# Crustal History and Plate Tectonic Development in the Southern Caribbean

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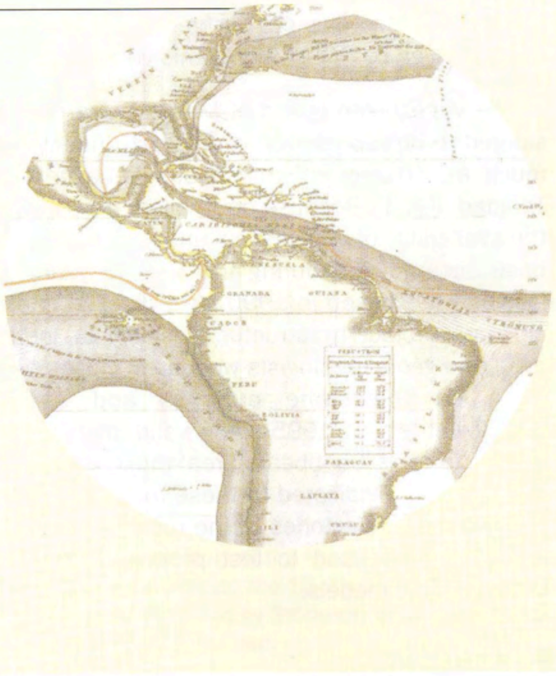
We dedicate this contribution to the memory of our colleagues and friends Alirio Bellizzia and Carlos Schubert, whose untimely and grievous deaths are a tragic blow to the Geosciences in Venezuela.

## ABSTRACT

Metamorphosed Aptian–Albian oceanic crust, Paleozoic continental basement and Cretaceous sediments form the basement of NE Venezuela. The pressure-temperature-deformation-time evolution of this crustal complex has been established as follows: accretion and common high-pressure metamorphism in a fore-arc (100 ± 10 Ma); ascent, cooling and emplacement into the intermediate crustal level of a volcanic arc (90–80 Ma); a transform plate - margin setting (80–50 Ma); a second episode of rapid uplift and cooling (50 Ma); a shallow crustal level close to a transform plate - margin (50 Ma to present). This complex evolutionary sequence agrees well with plate-tectonic scenarios restricting collision, accretion and high-pressure metamorphism to the western margin of South America, followed by passive eastward migration of large slivers of this crust along the northern margin since the Late Cretaceous; it does not support models proposing in situ collision with high-pressure metamorphism along the northern margin itself.

## RESUMEN

Se ha establecido la siguiente evolución en las condiciones de presión-temperatura-deformación-tiempo en el basamento expuesto al NE de Venezuela: (i) un protolito, compuesto por corteza oceánica (Aptiano - Albiano), basamento continental paleozoico y sedimentos cretácicos, sufre acreción y metamorfismo de alta presión en un antearco (100 ± 10 Ma); (ii) posterior ascensión, enfriamiento y emplazamiento en un nivel intermedio cortical de un arco volcánico (90 - 80 Ma); (iii) desarrollo de una falla transformante (80 - 50 Ma); (iv) segundo episodio de ascenso rápido y enfriamiento (50 Ma); (v) emplazamiento en un nivel cortical poco profundo cerca de un margen transformante (50 Ma hasta la actualidad). Esta secuencia compleja concuerda bien con los modelos de la tectónica de placas que requieren colisión, acreción y metamorfismo de alta presión a lo largo del oeste de Suramérica, con una migración hacia el este de largas cuñas de esta corteza a lo largo del norte de Sudamérica desde el Cretácico Superior. No apoya modelos que proponen una colisión y metamorfismo de alta presión in situ a lo largo del norte de Sudamérica.



## Introduction

■ Plate tectonic models are notoriously difficult to "prove" or "disprove", because of the innumerable variables involved in reconstructing the tectonic history of a given region. In this sense the Caribbean area (Fig. 1) represents a particularly favorable case study for optimizing interactively the available data set and the models derived therefrom, because the history of the present Caribbean is relatively short, probably not extending back for more than 165 Ma, and the present-day kinematics of the Caribbean plate and the plates surrounding it are now well-known from geophysical investigations.

