is interpreted as created by the rotation of two strike-slip faults at the east and west boundaries of this depression, that create transtensional and transpressional features such as inverted basins and normal faulting (Figure 5), or, alternatively, as a releasing bend of the strike-slip fault (Romeral?) that acts as the tectonic boundary between the South American plate and the SCDB. The eastern boundary shows a strong normal displacement that in areas appears as a complete collapse of the flank of the antiform found in this subbasin (Figure 5). It is also worthy to note how in the structural map of the basement (Figure 3) and gravity anomaly map (Figure 4), it appears that the Chimare depression is a continuation of the Tayrona Subbasin displaced along the Chimare suture and/or Mochila–Carpintero fault system. The northwestern segment of the study area, although part of the SCDB, exhibits two narrow but elongated depressions that are formed by transcurrent stresses (Figure 3). It is not clear either if any of these basins could be interpreted as a continuation of the Tayrona Subbasin, but this area appears clearly more deformed as the SCDB bends in a more east–west orientation. The western segment, formed by the SCDB, shows typical geometries expected in these convergent tectonic settings, that is, an accretionary prism or thrust belt with abundant fault-related folds and what appears to be mud diapirism. This thrust belt is overriding the oceanic lithosphere of the Caribbean plate. It also bends in the southwestern end of the Guajira Offshore Basin changing orientation from a NW–SE to a more N–S trend (Figures 1 and 3).

DISCUSSION

It is difficult to accurately determine, with the current dataset available in the Guajira Offshore Basin, what the origin of the main basement block is in the area. The diverse age and nature of the different blocks favor accretion of diverse terranes at different times. For example the Triassic granodioritic gneiss found in Well 1 in the Carpintero Block contiguous to the Pre-Campanian Cabo De La Vela ultramafic complex is hard to explain with a single accretion-collision model.

Furthermore, previous works (Pindell et al., 2006; Vence, 2008) suggested the pervasive presence of the GAC along the entire margin of the Guajira Offshore Basin; however, the presence of the Triassic gneiss is also in conflict with this interpretation. Given the isolated nature of the ultramafic complex in the area, it would be easier to explain it either as a tectonic sliver of a Cretaceous oceanic block or as a terrane accreted to what we interpreted here as the autochthon Carpintero Block. Weber et al. (2009) interpreted parts of the Cabo De La Vela ultramafic complex as created in a back-arc setting, tectonically west of today's location of the complex. However, such features are usually hundreds of kilometers long and tens of kilometers wide (Marsaglia, 1995), and in the Guajira Offshore Basin no seismic data show elements that allow the interpretation of any remnants of a back-arc setting. Well 2 (Figure 2) tested granites of continental affinity that would be hard to explain as part of the GAC. The model described by Cardona (2009) trying to justify the granite embedded in the GAC requires a really complex and challenging geodynamic evolution of continental subduction below a thickened Caribbean plate and later a subduction polarity-change involving the same lithospheric plates. It would be easier to explain it with a middle–late Cretaceous east dipping subduction model involving normal-thickness proto-Caribbean plate below the South American autochthon, as proposed by Giunta and Oliveri (2009).

The gravity map in Figure 4, shows a clear regional fabric contrast between the eastern GAC domain (the NW–SE trend of the Aruba Basin, West Curacao Basin, and East Curacao Basin [ABC complex]) and the western anomaly geometry found in the Guajira domain separated by the Chimare suture. Locally, the later domain shows two contrasting fabrics when the main basement block and the suspect terranes are considered. The mostly NNE Chirrinche, Chinchorro, and Mochila highs do not form a continuum with the Chuchupa, Dorado, and Carpintero basement highs. Not only does their tectonic trend appear to be different, but also their corresponding gravity anomaly appears to be at a different scale and magnitude. The 2-D gravity forward models (Figure 6), both the model of this work, and that of Ceron-Abril (2008), appear to be consistent with a continental crust overriding the subducting Caribbean plate in a seemingly simple model. No high-density lithologies, typical of oceanic crust, are needed to replicate the gravity anomaly. It is also interesting to note how both gravity models require thickened oceanic crust as part of the subducting Caribbean plate. The lack of seismic activity or evidence of volcanism younger than Eocene in the Guajira Offshore area (Ceron-Abril, 2008) supports a buoyant "subducting" oceanic plate, consistent with the collision of the CLIP with the South American autochthon, after the subduction of the normal-thickness proto-Caribbean oceanic crust in Cretaceous time, as proposed by Giunta and Oliveri (2009). Although Vence (2008) invokes the dome-like geometry of the main continental block as evidence to interpret the presence of the GAC in the area, in this chapter it is considered that the geometry of the basement is neither that of an island arc nor that of a typical passive margin as most of the authors have previously interpreted this margin. Figure 7 shows clearly how the Guajira Margin step-gradient falls within the transform margin cluster in the compilation of Harry et al. (2003).

