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CENOZOIC PLATE TECTONIC HISTORY OF THE NORTHERN VENEZUELA-TRINIDAD AREA

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Abstract. Geological and geophysical data, coupled with recent plate tectonic reconstructions, suggest that the Cenozoic geologic history of the northern Venezuela-Trinidad area has been dominated by strike-slip displacement of discrete crustal blocks. Allochthonous terranes within the area include metavolcanic rocks of the Cretaceous Villa de Cura Group and metamorphic rocks of the Precambrian to Cretaceous Cordillera de la Costa. A relatively competent crustal block (Margarita Block) is defined by an outline around the metamorphic basement of Margarita Island, the Araya/Paria peninsula, the Northern Range of Trinidad, and Tobago Island. Reconstruction of the Margarita Block to its original position requires at least partial closure of the Falcon Basin, closure of the Bonaire and Cariaco basins, and restoration of about 50 km of motion on both the Oca and Bocono faults. Post middle Eocene eastward translation of the Caribbean plate caused eastward motion of the Margarita Block. A minor change in relative plate motion during the late Oligocene or early Miocene produced a right step in the Moron fault, forming the Cariaco pull-apart basin and El Pilar fault zone. Maximum offset on El Pilar fault is estimated to be no more than 125 km, though displacement along the entire fault zone may have been greater. Transpressional stresses between the Caribbean plate and northern South America caused folding of the Serrania del Interior of Venezuela and the Central Range of Trinidad. Eastward migration of transpressional stresses at the southeastern corner of the Caribbean-South American plate boundary is being accommodated by formation of oblique thrusts, transpressive anticlines, and downwarping of the crust. Bouguer gravity data suggest that Jurassic-aged Atlantic oceanic crust is being depressed as the Caribbean plate expands into the Demerara Plateau area. This study suggests that the faults and transtensional/transpressional/compressional structures identified in this study are the result of stresses produced during the large eastward translation of the Caribbean plate since the Paleocene, and are not the product of a shear couple.

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INTRODUCTION

The location of the Caribbean-South American plate boundary has been a point of debate for some time. In northern Venezuela and Trinidad, the plate boundary has been defined by many workers [e.g., Malfait and Dinkelman, 1972; Silver et al., 1975; Pindell and Dewey, 1982; Mattson, 1984; Muessig, 1984; Vierbuchen, 1984; Speed, 1985; Ross and Scotese, 1988; Robertson and Burke, 1989; Pindell and Barrett, 1989] as being parallel to subparallel to the northern margin of South America and at some position between 10° and 13° north latitude (Figure 1).

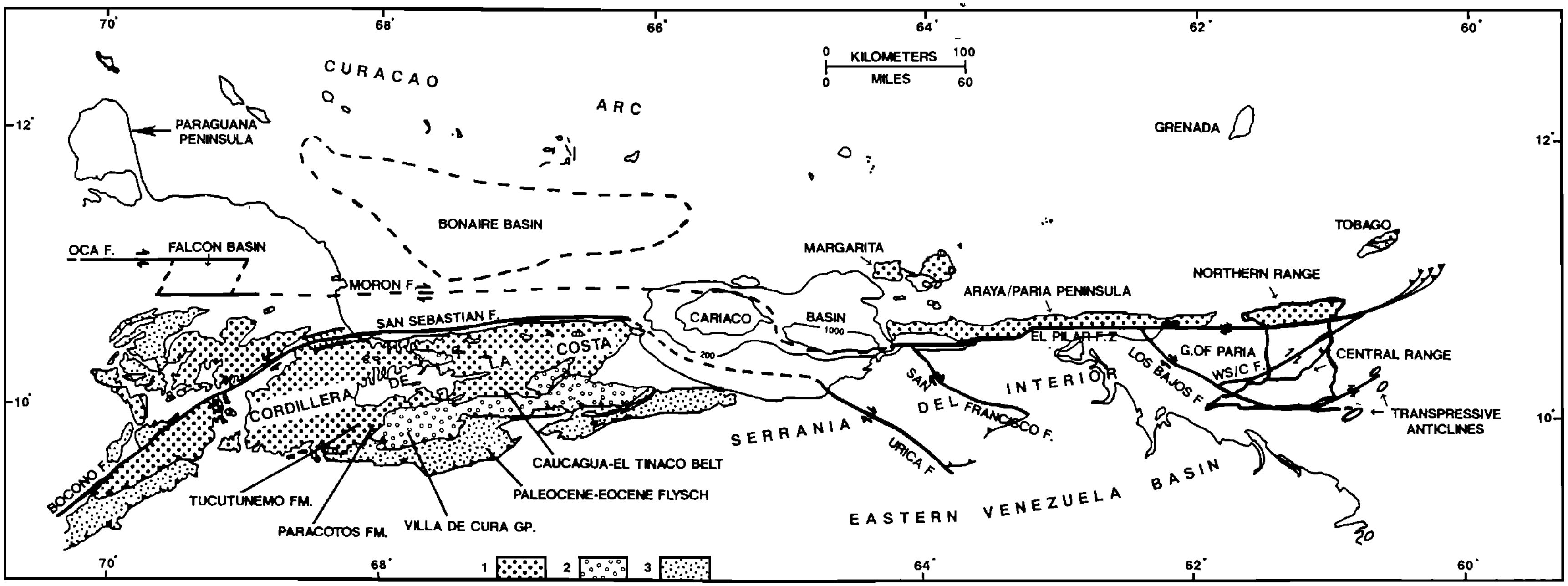


Fig. 1. Present-day tectonic elements of the Venezuela-Trinidad (northern South America) area. Stipple patterns are 1, Cordillera de la Costa metamorphic belt; 2, Villa de Cura Group; 3, Paleocene-Eocene flysch deposits. Bathymetry in the Cariaco Basin is in meters. WS/C F, Warm Springs/Caigual fault.

Uncertainty about the exact position of the plate boundary is caused by the complexities within a plate boundary zone nearly 200 km wide.

Many studies of the Caribbean-South American plate boundary zone have assumed that the amount of displacement along real and hypothesized faults within the plate boundary zone is directly or indirectly related to the relative amount of eastward motion of the Caribbean plate. Estimates of post-Paleocene eastward motion of the Caribbean plate relative to South America range from 500 to 1100 km [Kellogg and Bonini, 1982; Pindell and Dewey, 1982; Burke et al., 1984; Speed, 1985; Burke, 1988; Pindell et al., 1988; Pindell and Barrett, 1989]. However, documenting displacements of these magnitudes along the faults that probably form the southern boundary has been difficult [Rod, 1956; Alberding, 1957; Metz, 1968; Vasquez and Dickey, 1972; Vignali, 1979; Schubert, 1982, 1984; Kellogg, 1984; Muessig, 1984; Vierbuchen, 1984].

Additionally, the stratigraphic and structural history of the area reflects numerous episodes of transpression, transtension, compression and associated overthrusting, and ophiolite obduction [Rod, 1956; Alberding, 1957; Schubert, 1982; Beets et al., 1984; Vierbuchen, 1984; Alvarez et al., 1985]. The emplacement of tectonically rotated exotic terranes has obscured the original outline of continental South America, further complicating reconstructions [Bellizzia, 1972; Maresch, 1974; Stephan, 1977; Skerlec and Hargraves, 1980; Duncan and Hargraves, 1984; Benjamini et al., 1987]. This study attempts to combine these various models with the available geologic data to form a unified model of the geotectonic evolution of the northern Venezuela-Trinidad area.

Several distinct structural elements are present within the northern Venezuela-Trinidad area (Figure 1). The major tectonic blocks or terranes are (1) Cordillera de la Costa metamorphic belt (including Araya/Paria peninsula, Northern Range of Trinidad, Margarita Island, Caucagua-El Tinaco Belt, Tucutunemo Formation [see Case et al., 1984]; (2) Villa de Cura Group (metavolcanic rocks); and (3) Serrania del Interior sedimentary section (including Central Range of Trinidad). The island of Tobago, which is part of element 1 above, is discussed in a subsequent section. Other important tectonic elements include the Cariaco Basin and El Pilar fault zone. The first two major tectonic blocks listed above (Cordillera de la Costa, Villa de Cura) may be allochthonous, but the Serrania del Interior is the autochthonous passive margin of Venezuela.

AUTOCHTHONOUS ELEMENTS

Passive margin sedimentation appears to have been dominant in the Serrania del Interior area of northern Venezuela and the Central Range of Trinidad from early Cretaceous (transgressive marine shales and carbonates) to early Paleocene (regressive deltaic clastics) (Figure 1) [see Hedberg, 1950; Carnevali, 1988a; Subieta et al., 1988]. A Paleocene to middle Eocene flysch sequence was deposited on top of the passive margin sequence in the west and extended from the Falcon area to the western edge of the Cariaco Basin [Bellizzia, 1972; Hunter, 1972; Direccion de Geologia, 1976; Stephan, 1977; Case and Holcombe, 1980]. Deposition of this sequence probably indicates the onset of active tectonism in the area. A flysch sequence of middle Eocene age also has been described from Margarita Island [Hunter, 1978].

Post middle Eocene sedimentation in western Venezuela reflects the influence of episodic tectonic activity. The presence of marine and nonmarine sedimentary sections cut by several unconformities suggests that the area underwent alternate episodes of uplift and subsidence since the Eocene (for detailed discussion see Patterson and Wilson [1953] and Gonzalez de Juana et al. [1980]). Farther to the east, in extreme northeastern Venezuela and Trinidad, passive margin sedimentation appears to have continued into the late Oligocene to early Miocene [R. N. Erlich et al., manuscript in preparation, 1989].