In order to understand how a transform margin involving continent-ocean transition would work in the Guajira Offshore Basin we need to take into account that transform margins have two common characteristics: (a) lack of synrift magmatism affecting the crust (Harry et al., 2003), and (b) oceanic crust adjacent to the transform margins (Bird, 2001). In the Guajira Offshore Basin no Jurassic synrift volcanism, plutonism, or magmatic underplating of the crust has been reported affecting the offshore basement. And despite the fact that it is not possible to establish with certainty the existence of a proto-Caribbean oceanic remnant in the area, the aforementioned rift system identified in both the Tayrona Subbasin and in the northern Guajira Offshore Basin (Figure 3) could have been part of the transition toward an oceanic realm (Figures 7 and 10). The data are inconclusive in regard to the position of the ocean-continent transition, but most models depict a rift system between the Yucatan Block and northwestern Colombia with a mostly NE–SW orientation (Lugo and Mann, 1995; Pindell et al., 2006; James, 2009; Pindell and Kennan, 2009). The main Guajira Block could be one branch of one of these transform systems (Figure 10) with an orientation mostly normal to the ridge, that is, NW–SE (although some transform margins exhibit an oblique orientation to the rift system). The Neogene Tayrona Subbasin that developed on top of stretched continental crust could represent the location of one rifted arm of the system in the south; and the Serrania de Cocinas Basin the other rifted arm in the north (Figure 10). According to Ceron-Abril (2008) the current preferential trend of the basement in the Guajira Offshore Basin is NE–SW and it would have required a rotation of almost 90° from its original position. Skerlec and Hargraves (1980) report that a collision with northwestern South America has been predicted to have produced a 90° clockwise rotation as the GAC swung into parallelism with the east–west-trending margin of northwestern South America. The model by Giunta and Oliveri (2009) also implies a clockwise rotation of the Guajira terrane since early Cretaceous times to its current position. The differences between the rifting-related domains and the eastern main autochthonous

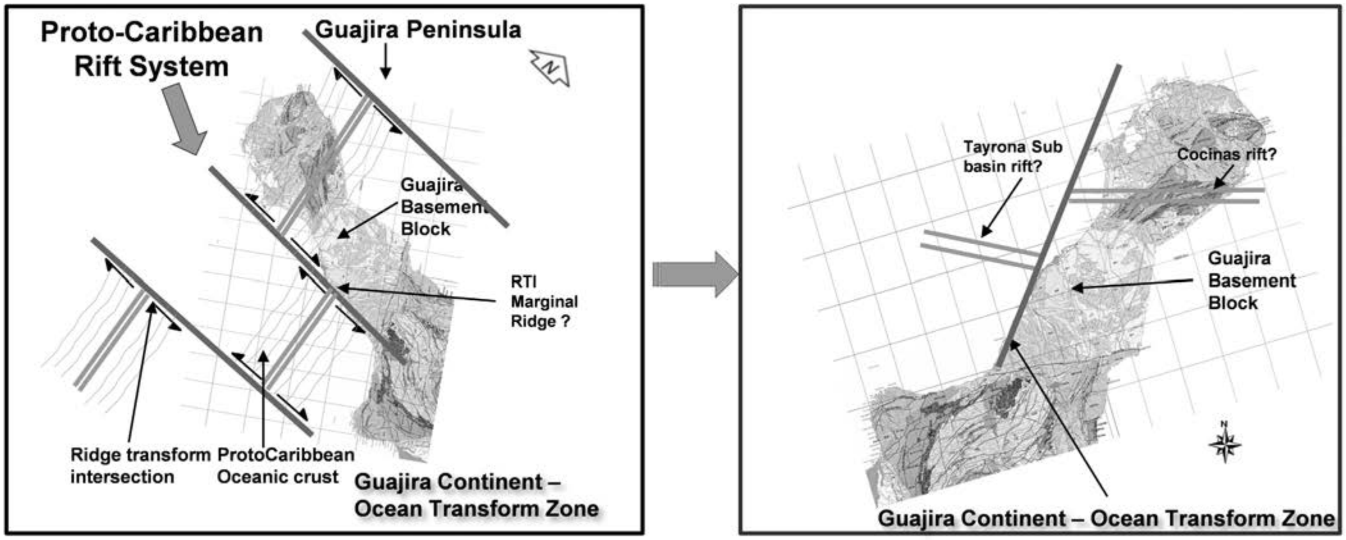

Figure 10. Proposed model for the continent-ocean transform fault affecting the Guajira basement autochthon during the late Jurassic rifting. This conceptual model, based on the dramatic basement-thickness change, requires a rotation of almost 90° to its current position. The northern Guajira sediment sequence found in the Serrania de Cocinas (Zuluaga and Stowell, 2012) could represent one of the arms of the rift system, later rotated by the Cuisa fault.

basement block are striking; we consider that a Jurassic transform fault/margin in the south would explain part of these differences.

Previous interpretations of rift-related normal faulting affecting basement east of the Chimare Subbasin area identified a preferential NW–SE trending orientation (Vence, 2008). This interpretation explains these rifts as the product of an Eocene event that subaerially exposed most of the Guajira Basin (Escalona and Mann, 2006). However, we have identified a contrasting NE–SW trend that is apparent in at least four parallel E–W seismic sections and in the gravity map (Figure 4). Paleontological data from nearby wells only allow dating seismic events above the synrift sequences as pre–mid-Paleogene in age (Figure 8A). Well 4, however, drilled a thick section of reworked Maastrichtian (?) shales and sandstones (Ramirez, 2008; Figure 2), the only reported non-metamorphous Cretaceous lithology in the Guajira Offshore Basin. These structures can be correlated to at least three independent tectonic events that have been reported to affect the basement in the area: (1) a Jurassic rifting phase preceding the development of the proto-Caribbean plate (Burke, 1988; Pindell et al., 2006; Pindell and Kennan, 2009); (2) a Pre-Campanian slow-spreading event related to a back-arc system west of El Cabo De La Vela where gabbros and serpentinites are found along the coastal area (Weber et al., 2009); and (3) a basin formed by rifting in a continental arc, as interpreted in the Guajira Onshore Basin (Zuluaga et al., 2015, this volume. Figure 2). In all cases the rift-related structures are Mesozoic in age. Based on the seismic facies of the synrift sequences, the late Triassic age of basement in Well 1, the required continental crust in the gravity 2-D forward models, and the lack of a regional context for the back-arc basin model, we favor a Jurassic age for these structures since they resemble those found in continental rifting events around the world. Nevertheless, these faults could have been reactivated at a later stage, as can be seen in the seismic data. We recognize the speculative nature of this interpretation as it also would have required the northern rifted block to have been transported east to its current location by the Chimare suture. Additionally, since the horsts and grabens in the northern block cannot be part of the GAC, according to our interpretation, we propose that the western limit of this arc is located east of this block and north of the Chimare suture (Figure 3).

The southern rifted province requires a complex geodynamic evolution, especially because it is separated from the basement for what we interpreted here as a set of suspect terranes. One model would require that the suspect blocks were part of the continental autochthon bounded by the late Jurassic rift-related transform faults (Figure 10), although attached to this terrane by an older suture. A second model would require both the paleohighs and the rifted area to be allochthonous in nature and attached to the South American plate probably during Cretaceous time, as proposed by Giunta and Oliveri (2009). With the current limited age constraints for this province, it is difficult to favor one model over the other. However, it is interesting to note the fact that it is possible to map the same event overlying the top of the rift-sequences as a single reflector, without major structural obstacles from the northern rifted province (Chimare depression) to the Tayrona Subbasin, in what appears to be a geographically continuous depositional frame. Thus, it is possible to speculate that this is a singular rift system of Jurassic age, later displaced and rotated toward the east by the Mochila fault /Chimare suture system (Figures 3 and 10). The western boundary of the Tayrona Subbasin is a suture that separates this block from the SCDB and it is interpreted in this chapter as the boundary between the South American autochthon and the Caribbean plate (Figure 8). Whether this suture is the northern continuation of the Romeral fault system or an independent system, is still in debate, but certainly, both sutures represent the same tectonic limit between the South American continental plate and Caribbean oceanic plate north and south of the Santa Martha massif (Figures 1 and 3).