ALLOCHTHONOUS ELEMENTS

Villa de Cura and Cordillera de la Costa rocks that border the Serrania del Interior passive margin sequence have been interpreted as allochthonous or exotic terranes for many years (see following section for description). Rod [1956] and Alberding [1957] used structural modelling and field evidence to suggest that Cordillera de la Costa metamorphic rocks were probably not deposited in their present locations. Salvador and Stainforth [1968] did not accept this idea but did believe that rocks from the Northern Range of Trinidad and the Cordillera de la Costa of Venezuela were "synonymous." Other workers [Bellizzia, 1972; Maresch, 1974; Stephan, 1977; Skerlec and Hargraves, 1980; Beets et al., 1984; Duncan and Hargraves, 1984; Benjamini et al., 1987; Beck, 1988] have suggested that Villa de Cura metavolcanic rocks are also exotic to Venezuela and were probably thrust over Paleocene to Eocene flysch from a north or northwesterly direction.

CARIACO BASIN AND EL PILAR FAULT ZONE

Peter [1972] suggested the Cariaco Basin originated through normal faulting of a stable continental shelf, with later right-lateral offset by the Urica fault. Silver et al. [1975] noted this idea, but stressed that no hard data existed that demonstrated an actual connection between the Urica fault and the Cariaco Basin. They suggested instead that the basin was generated by shear along parallel extensions of the San Sebastian and El Pilar faults (Figure 1). This idea was later modified by Schubert [1982], who identified the basin as a pull-apart, formed by a right step in the Moron/El Pilar fault zone.

Estimates of offset along El Pilar fault zone vary greatly [Metz, 1968; Salvador and Stainforth, 1968; Vignali, 1979; Schubert, 1984; Vierbuchen, 1984; Speed, 1985; Burke, 1988]. Nevertheless, the fault zone does appear to be part of a major tectonic boundary, juxtaposing Cordillera de la Costa metamorphic rocks and Serrania del Interior sedimentary rocks in northeastern Venezuela and Trinidad.

ORIGIN OF STRUCTURAL ELEMENTS

Pre-Strike-Slip Reconstruction

An outline drawn around the Tobago-Margarita-Araya/Paria/Northern Range, Trinidad, area defines a block approximately 100 x 425 km in size (Figure 2). Limited well data between Tobago and the north coast of Trinidad show that metamorphic rock underlies the sedimentary cover (Figure 3) [see Robertson and Burke, 1989]. On the basis of seismic, gravity, and magnetic data, the area between Margarita and Tobago has been interpreted as a single complexly deformed metamorphic terrane [Lattimore et al., 1971; Morelock et al., 1972; Bonini, 1978; Gonzalez de Juana et al., 1980; Schubert, 1982; Ramroop, 1986; Wadge and Hudson, 1986]. Westward restoration of this "Margarita Block" to its reconstructed position (Figure 4) requires removal of about 50 km of motion on the Oca fault and 50 km of motion on the Bocono fault, closure of the Cariaco Basin (40-125 km), partial partial closure (25-50 km) of the Falcon Basin, and complete closure (250-300 km) of the Bonaire Basin [Muessig, 1984]. These fault offsets are well within the range of previous estimates [Vasquez and Dickey, 1972; Tschanz et al., 1974; Burke et al., 1984; Schubert, 1984; Dewey and Pindell, 1985, 1986; Laubscher, 1987] but consider translation and crustal attenuation (in the Bonaire, Falcon, and Cariaco basins) only. The model also suggests that some component of dextral motion existed on the Oca and Bocono faults prior to the Oligocene. It should be noted, however, that the existence of measurable offset on the Bocono fault has been disputed [Salvador, 1986].

This reconstruction positions the Margarita Block and the Cordillera de la Costa immediately adjacent (north-south) to each other, suggesting a formerly closer geographic link between these geologically similar terranes.

Geology of Allochthonous Rocks

Lithologic, biostratigraphic, and geochemical data suggest that metamorphic rocks of the Araya/Paria peninsula, Margarita, Tobago, and the Northern Range of Trinidad were once part of the Cordillera de la Costa (Figure 1). The premetamorphic stratigraphy of these rocks is suggestive of deposition in a marine, continental margin setting [e.g., Barr, 1962, 1963; Gonzalez de Juana et al., 1968; Kugler, 1972; Maresch, 1974; Vignali, 1979; Kohn et al., 1984]. Rocks that compose these terranes include metamorphic, metasedimentary, and metavolcanic rocks ranging in age from Precambrian to Cretaceous. In the Cordillera de la Costa of Venezuela, schists and gneisses of the Precambrian Caucagua-El Tinaco Belt (Figure 1) occur in fault contact with Permian metasedimentary rocks of the Tucutunemo Formation [Benjamini et al., 1987]. The

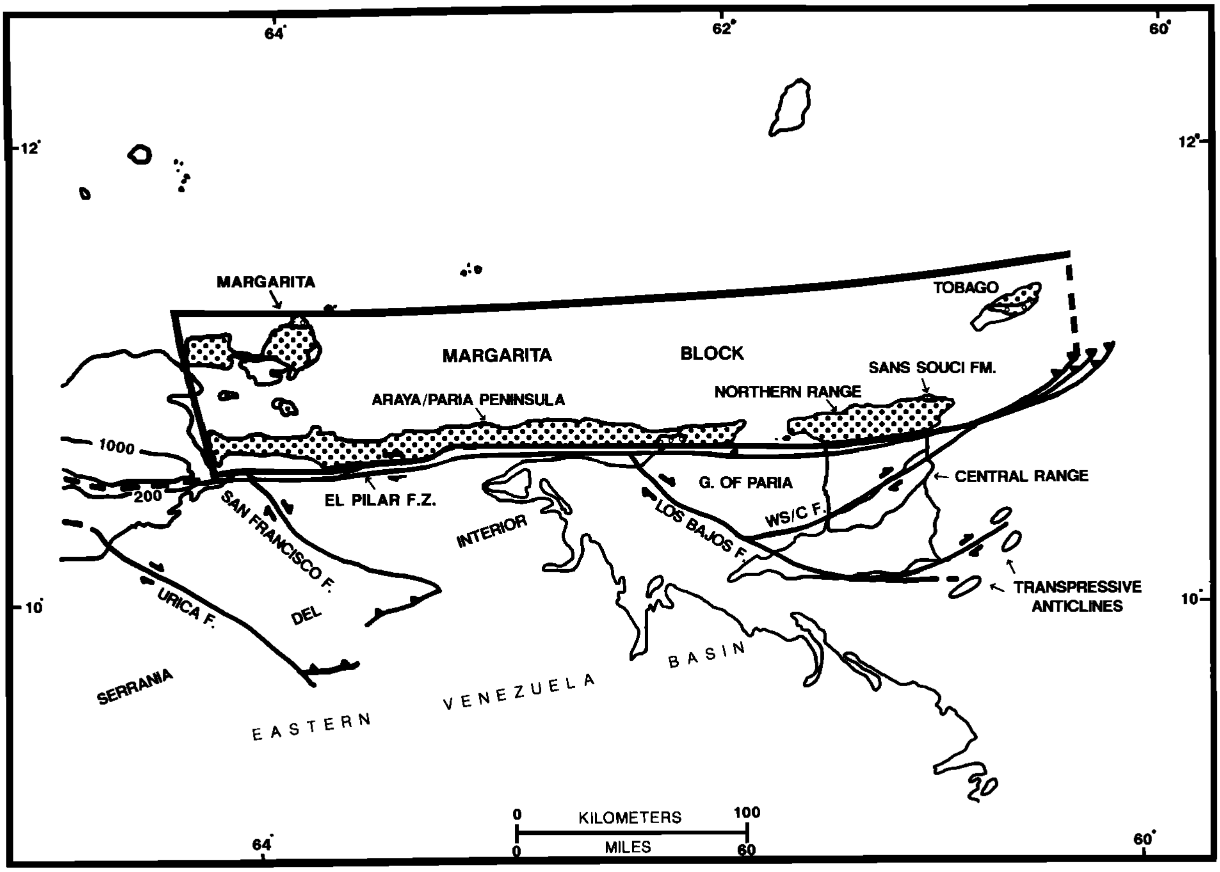
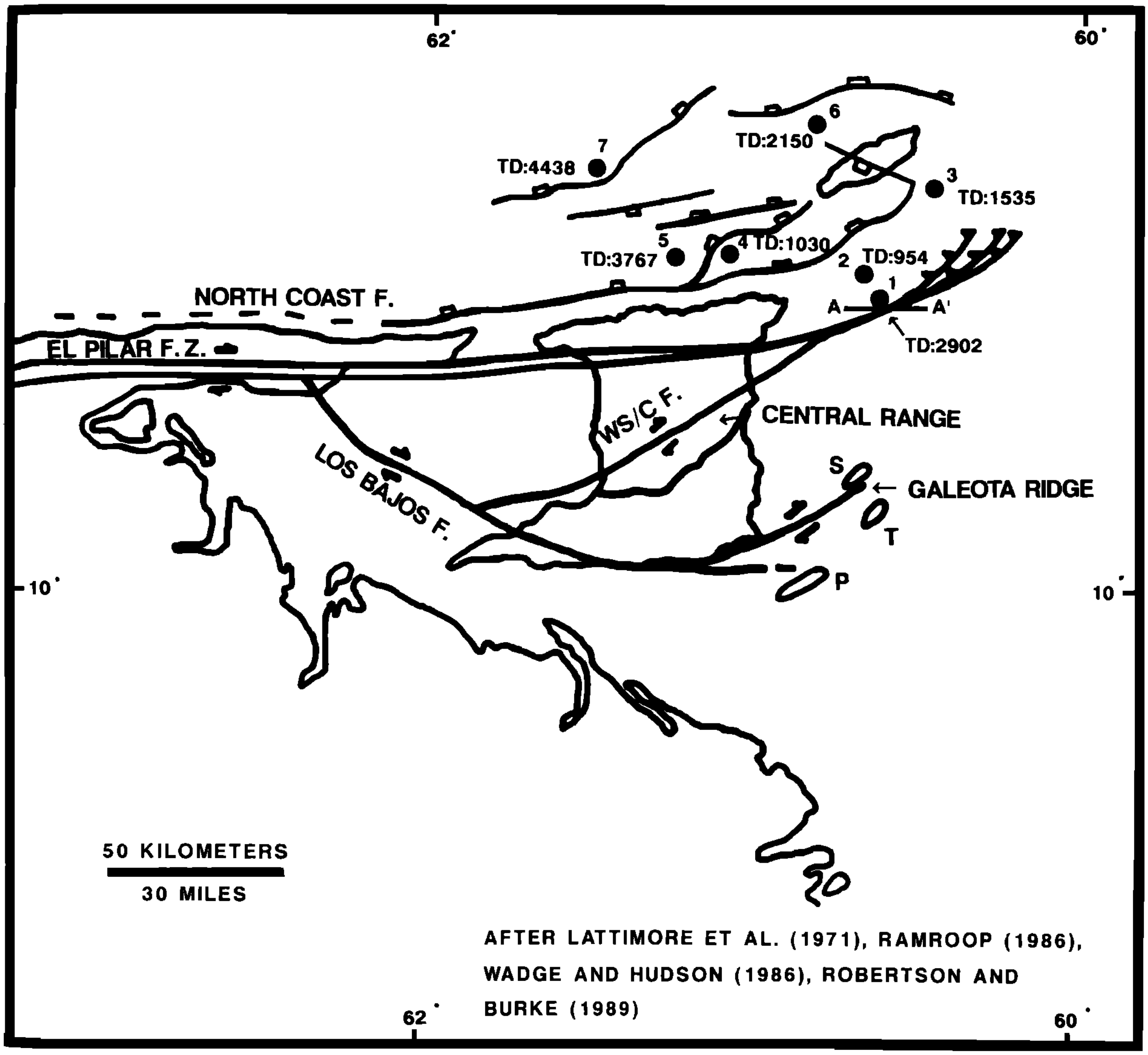


Fig. 2. The Margarita Block, as defined in the text (outlined area). See Figure 1 for symbol key. For the purposes of this study, the Margarita Block was treated as a rigid feature; however, some internal extension and fragmentation must have occurred prior to and during its translation.

work of Benjamini et al. [1987] suggest that rocks belonging to the adjacent Paracotos Formation may also be of Paleozoic, and not Cretaceous age [e.g., Maresch, 1974]. The preceding formations are also in fault contact with metamorphic and metasedimentary rocks of the Jurassic to Cretaceous Caracas Group of the northern Cordillera de la Costa [Maresch, 1974; Gonzalez de Juana et al., 1980; Kohn et al., 1984]. Similar sequences of rocks also occur on Margarita (Juan Griego Group) and Tobago (North Coast Schist Group) islands [Maresch, 1974; Rowley and Roobol, 1978; Vignali, 1979; Wadge and Hudson, 1986].

Metamorphic and metasedimentary rocks of the Araya/Paria peninsula and the Northern Range of Trinidad are very similar to those in the northern Cordillera de la Costa of Venezuela. In the Araya/Paria peninsula, probable Jurassic quartzites, phyllites, and schists of the Uquire and Macuro formations have been biostratigraphically correlated to similar rocks of the Jurassic Maracas and Rio Seco formations of the Northern Range of Trinidad [Kugler, 1953; Barr, 1962, 1963; Gonzalez de Juana et al., 1968; Potter, 1968; Vignali, 1979]. A sequence of schists and gneisses (Dragon Gneiss) yielding one mid-Triassic Rb-Sr age (230 ± 100 Ma) is found in the eastern Paria area but probably occurs as a slump block within the Jurassic Macuro Formation [Kugler, 1972]. Vignali [1979], however, considered the Dragon Gneiss to be an intrusive body within the Macuro. Late Jurassic to early Cretaceous phyllites and dense limestones found in



AFTER LATTIMORE ET AL. (1971), RAMROOP (1986), WADGE AND HUDSON (1986), ROBERTSON AND BURKE (1989)

Fig. 3. Major faults and important wells, offshore Trinidad. Well depths are in meters (TD, total depth); all wells reached total depth in metamorphic rock. P, Poui; T, Teak; S, Samaan transpressive anticlines.

the Cariaquito and Güinimita formations of the Araya/Paria peninsula are coeval with phyllites and limestones of the Maraval, Grande Riviere, Tompire, and Toco formations of the Northern Range of Trinidad [Barr, 1962, 1963; Gonzalez de Juana et al., 1968; Potter, 1968, 1972; Saunders, 1972; Vignali, 1979].

The origin of the Villa de Cura Group is problematic. Villa de Cura metavolcanic rocks have been linked to the Curacao island arc (Figure 1) by Beets et al. [1984], who inferred a genetic relationship (arc or possibly forearc setting) based on geochemical data. A similar proposal was made by Wadge and Macdonald [1985], who in addition suggested that the geochemistries of some members of the Villa de Cura Group had mid-ocean ridge affinities. An alternative explanation was offered by Pindell and Barrett [1989], who suggested that a loose relationship might have existed between the Aves part of the Greater Antilles arc system, the

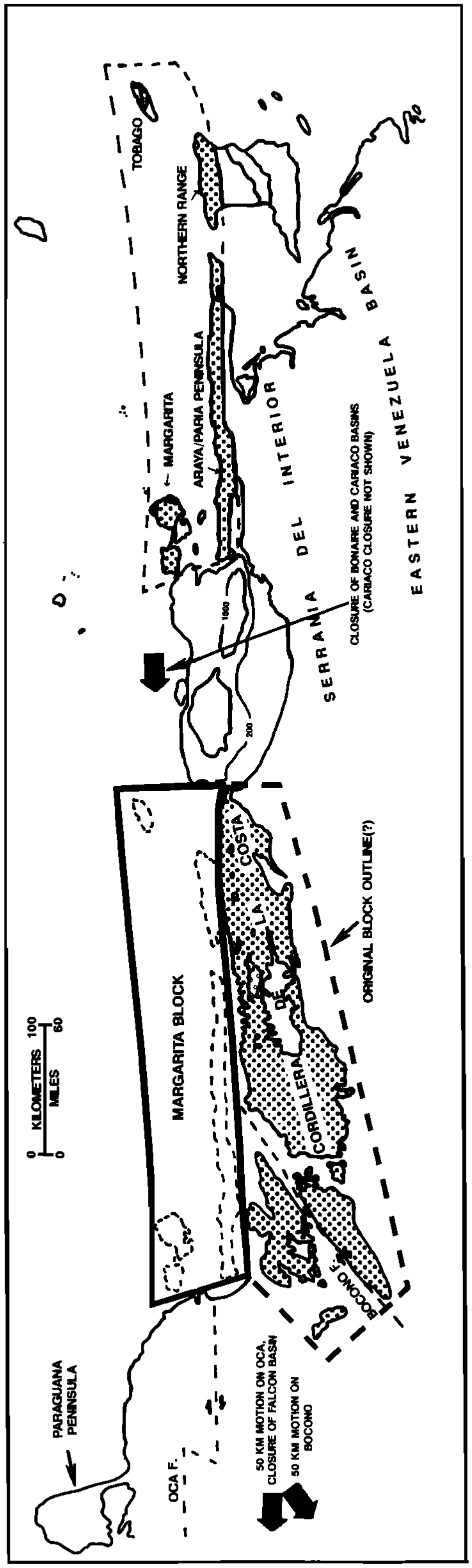


Fig. 4. The Margarita Block restored to its middle to late Eocene position. See Figure 1 for symbol key. Amount of internal extension and fragmentation is unknown.

Curacao arc (remnants of the Aves arc), and the Villa de Cura Group. Paleomagnetic data from the Curacao arc and other islands are inconclusive [Hargraves and Skerlec, 1980]. Another possibility is that Villa de Cura rocks are genetically unrelated to the Curacao arc. Other theories on the origin of the Villa de Cura Group may have equal merit, but evaluation of them is beyond the scope of this study. However, some genetic link may exist between this sequence and similar rocks on Tobago and in the Northern Range of Trinidad.

Metavolcanic rocks of the Villa de Cura Group consist of basic metatuffs of El Cano and El Chino formations, metabasalts of El Carmen Formation, and associated quartz-albite granulites of the Santa Isabel Formation [see Beets et al., 1984]. Rocks within the formations have variable geochemistries due to different degrees of alteration and weathering. Piburn [1967], Santamaria [1972], and Hebeda et al. [1984] report K-Ar ages ranging from 65 ± 5 to 107 ± 3 Ma. The younger ages were probably reset from older rocks during a late Cretaceous to Paleocene (or Eocene) thermal event [Santamaria, 1972; Beets et al., 1984], while the oldest age (107 Ma) is from an unaltered intrusive body, and therefore represents a minimum age only.

Metavolcanic rocks of Tobago have whole rock K-Ar ages suggestive of Villa de Cura rocks, though their geochemistries are different [Santamaria, 1972; Rowley and Roobol, 1978]. Geochemistries of metamorphosed basalts, gabbros, and diorites of the Tobago Volcanic Group and the central intrusive complex were interpreted by Rowley and Roobol [1978] as indicative of island arc rocks; whole rock and mineral separate K-Ar ages ranged from 62 ± 3 to 127 ± 7 Ma. Rowley and Roobol suggested that the late Cretaceous and Paleocene ages in their data set may reflect a post-Cretaceous alteration episode. These conclusions were supported in a similar study by Wadge and Macdonald [1985].

Basic igneous rocks also occur within the Northern Range metamorphic belt of Trinidad. Metabasalts of the Sans Souci Formation are in fault contact with surrounding early Cretaceous metasedimentary rocks [Barr, 1962, 1963], though data from Wadge and Macdonald [1985] suggest that some stratigraphic equivalency may exist. Geochemical data led Wadge and Macdonald [1985] to suggest that Sans Souci basalts may have mid-ocean ridge affinities, though they also suggested that the Sans Souci basalts could have been erupted onto the passive continental margin (possibly in a back arc setting) of northern South America during an episode of Middle Cretaceous intraplate vulcanism.