The Chimare suture (Figures 3, 4, and 9) seems to be a deep-rooted structure generated by compression during the rotation of the SCDB from a NNE–SSW to a more E–W trend. This feature aligns parallel to the main structural fabric found in the leeward Antilles (e.g., Aruba Basin, West Curacao Basin, East Curacao Basin, and associated normal faults [ABC complex, Macellari, 1998]), and could be a continuation of the western edge of the Urumaco trough in Venezuela, as is evident in the gravity map (Figures 1 and 3). The western block that bounds the Urumaco depression is considered as part of the autochthonous Venezuelan Block. Figure 9 shows a seismic section throughout the Urumaco trough: the Guajira domain exhibits a thin Neogene sedimentary column on top of the regional middle Eocene unconformity (Malave and Contreras, 2012), also identified by Macellari (1995) in the nearby Guajira 1 well in the Cocinetas Basin of the Alta Guajira Onshore Basin. This angular unconformity tops a thick Mesozoic sedimentary sequence that includes Jurassic, Cretaceous, and Paleogene sequences. The eastern block, by contrast, exhibits a thick middle to late Tertiary sedimentary section overlying the late Cretaceous basement of Caribbean affinity (GAC). The structural styles are completely different in both domains: the Guajira domain exhibits a typical fault-related folding geometry of a compressional setting, while the Urumaco trough domain exhibits normal faulting related to the transtension produced by the Chimare suture strike-slip component. Since the suture appears to have a right-lateral displacement, this implies that the eastern domain was transported to its current position from the N–NW. Given the structural alignment between the Chimare suture and the western boundary of the Urumaco trough, in this chapter we interpret the suture as the main boundary between the South American autochthonous block and the Caribbean realm at the northern end of the Guajira terrane. Its northernmost trace is still uncertain, since it appears to bifurcate into two branches that frame the northern block-tectonics terrane of proto-Caribbean affinity and separate it from the Carpintero Block in the south and the Los Monjes Island Block, of GAC affinity (Vence, 2008), in the north (Figure 4).

The Chirrinche, Chinchorro, and Mochila highs (Figures 3 and 4) may form a small mountain chain with similar genesis given the similarities in character of the gravity anomaly produced by these features (Figure 4). Seismic data may also indicate that a strike-slip fault, with a strong vertical component, can separate this chain from the main basement block toward the east (Figures 3, 4, and 5). Additionally, the magnetic imprint of these blocks allows us to differentiate these from the Guajira basement in the east. Therefore, we interpret this chain of paleohighs as an accreted suspect terrane, displaced by the Mochila fault (Figure 1), with no oceanic affinity. Alternatively they also may be part of the same Carpintero Block, but displaced by a combination of movements of the Mochila, the Carpintero, and the N–S strike-slip faults affecting the edge of the main-block basement block (Figure 3). The age of the accretion, based on onlap relationships, can be constrained to be older than early Paleogene. The age and detailed nature of the paleohighs, however, is uncertain.

The Tayrona Subbasin appears to be a transtensional basin that aligns along the SCDB. The gravity 2-D forward model and seismic data (Figures 6 and 8) show how stretched continental crust is underneath this subbasin. In the deepest part of the basin (Figure 8B) it is possible to infer a remnant of proto-Caribbean oceanic crust. The nature of the basement underlying the SCDB domain is uncertain, although gravity models (Ceron-Abril, 2008) show the subducting Caribbean plate below this domain. The northern limit of this depression is the Mochila fault. We interpret that this fault is generated by stresses due to the change of orientation of the SCDB from a NW–SW to a more E–W trend. And it also can potentially act as a releasing bend of the Romeral (?) mega-suture (Figures 4 and 8B) creating tensional stresses needed to form the subbasin. Thus, we infer a right-lateral rotation that displaced the northern domain putting the SCDB as the boundary of the Tayrona Subbasin. The relationship between the Mochila fault and the Chimare suture is uncertain, although both features appear to converge at the mentioned point of change of direction of the SCDB. The northern domain of the SCDB appears to be overriding oceanic crust. The main features of this domain are the two elongated transcurrent-related depressions that aligned along the main structural trend. We interpret that they formed as part of the strain field created by the oblique convergence between the Caribbean plate and the South American terrane. It is interesting to note though, that these features are oriented normal to the main tectonic transport of the SCDB. The age of these strike-slip faults is uncertain, but they appear to be currently active. Finally, we agree with previous authors that the SCDB represents a compressive phase originated by the convergence of the Caribbean plate and the South American terrane.