Radiometric age dates of Sans Souci metabasalts imply some age equivalency with Villa de Cura mafic rocks. In this study a whole rock sample of Sans Souci metabasalt was dated by the K-Ar method as early-late Cretaceous (89.8 ± 4.5 Ma), while Wadge and Macdonald [1985], using the same dating method, reported a similar whole rock age (87 ± 4.4 Ma). These ages may reflect a late alteration episode like the one shown by Rowley and Roobol [1978] for Cretaceous metavolcanic rocks of Tobago.

Emplacement of Exotic Terranes

Models explaining the emplacement of Cordillera de la Costa and Villa de Cura rocks have been proposed by many workers [Bellizzia, 1972; Maresch, 1974; Stephan, 1977; Skerlec and Hargraves, 1980; Beets et al., 1984; Duncan and Hargraves, 1984; Benjamini et al., 1987]. Using the plate kinematic models of Pindell and Dewey [1982], Pindell et al. [1988], and Pindell and Barrett [1989], the existing terrane emplacement models, and available geologic data, an integrated model of the emplacement and origin of these rocks can be derived (Figures 5 and 6).

Plate tectonic models [Pindell et al., 1988; Pindell and Barrett, 1989] have suggested that the ancestral Greater Antilles island arc originated in the eastern Pacific during the late Jurassic to early Cretaceous and was interacting with western or northwestern South America by the late Cretaceous to early Paleocene (Figure 5a). The problematic Villa de Cura Group, which formed during the early Cretaceous, therefore could represent pieces of the Aves part of the Greater Antilles arc or forearc that were obducted onto northwestern South America (represented by the Cordillera de la Costa part of the Margarita Block) as the arc migrated northward out of the Pacific. Beck [1988] suggested that at least part of the Margarita Block (including the Villa de Cura) may have originated as much as 1600 km to the south of its present location. Another explanation for the origin of the Villa de Cura Group is that it is actually an autochthonous (with respect to the Curacao arc) South American arc-back arc sequence, coeval with at least the early Cretaceous part of the Cordillera de la Costa (Figure 5b). In either case, the proto-Margarita Block (Cordillera de la Costa and Villa de Cura rocks) was subsequently sheared off northwestern South America during the early to middle Paleocene (Figure 6a) and transported along the southern boundary of the Caribbean plate as it moved east around the north coast of South America (Figure 6b). The paleomagnetic data of Skerlec and Hargraves [1980] and Beck [1988] indicate that the Villa de Cura probably underwent a 90° clockwise rotation. This is consistent with the approximate orientation and subsequent rotation of the Villa de Cura and Cordillera de la Costa (Margarita Block) shown in Figures 5 and 6.

During the late Paleocene to early-middle Eocene, a change in relative motion of the Caribbean caused oblique collision and overthrusting of the Margarita Block onto South America (northwestern Venezuela, Figure 6c). This northwest-southeast convergence also resulted in formation of abundant Paleocene-Eocene flysch (eroded from the Margarita Block?) in northwestern Venezuela [Bellizzia, 1972; Stephan, 1977; Gonzalez de Juana et al., 1980; Benjamini et al., 1987]. The overthrust contact of Villa de Cura rocks on flysch may represent the original leading edge of the Margarita Block, or a reactivation of pre-Tertiary thrusts within the Villa de Cura allochthon. Possible examples of the original Cordillera de la Costa-Villa de Cura stratigraphic relationship may be preserved on Tobago and in the Sans Souci Formation, Northern Range of Trinidad [Wadge and Macdonald, 1985].

Relative eastward motion of the Caribbean continued after emplacement of Cordillera de la Costa and Villa de Cura rocks [Pindell and Dewey, 1982; Pindell et al., 1988; Pindell and Barrett, 1989]. Continued right-lateral motion of the Oca fault or a parallel but different fault caused fracturing and translation of the Margarita Block during the late Eocene to early Oligocene (Figure 7a).

Differential motion produced by drag along the southern edge of the Caribbean-South American plate boundary caused extension and transtension in the Bonaire and Falcon basins (Figure 7b). Significant thinning of the crust in the

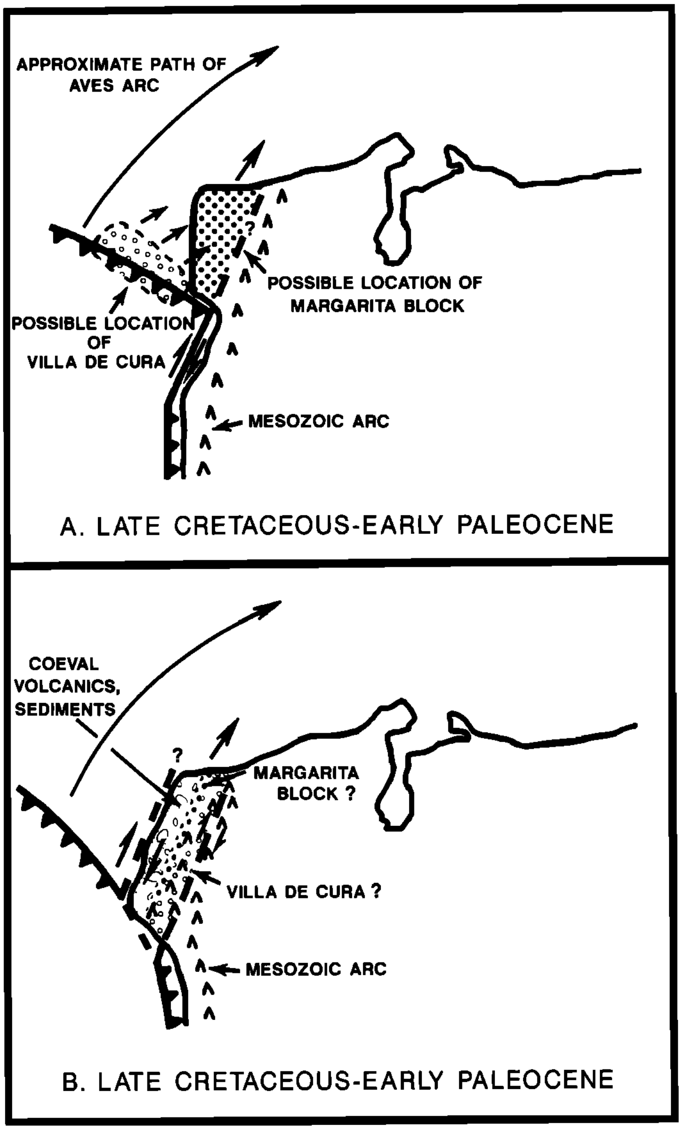


Fig. 5. Two possible models for the origin of Villa de Cura and Cordillera de la Costa (Margarita Block) rocks. (a) Late Cretaceous-early Paleocene: Position of the Margarita Block was in northwestern South America. As the Aves arc passed, pieces of the arc and forearc were tectonically emplaced within the Margarita Block. Entire sequence was then sheared off and transported north and east along the plate boundary. (b) Late Cretaceous-early Paleocene: Villa de Cura was an autochthonous arc on the South American plate, and partly interfingered with coeval (Cretaceous) back arc sediments. Entire sequence was then sheared off and transported as in model in Figure 5a.

Bonaire Basin has been noted by Silver et al. [1975], and Case et al. [1984], who interpreted this thinning as indicative of a rifted or highly extended and intruded origin. A similar extensional/transtensional model for the origin of the Bonaire and Falcon basins was proposed by Muessig [1984].

A slight shift in relative plate motion probably occurred in the late Oligocene or early Miocene, causing compression and transpression of the Margarita Block against northern South America (Figure 7c). This may have produced the northeast-southwest oriented folds and thrusts of the Serrania del Interior and Central Range areas of Venezuela and Trinidad. The stratigraphic and structural data of Carnevali [1988a,b] and Subieta et al. [1988] support the timing of this event and the structures formed as a result of these motions. Estimates of crustal shortening of these areas vary [see Speed, 1985; Rossi et al., 1987], though the timing of the event is consistent with ages of uplift of the area suggested by Hedberg [1950], Vierbuchen [1984], and R. N. Erlich et al. [manuscript in preparation, 1989]. This thrust loading of northern South America probably induced flexural downwarping of the Eastern Venezuela Basin, with subsequent infilling by Miocene Carapita Formation sediments [Lamb and Sulek, 1968; Bonini, 1978; Carnevali, 1988a].

Formation of the Cariaco Basin and El Pilar Fault Zone

This short-lived change in relative plate motion during the late Oligocene or early Miocene may have also induced a right step in the Moron fault and formation of the Cariaco Basin and El Pilar fault (Figure 7c). Schubert [1982] first proposed a pull-apart origin for the Cariaco Basin but constrained its opening to the late Neogene. He based this conclusion mostly on paleontologic data from the Deep Sea Drilling Project (DSDP)

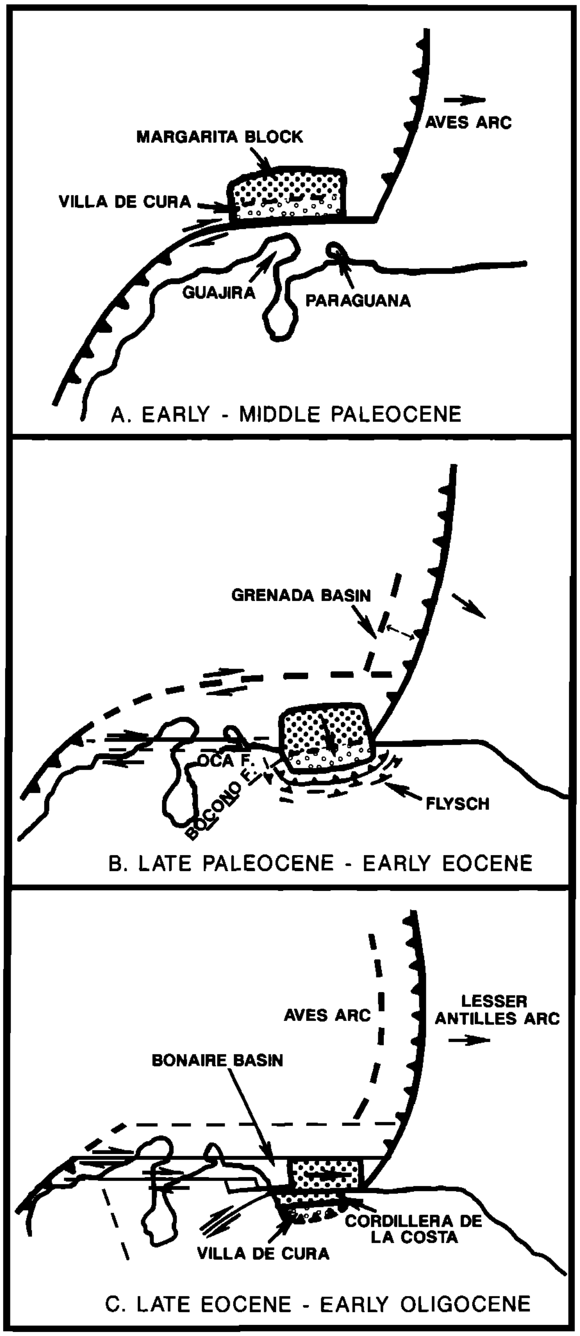


Fig. 6. One possible model for the emplacement of the Margarita Block (Cordillera de la Costa and Villa de Cura Group). (a) Early-middle Paleocene: Margarita Block is sheared off northwestern South America and transported north and east along plate boundary (see Figure 5). Eastward migration of the Aves arc caused eastward motion of the allochthonous blocks along the southern part of the plate boundary. (b) Late Paleocene-early Eocene: A change in Caribbean-South American relative plate motions (opening of the Grenada Basin?) caused oblique collision and overthrusting of the Margarita Block with autochthonous South America (northern Venezuela). Approximately 400 km of convergence is predicted by this model; however, this number could be much less depending on the original location of the Margarita Block and the shape of the Guajira-Paraguana area. (c) Late Eocene-early Oligocene: Post-collisional model. Continued eastward migration of the Caribbean plate caused internal shearing and extension within the Margarita Block.

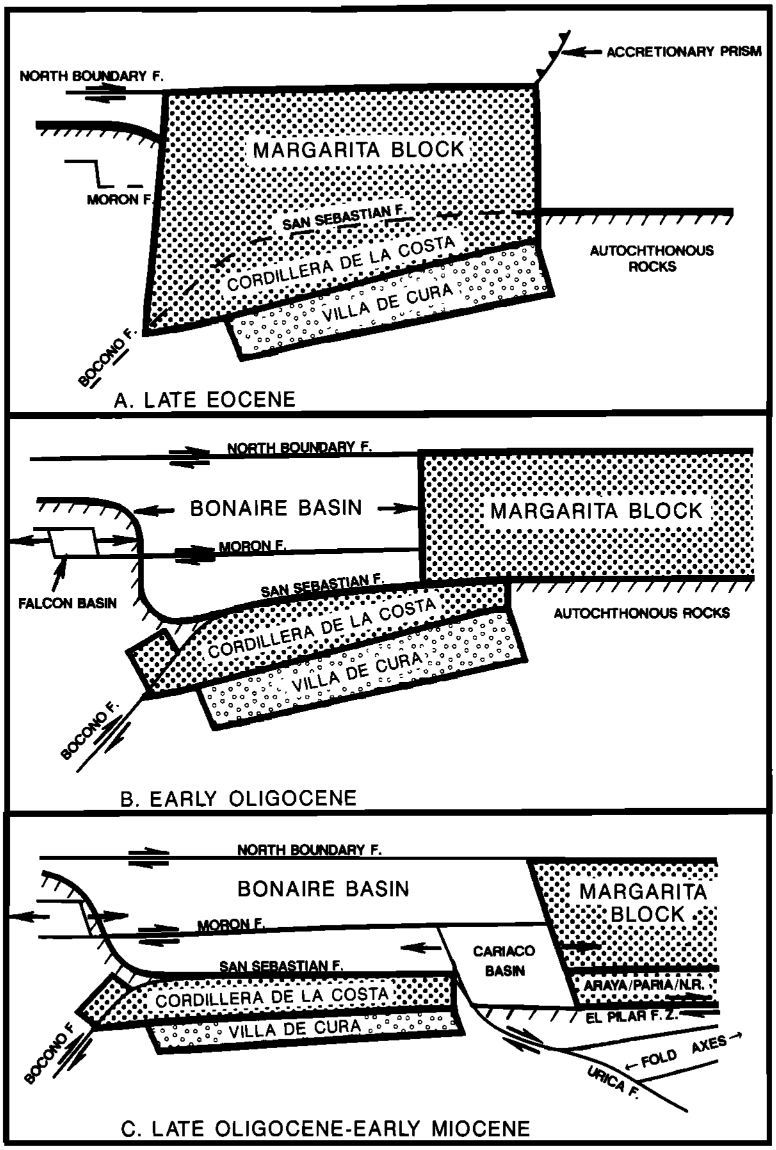


Fig. 7. Late Eocene-early Miocene translation of the Margarita Block. (a) Late Eocene-early Oligocene: Post-collisional model of the Margarita Block (see Figure 6c). Block was recently overthrust onto autochthonous South America. (b) Early Oligocene: Eastward relative motion of the Caribbean caused internal fracturing within the Margarita Block and extension in the Bonaire and Falcon basins. (c) Late Oligocene-early Miocene: Minor shift in Caribbean-South American relative motion caused Moron (and possibly San Sebastian?) fault to step to the right, forming the Cariaco pull-apart basin. Minor Caribbean-South American convergence (approximately 25 km) caused thrusting and folding of the Serrania del Interior. Urica and San Francisco faults may be thrust-ramp breaks.

site 147 core, which penetrated 189 m of middle Pleistocene to Holocene sediment. However, seismic reflection profiles across the basin (data of Ball et al. [1971], Peter [1972], Morelock et al. [1972], Silver et al. [1975], compiled by Schubert [1982]) suggest the presence of at least 1-2 s (two-way travel time) of sedimentary fill. Schubert used seismic velocities of between 1.7 and 2.3 km/s to suggest a minimum thickness of 1000 m of sedimentary fill in the western part of the basin. The total thickness of sedimentary fill within the basin may range from 1700 to 4600 m, and it is entirely possible sections of this fill could be as old as late Oligocene to early Miocene age. Evidence of motion along the Moron fault can be found on these profiles [Schubert, 1982, Figure 3, lines 1 and 2], and on Bouguer gravity data [Bonini, 1978]. An oval, +90 mGal gravity high just north of the fault (Figure 8) corresponds to a small horst block shown by Schubert on lines 1 and 2. This feature actually may be a flower structure produced by transpressional motion along the fault.

Because the Cariaco Basin is an east-west oriented pull-apart, it must possess northern (Moron fault) and southern (El Pilar fault) bounding faults in similar orientations. Other faults exist in this area (San Sebastian, Urica faults), but seismic and potential fields data compiled by Schubert [1982] and Bonini [1978] indicate that neither the San Sebastian nor Urica faults intersect the basin and probably are not directly related to it. The origin of El Pilar fault and parallel faults within El Pilar fault zone [see Vignali, 1979; Alvarez et al., 1985] therefore can be linked to formation of the Cariaco Basin [Schubert, 1982].

Cumulative displacement along El Pilar fault zone (in general) and El Pilar fault (in particular) has been the subject of much discussion [e.g., Rod, 1956; Alberding, 1957; Metz, 1968; Salvador and Stainforth, 1968; Vignali, 1979; Vierbuchen, 1984; Speed, 1985; Robertson and Burke, 1989]. Based on its origin as a right step in the Moron fault, maximum offset along the fault is estimated to be about 125 km, as originally proposed by Schubert [1984], assuming 50% crustal attenuation. A smaller displacement of 40 km can be derived from field and subsurface data shown by Vignali [1979] and Alvarez et al. [1985]. An estimate of 40-125 km of offset should therefore be considered reasonable for El Pilar fault. Greater displacement along the entire fault zone is possible, considering the number of smaller fault segments present, but is not known.