Figure 11 shows a simplified and speculative evolution model for the Guajira Offshore Basin, incorporating the tectonic provinces described before. The model agrees with most of the regional tectonic elements identified by Giunta and Orioli (2011) for the Caribbean Margin:

1. Late Jurassic–early Cretaceous: opening of the proto-Caribbean Sea between the South American Block and the North American plate (Yucatan Block); development of the transitional continent-ocean transform boundary along today's Guajira Offshore Basin.
2. Middle–late Cretaceous: subduction of normal-thickness proto-Caribbean crust below the South American Block; plutonism in the Colombian Margin and possible metamorphism; formation of the Caribbean Large Igneous Province (CLIP).
3. Late Cretaceous–Paleogene: CLIP collides with South America; subduction ceases under South American plate; formation of the GAC north and east of the Guajira Offshore Basin; arrival of suspect terranes and/or tectonic sliver (?).
4. Late Paleogene–Neogene: Cenozoic evolution with strong strike-slip deformation caused by oblique convergence of the Caribbean plate; thrust belt develops similar to current configuration; main displacement occurs along the Chimare suture; during Miocene development of Tayrona and Chimare Subbasins.

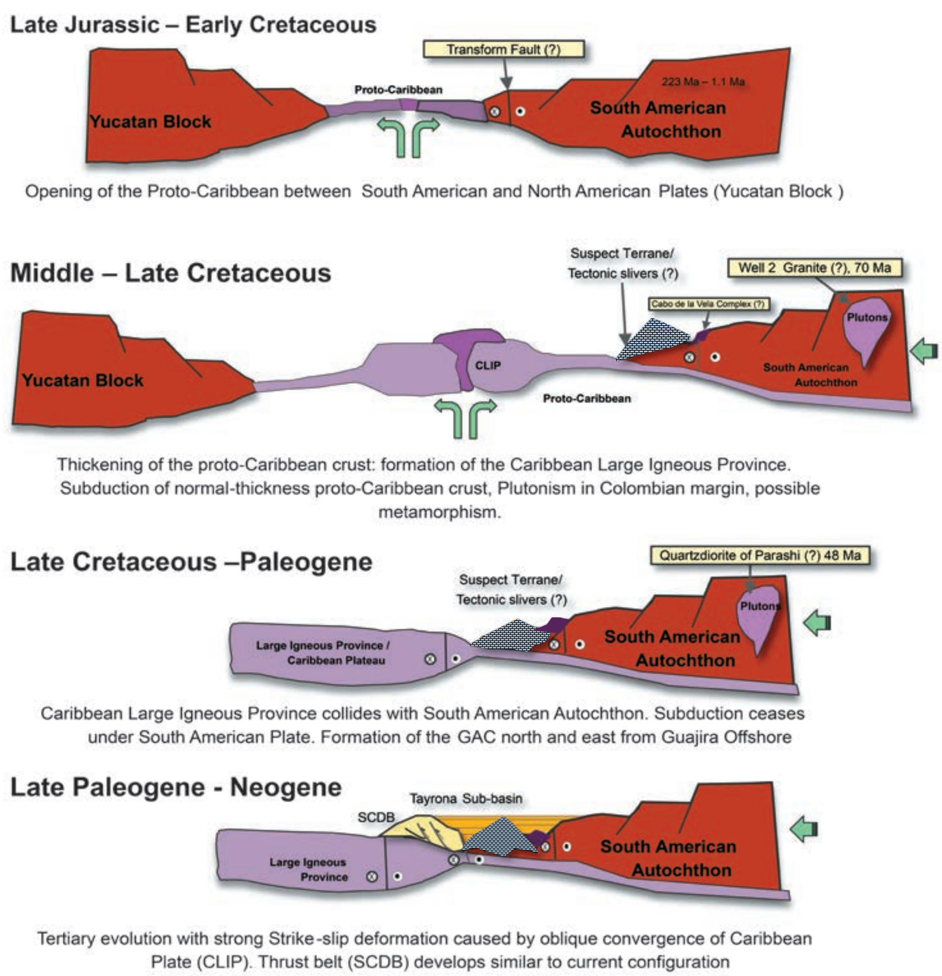

Figure 11. Simplified evolution model for the Guajira Offshore Basin in Colombia.