Relatively recent motion of El Pilar fault has been documented in Venezuela by Vierbuchen [1984] and Alvarez et al. [1985] and in Trinidad by Robertson and

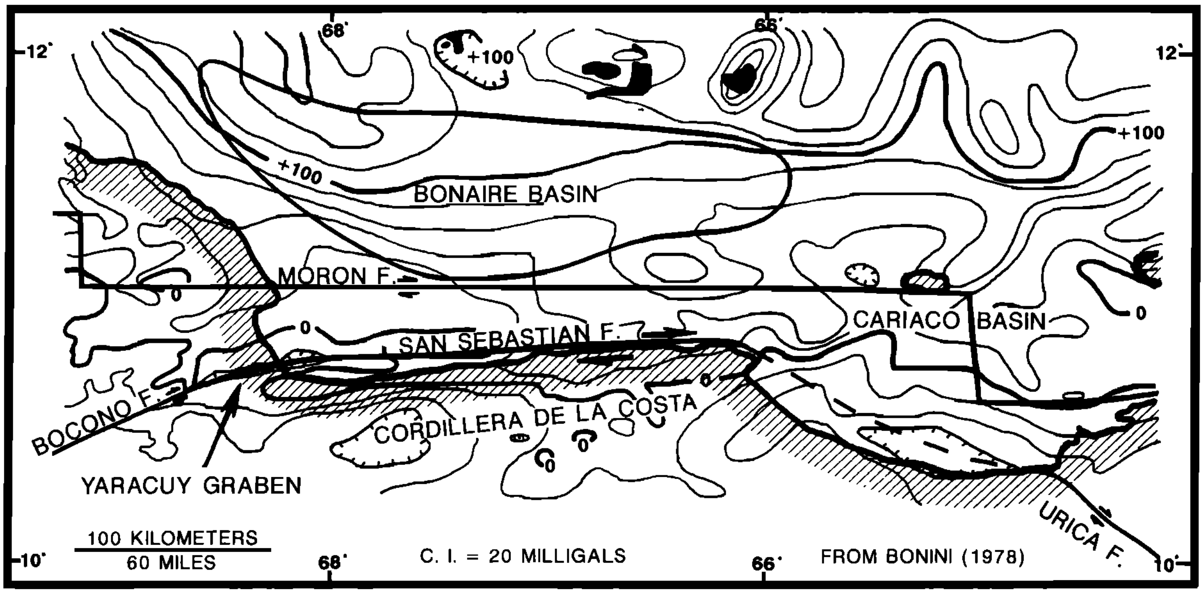


Fig. 8. Bouguer gravity of northern Venezuela [from Bonini, 1978]. Circular +90 mGal anomaly just north of the Moron fault at about 66.5° west may be the horst block (flower structure?) shown on Schubert's [1982] Figure 3, lines 1 and 2. Note location of the Yaracuy graben (with respect to the Bocono-San Sebastian fault intersection) and the linear -70 mGal anomaly just northwest of the Urica fault (Urica-San Sebastian fault intersection?).

Burke [1989]. Seismic and well data east of Trinidad indicate that El Pilar fault has undergone little dextral offset since the early to middle Pliocene (Figure 9). Speed's [1985] proposal that El Pilar fault is a thrust fault in eastern Trinidad is partially correct, in that the translation associated with the component of dextral motion has been incorporated by a series of thrust faults at the eastern terminus of the fault (Figure 3). This configuration is quite common along transpressive fault zones [Christie-Blick and Biddle, 1985]. This area is where El Pilar loses its distinctiveness as a separate fault and merges with structures formed in the stress regime of the Barbados accretionary prism [Bassinger et al., 1971; Case and Holcombe, 1980; Wadge and Hudson, 1986]. In light of the previous discussion, El Pilar fault can be described as part of a zone of faults (El Pilar fault zone) along which the amount and sense of displacement has varied through time [see Vignali, 1979; Alvarez et al., 1985].

Origin of the Urica, San Francisco, and Los Bajos Faults

Major right-lateral motion is also inferred for the Urica, San Francisco, and Los Bajos faults [Burke, 1988; Robertson and Burke, 1989], although offsets of large magnitude are difficult to demonstrate. Dextral offset along the San Francisco fault is probably no greater than 25 km [Rosales, 1972; Rossi et al., 1987], and offset along the Urica fault is probably no more than 35 km [Salvador and Stainforth, 1968; Gonzalez de Juana et al., 1980; Munro and Smith, 1984]. Wilson [1968] has shown approximately 10.5 km of post-Pleistocene motion along Los Bajos fault in southwest Trinidad. These displacements do not lend support to the notion that any of these faults have acted as a principal displacement zone of the Caribbean-South American plate boundary [as by Robertson and Burke, 1989]. However, present rates of motion on Los Bajos fault suggest it has become an increasingly important component within the plate boundary system, especially since 1 Ma.

Origin of the Urica, San Francisco, and Los Bajos faults has been linked to motion along El Pilar fault zone or to Caribbean-South American plate motion in general. Rod [1956], Leonard [1983], Burke [1988], and Robertson and Burke [1989] have suggested that these faults, and the structural orientations within the Serrania del Interior, were created within a shear couple [e.g., see Tchalenko and Ambraseys, 1970]. However, the southern boundary fault needed to form the shear couple has never been documented [Case and Holcombe, 1980; Gonzalez de Juana et al., 1980], and recently published geological and geophysical data from the eastern Serrania del Interior also dispute a shear couple origin for the fold belt area [Carnevali, 1988a,b; Subieta et al., 1988].

An alternative explanation for the origin of the Urica, San Francisco, and Los Bajos faults involves post-Oligocene translation of the Margarita Block. This translation has produced the episodic activity found along the faults. For example, the Urica fault appears to be seismically inactive now [Molnar and Sykes, 1969; Burke et al., 1984], but Bouguer gravity data (Figure 8) suggest a connection with the more recently active Bocono-San Sebastian system [Schubert, 1984; Laubscher, 1987]. The San Francisco fault was active only until the Pliocene [Salvador and Stainforth, 1968], while Wilson [1968] has demonstrated recent activity on Los Bajos fault. This eastward trend in activity is probably related to an eastward migration of stresses along the plate boundary. The relatively minor offsets along the San Francisco and Urica faults suggest that they acted only as episodic stress-releasing breaks (thrust ramp edges) during transpressive plate interactions, and may have moved simultaneously with El Pilar fault.

This interpretation conflicts with Rod's [1956] suggestion of a shear couple origin for the Urica, San Francisco, and Los Bajos faults and the Serrania del Interior foldbelt, which required the rotation of discrete blocks bordered by the faults [Gonzalez de Juana et al., 1980]. Simultaneous activity between El Pilar fault zone and the Urica, San Francisco, and Los Bajos faults would have produced a gap in the western part of each block (Figure 10). Although these types of features are quite common within similar fault systems [Christie-Blick and Biddle, 1985], the only apparent example of such a graben in El Pilar fault system is the eastern Gulf of Paria basin (Figure 1).

A Miocene age for initiation of motion along Los Bajos fault, and hence for formation of the Gulf of Paria basin, can

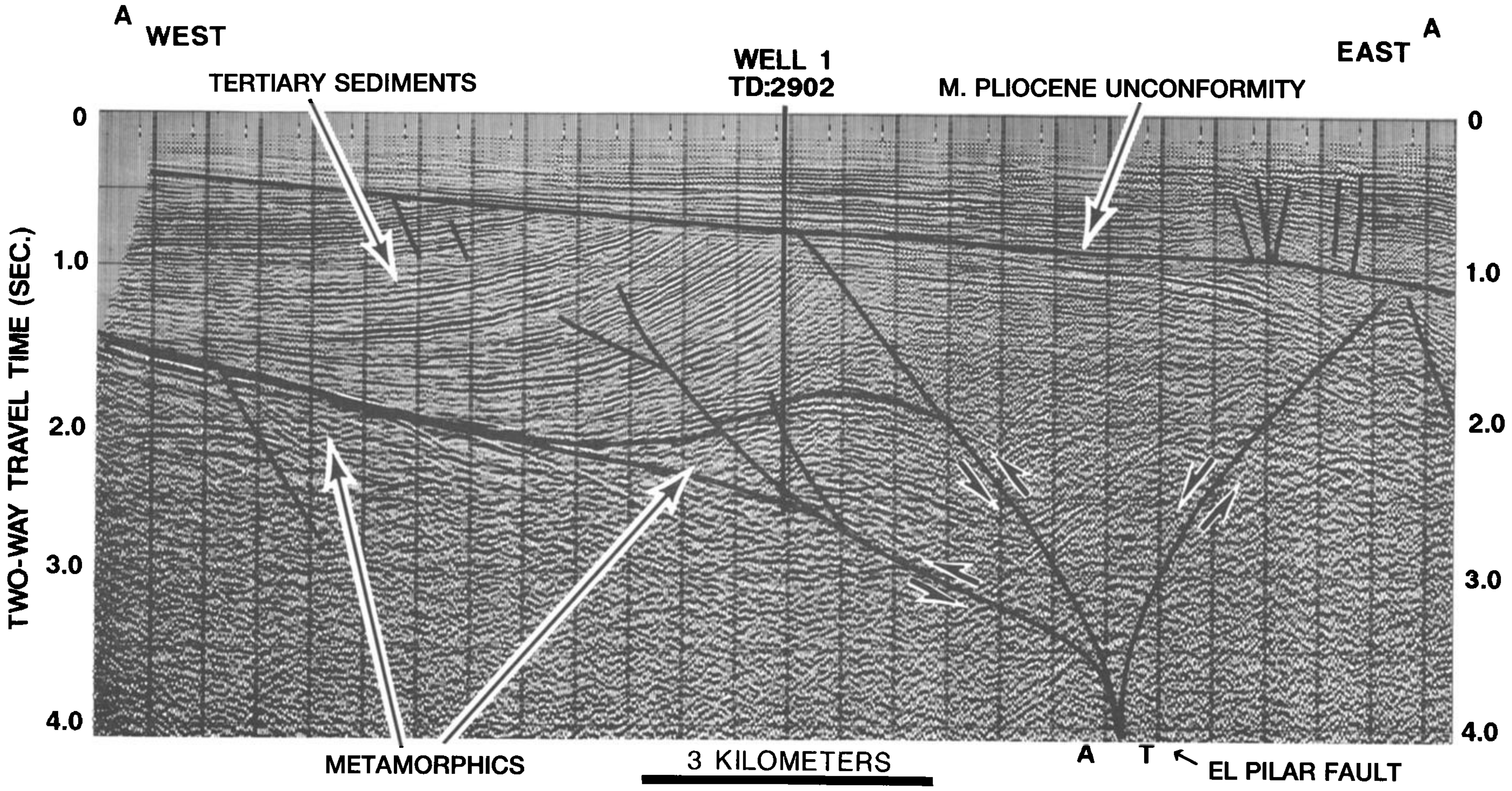


Fig. 9. Amoco seismic line A-A' across El Pilar fault east of Trinidad (see Figure 3 for location). Fault shows little evidence of strike-slip displacement after about the middle Pleistocene. Expression of El Pilar in this area is very similar to convergent wrench faults and positive flower structures of the Ardmore Basin, Oklahoma [see Harding et al., 1983].

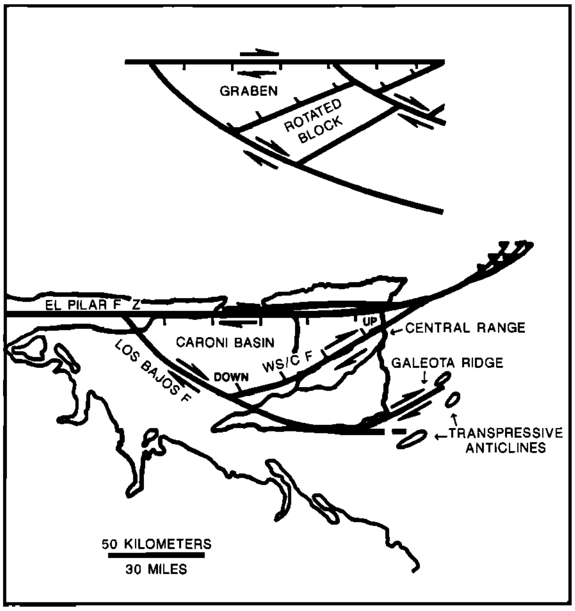


Fig. 10. Basin formation along El Pilar-Los Bajos faults. Early model presented by Rod [1956] for the area suggests graben formation at divergent intersections (top). The only recognized example of this occurs at El Pilar-Los Bajos fault intersection, resulting in formation of the Caroni Basin (bottom). Basin is low to the southwest, high to the northeast (where Warm Springs/Caigual fault intersects El Pilar). Rotated block is represented by the Central Range. Amount of rotation is unknown but may be greater than 10.5 km (measured offset on Los Bajos [Wilson, 1968]). Horsetail splays from Los Bajos (and Los Bajos itself) terminate in transpressive anticlines which accommodate translation.

be inferred from stratigraphic and structural data (Figure 11a). Kugler [1959], Ablewhite and Higgins [1968], and Salvador and Stainforth [1968] showed that early to late Miocene and Pliocene sediments thicken southwest toward Los Bajos fault. Wilson's [1968] minimum estimate of at least 630 m of dip-slip movement on Los Bajos and Salvador and Stainforth's observation of down-to-the-south dip-slip movement on El Pilar fault also support this model.

Along with formation of the Gulf of Paria basin, this model suggests that some block rotation has probably taken place along Los Bajos fault, producing counterclockwise motion of the Central Range foldbelt of Trinidad (Figure 11b). Horsetail splays [Christie-Blick and Biddle, 1985] such as the Warm Springs/Caigual fault system have developed from Los Bajos since the Miocene, accommodating small amounts of transpressive stress. Many of these splays terminate in transpressive anticlines [Leonard, 1983]. Although Los Bajos alone is not a major plate boundary fault within the system, it and the features associated with it probably are acting to accommodate some of the present transpressive stresses at the southeastern corner of the plate boundary zone. In that sense, Los Bajos fault may be the early representation of a right step in El Pilar fault zone, transferring displacement across the plate boundary zone through the Gulf of Paria. If this is true, it is conceivable that the Gulf of Paria may eventually develop into a pull-apart basin similar to the Cariaco Basin to the west (see Figure 1).

Other Faults in the Plate Boundary System

Other dextral faults with east-west orientations may have aided in translation of the Margarita Block to its present location (Figures 11a and 11b). Existence of faults with the appropriate orientation or sense of displacement has been shown by Vignali [1979], Case and Holcombe [1980], Gonzalez de Juana et al. [1980], Ramroop [1986], Wadge and Hudson [1986], and Robertson and Burke [1989] and provides evidence of the diffuse and fragmented nature of the plate boundary zone.

Fault patterns and basement configurations between Trinidad and Tobago were shown by Robertson and Burke [1989]. These faults, along with faults that have been hypothesized to the west within the Margarita Block area (Figures 11a and 11b), may have accommodated nearly half of the dextral offset within the plate boundary zone. Assuming approximately 1100 km of eastward translation of the Caribbean plate since the late Paleocene, almost 500 km of that offset can be accommodated by offset along the Oca fault (about 50 km), and closure of the Bonaire (about 250 km), Falcon (about 50 km), and Cariaco (maximum of 125 km) basins (Figure 4). These figures are estimates of translational motion and crustal attenuation only and do not include offsets for the Urica, San Francisco, and Los Bajos faults nor any estimate of

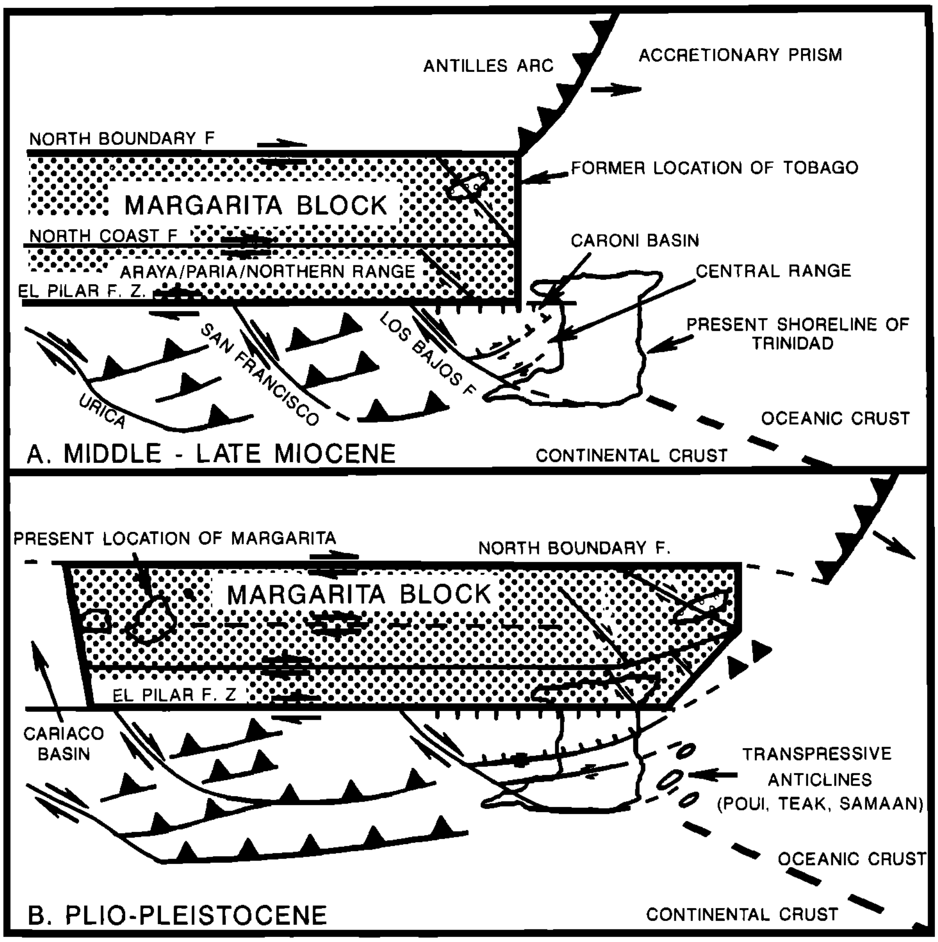


Fig. 11. Middle Miocene-Pleistocene translation of the Margarita Block. (a) Middle-late Miocene: Eastward relative motion of the Caribbean caused continued eastward translation of the Margarita Block. Time of origin for many of the seismically defined faults within and bordering the Margarita Block (see Figure 3) is not clear. Present shoreline of Trinidad shown for reference. (b) Plio-Pleistocene: Emplacement of the Margarita Block to its modern location. Northwest-southeast oriented faults within the block may be due to the recent change in relative motion of the Caribbean at its south-eastern corner. Outline of Margarita Island shown for reference. Crustal boundaries are only approximations based on data shown by Bonini [1978] and Case and Holcombe [1980]. See Figure 1 for symbol key.

crustal shortening within the Serrania del Interior. These figures are speculative at best but suggest that other (poorly documented) faults within the system may have significant dextral offset. Since recent evidence implies a dip-slip vector for El Pilar fault motion during the late Pleistocene to Holocene (in eastern Venezuela and Trinidad [Salvador and Stainforth, 1968; Vierbuchen, 1984; Speed, 1985]), some of the present relative motion between the Caribbean and South American plates is probably being accommodated by the other faults within the system, by formation of transpressive anticlines in Trinidad and by crustal downwarping southeast of Trinidad.

CRUSTAL DOWNWARPING

Stress at the southeastern corner of the plate boundary zone may also be

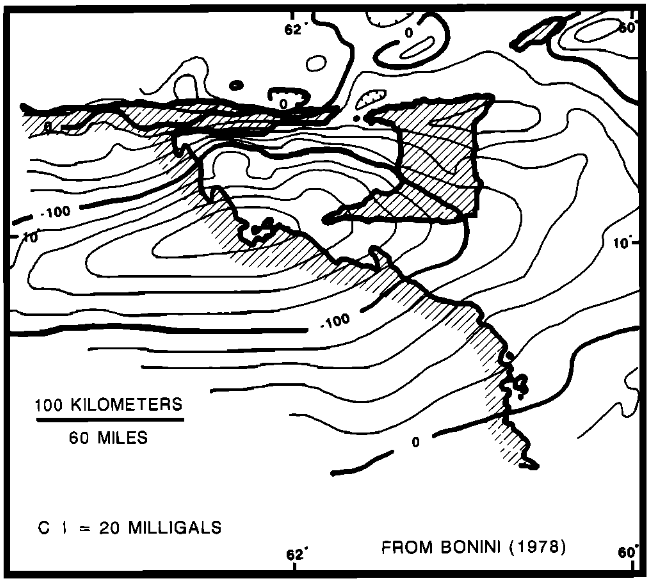


Fig. 12. Bouguer gravity of northeastern Venezuela and Trinidad [from Bonini, 1978]. Circular -180 mGal anomaly centered over the Eastern Venezuela Basin suggests greatly depressed crust in the area. Initiation of the basin was probably due to flexural downwarping after thrust loading of the Serrania del Interior area, later aided by lithostatic loading during deltaic sedimentation. Late Tertiary sediment loading off the southeast coast of Trinidad may be accommodated by recent downwarping of Atlantic oceanic crust (see Figure 10 for approximate crustal boundaries).

accommodated by downwarping of the crust. Bouguer gravity data (Figure 12) suggest a present crustal depth of 10-14 km. Recent plate tectonic reconstructions [Burke, 1988; Pindell et al., 1988; Pindell and Barrett, 1989] have proposed that straight-edged margins on the west and southwest side of the Demerara Plateau (offshore northern Surinam) were produced by transform faulting during the early opening of the central North Atlantic. Atlantic oceanic crust of Jurassic age was formed immediately adjacent to South American continental crust; recent expansion of the southeastern edge of the Caribbean plate into this area may be causing downwarping of the old oceanic crust [Bayly, 1982]. Lithostatic loading during the late Teriary-Quaternary may also be responsible for some of the crustal downwarping [Bonini, 1978].