CONCLUSIONS

The basement in the Guajira Offshore Basin shows four different fabric styles:

- A Pre-Cambrian to late Triassic autochthonous block, that was part of a continental-ocean transform zone whose thickness in the Guajira Offshore Basin decreases abruptly across the margin over a distance of ca 80 km (49.7 mi), from ca 20 km (12.4 mi) near the coastline to less than ca 3 km (1.8 mi) near the so-called Tayrona Subbasin. The transform fault was formed during the opening of the proto-Caribbean Sea in late Jurassic–early Cretaceous times that later rotated to its current position.
- Two areas exhibit what appears to be block-tectonics geometry: one area is identified north of the Chimare suture and the other is located further south in the Tayrona Subbasin. Even though their age is currently difficult to establish, our interpretation is that they may correspond to remnants of the rift system and proto-Caribbean crust that separated North America from South America during Jurassic time. The stretched crust underlying both the Tayrona Subbasin and the Chimare depression could correspond to the same rift that was later displaced and rotated by the Mochila fault and Chimare suture to its current configuration. At the same time, the Cocinas Basin could correspond to the eastern arm of the proto-Caribbean rift system, displaced by the hypothesized late Jurassic transitional continent-ocean transform fault that involved the Guajira basement block (Figure 10). The presence of remnants of proto-Caribbean oceanic crust should not be disregarded in the deepest part of these subbasins. The western boundary of the Tayrona Subbasin is the tectonic limit between the autochthonous South America and the Caribbean plate. This suture could represent the northern continuation of the Romeral fault system.
- The Chirrinche, Chinchorro, and Mochila paleohighs suspect terranes whose nonmagnetic character separated them from the autochthonous continental basement further east, are interpreted as carbonate or metashales, attached to the South American Block during the early–middle Cretaceous period. Although, based on the low magnetic susceptibility found in this chain, it could also be a detached segment of the Carpintero high basement, which also exhibits low magnetic susceptibility values.
- Basins associated to Neogene transcurrent fault systems generated by the oblique convergence of the Caribbean and the South American plates appear to be developed in areas of stretched continental crust and proto-Caribbean remnants.

The Chimare suture appears to be the main boundary between the continental South America and the Caribbean realm, at least in the northern part of the Guajira. This suture can be continuously traced further south into the Gulf of Coquivacoa and Venezuela, where it acts as the boundary between the Tertiary Urumaco trough and the Venezuelan–Guajira main continental block toward the west. The northwestern limit of this structure appears to coincide with the change in orientation of the SCDB, from a NNE to a more E–W defined attitude, although its trace is still uncertain.

Our observations do not allow interpreting a pervasive Great Arc of the Caribbean attached to the entire offshore region of the Guajira Peninsula; although the limited amount of data do not admit a definite conclusion. This chapter favors an autochthonous block accreted by numerous suspect terranes: the Chirrinche, Chinchorro, and Mochila paleohighs, and includes slivers such as the Cabo De La Vela ultramafic complex.

Gravity models support a continental affinity block overriding the Caribbean plate with an angle of ca 17°, in agreement with previous assessment of a flat/shallow subduction zone in the area (Ceron-Abril, 2008). There was no need to invoke oceanic affinity block to match the gravity anomaly during 2-D forward modeling. These results supported the model proposed by Giunta and Oliveri (2009) with an early–middle Cretaceous subduction event of normal-thickness Caribbean crust followed by the collision of the thickened crust of the CLIP against the South American autochthon.

A simplified evolution model of the Guajira Offshore Basin, based on basement distribution, includes four main phases: opening of the proto-Caribbean seaway during the late Jurassic period as North and South American blocks drift apart; subduction of normal-thickness oceanic crust of proto-Caribbean affinity under the continental South American plate and development of associated volcanism during the Cretaceous period; collision of the buoyant CLIP with the continental autochthonous block, effectively ceasing the ongoing subduction process in the late Cretaceous–early Paleogene time; and the development of the still active South Caribbean deformed belt mostly on oceanic crust since mid-Paleogene times.

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