SUMMARY

In this study, an attempt has been made to combine plate kinematic models with the problematic geology of the area. As a result, several significant points can be made regarding future paleogeographic work.

Although it is generally recognized that the Caribbean-South American plate boundary zone is complex and diffuse, several major faults can be defined as important components in the system. The origin of El Pilar fault can be related to formation of the Cariaco Basin. The fault's eastern terminus ends in several oblique thrust faults that accommodate transpressive stresses within the southeastern corner of the plate boundary zone. Total offset along the fault is probably no greater than 125 km, though its most recent motion (in Trinidad) is apparently not strike-slip. This suggests that El Pilar fault has played a relatively minor role in the overall eastward translation of the Caribbean plate, though displacement along the entire fault zone may be significant. This also suggests that other east-west and northwest-southeast trending faults within the plate boundary zone [e.g., Vignali, 1979; Alvarez et al., 1985] may accommodate much of the translation produced within the system. At the present time, much of the

Caribbean-South American relative motion may be occurring along faults within and north of the Margarita Block, though recent motion on Los Bajos fault may indicate it is now becoming a more important part of the plate boundary system. This observation leads to the conclusion that faulting within the plate boundary zone has been episodic and that any fault within the plate boundary system may have alternated as a major or minor component through time.

Strain resulting from present-day transpressive stress within the plate boundary zone also is being accommodated at the southeastern corner of the plate boundary by formation of transpressive anticlines, and compressive downwarping of Jurassic Atlantic oceanic crust southeast of Trinidad.

The terrane designated here as the Margarita Block (including the Villa de Cura and Cordillera de la Costa) has behaved as a relatively competent crustal block; it can be reconstructed to a partially restored (though not original) position in northwestern Venezuela. This combined terrane was probably emplaced during the Paleocene to middle Eocene as a single allochthonous mass [see Skerlec and Hargraves, 1980] that was then broken and dextrally sheared by later strike-slip faulting. Metamorphic rocks of the Araya/Paria peninsula, Margarita, Tobago, and the Northern Range of Trinidad arrived at their present locations during relative eastward translation of the Caribbean plate. Structural and stratigraphic data [e.g., Hedberg, 1950; Gonzalez de Juana et al., 1980; Carnevali, 1988a] suggest that these rocks were not emplaced in their present linear configuration during a single compressive(?) event (in the late Tertiary) but have been translated from west to east along a number of dextral strike-slip faults.

Allochthonous metavolcanic rocks of the Villa de Cura Group were either thrust onto the Margarita Block (Cordillera de la Costa part) or are partial stratigraphic equivalents to it. The entire block was then emplaced within the passive margin sedimentary section of northern Venezuela by the late-middle Eocene (Figure 7), prior to the block's eastward translation. Possible examples of the original Cordillera de la Costa-Villa de Cura stratigraphic relationship may exist on Tobago and in the Sans Souci Formation, Northern Range of Trinidad.

The structural and stratigraphic history of the northern Venezuela-Trinidad area reflects active transpression along the southern part of the Caribbean-South American plate boundary. Structural features examined in this study probably formed as a result of transpressive stresses applied within the plate boundary zone and were not produced within an idealized shear couple [see Tchalenko and Ambraseys, 1970].

IMPLICATIONS FOR PALEOGEOGRAPHIC RECONSTRUCTIONS

Some of the implications of the tectonic model presented here may illustrate problems with the model, or avenues for further work. One implication of Figures 5 and 6 is that the emplacement of the Margarita Block involved as much as 400 km of convergence between it and northern South America during the Paleocene-Eocene interval. The amount of convergence could be reduced by at least 50-100 km by adjusting the size and shape of northwestern South America (Guajira-Paraguana area); considering the tectonic rotations proposed for this area by MacDonald and Opdyke [1972], Skerlec and Hargraves [1980], and Stearns et al. [1982], this should not be difficult. The resulting numbers, however, are still much greater than the amount of Caribbean-South American convergence predicted by recent plate tectonic models [e.g., Pindell et al., 1988]. Nevertheless, the Margarita Block does appear to have been emplaced by some definable amount of convergence.

One explanation for at least 100-200 km of convergence may be the opening of the Grenada Basin (either northwest-southeast or north-south opening as postulated by Pindell and Barrett, [1989]; see Figure 6b). Bouysse [1988] used a set of poorly defined magnetic anomalies to suggest a Paleocene age for this opening, in a northeast-southwest direction. If the convergence is truly linked to formation of the Grenada Basin, then a three-plate system (Caribbean-South America-Margarita Block) rather than a two-plate system (Caribbean-South America) is required to derive the correct relative motions. Given the information available (such as direction and timing of the Margarita Block's emplacement and the contemporaneous major plate motions), a vector-triangle solution for the Caribbean-Margarita Block-South America interaction should be possible.

Another problem related to the amount of convergence between the Caribbean and

South America involves the origin and original location of the Margarita Block. Paleomagnetic data [e.g., MacDonald and Opdyke, 1972; Skerlec and Hargraves, 1980; Stearns et al., 1982] support the proposed original location of the block near the Pacific coast of Colombia (Figure 5), and paleontologic data [Benjamini et al., 1987] suggest that the fauna of the Tucutunemo Formation may possess Andean affinities. If the Margarita Block consists of passive margin rocks, then a likely original location may have been in western or northwestern Colombia, north of the former Pacific-South America convergent margin (Central Cordillera arc and possibly the Santa Marta Block). The Guajira-Paraguana area (though its original location also is not known) is another possible location. However, if the Cordillera de la Costa represents sediments formed in a volcanic arc, forearc, or back arc setting, then a location farther to the southwest is possible.

This latter idea is supported by the work of Wadge and Macdonald [1985] on the Sans Souci Formation of the Northern Range of Trinidad. Their data suggest that metabasalts of the Sans Souci actually may be partial stratigraphic equivalents to Cordillera de la Costa metasedimentary rocks. If their geochemical data and the geochemical data of Piburn [1967], Santamaria [1972], Rowley and Roobol [1978], Beets et al. [1984], and Hebeda et al. [1984] are correct, some stratigraphic equivalency may exist between Villa de Cura metavolcanic and Cordillera de la Costa metasedimentary rocks. This would suggest that rather than being emplaced separately [i.e., Benjamini et al., 1987], the Villa de Cura and Cordillera de la Costa sequences were emplaced as a single large allochthonous block (Margarita Block). Further support for this model can be found in the paleomagnetic work of Skerlec and Hargraves [1980], who documented an average of 90° of tectonic rotation for both the Villa de Cura and the Precambrian Caucagua-El Tinaco sequences (see Figure 1 and discussion of Cordillera de la Costa lithologies). Allowing for variations in original geometry and block orientation, this number may be a good estimate of the amount of rotation of the Margarita Block prior to its emplacement in northwestern Venezuela [also see Beck, 1988].

The proximity of the Curacao arc to the Villa de Cura Group therefore may be only coincidental. Geochemical [Beets et al., 1984], paleo-magnetic [Stearns et al., 1982; Beck, 1988], and plate kinematic work [Pindell and Barrett, 1989] implies a genetic link exists between the Aves and Curacao arcs. Though the model shown in Figure 5a genetically relates the Aves part of the Greater Antilles arc to the Villa de Cura Group, no such relationship can be suggested for the Curacao arc and the Villa de Cura Group. Uncertainty over the origins of metavolcanic rocks of the Villa de Cura, as well as the Tobago and Sans Souci sequences, plus the possible stratigraphic equivalency of the Sans Souci metabasalts to the Cordillera de la Costa metasediments, makes any genetic link tenuous. Regardless of these considerations, the exact positioning of the Curacao "segment" of the Aves arc with respect to the Villa de Cura Group remains uncertain and may never be clearly established. In light of the available data, it would not be surprising to discover that the Guajira and Paraguana areas, and possibly other parts of northwestern South America, were also rotated and translated great distances northward to their present positions during northward migration of the Caribbean plate. Modifying the outline of northwestern South America in this manner would greatly alter plate tectonic reconstructions of the Caribbean, as well as the Gulf of Mexico and the central North Atlantic.

Finally, although downwarping of Atlantic oceanic crust seems to be occurring at the southeastern corner of the Caribbean plate, the mechanisms are unknown. In contrast to the explanation suggested above, it is possible that this downwarping may not have a plate tectonic cause.

The model presented here is an attempt to reconcile existing plate tectonic models with the available geologic and geophysical data. Questions should be raised not only about the model but also about existing geological interpretations of the area. The problems or implications arising from this study point out the need for additional geological and geophysical data, and should suggest topics for further research that will help to better constrain models of Caribbean-South American plate interactions.

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