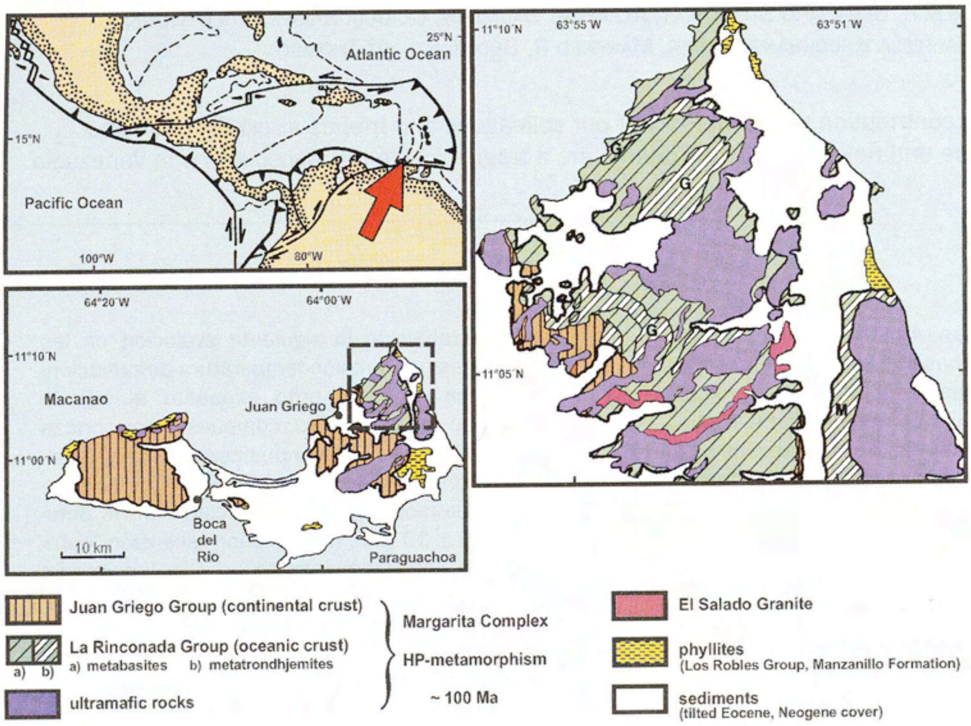



**Fig. 1:**

Margarita Island and its regional setting. Detail of northeastern Margarita indicates the leucocratic intrusive rock types providing a geochronological reference system (El Salado granite and the metatrondhjemites Guayacán orthogneiss (G) and Matasiete trondhjemite (M)). Modified from STÖCKHERT et al. (1995).

A wide-spread consensus has developed on a basic theme involving "snow-plow-like" eastward movement of the Caribbean plate relative to North and South America, at least since the Cretaceous (cf. PINDELL 1993, and references therein). The Caribbean "plow" or "Great Arc" amalgamated and swept a series of island arcs and terrane fragments to the east, as well as onto the margins of the North and South American plates. Many models now favor a Pacific origin for the Caribbean plate (e.g. PINDELL 1993; hereafter termed the "Pacific" model), but proponents of an intra-American origin have recently presented detailed alternative scenarios (MESCHEDE & FRISCH 1998; MESCHEDE et al., this volume).

The historical development of plate tectonic models in the Caribbean is almost exclusively based on a two-dimensional perspective, augmented by information on timing and type of volcanic activity. The information on the "third" dimension, the pressure (i.e. depth)-temperature-deformation-time development of crystalline rocks, has not been widely used to test and/or develop plate-tectonic models until recently. The German Research Society (Deutsche Forschungsgemeinschaft) has been actively funding German researchers involved in international project groups working in key areas along the northern and southern margins of the Caribbean, where P-T-d-t-paths of the exposed high-pressure metamorphic rocks are being worked out. Detailed results are now available for the Caribbean borderland of Venezuela and will be summarized in this paper. Projects in the northern Caribbean are underway; an up-to-date summary of the present status of knowledge on the geological history of Cuba is given by STANEK et al. (this volume).

The Venezuelan Island of Margarita can be considered to be representative of crust underlying as much as 70,000 km$^2$ of coastal Venezuela and Trinidad (Fig. 1). Because of excellent exposure and the availability of a geological and petrological data base accumulated during the last 50 years, this locality was chosen in 1990 for a detailed interdisciplinary project by structural geologists, petrologists and geochronologists working in close cooperation on the same outcrops and samples (STÖCKHERT et al. 1995). Any valid plate-tectonic model for the Caribbean area must explain the crustal history indicated by these rocks, or, inversely, the P-T-d-t trajectories of the rocks on Margarita Island can be used to test proposed Caribbean plate-tectonic models.

## Geological setting of Margarita Island

Margarita Island is composed of two cores consisting of a complex of igneous/metamorphic rocks, overlain by unmetamorphosed sediments of Eocene or younger age (Fig. 1). The main units are the La Rinconada and Juan Griego Groups. The La Rinconada Group comprises high-pressure amphibole-gneisses and eclogites (Fig. 1), the Juan Griego Group is composed of quartzo-feldspathic schists and gneisses with intercalated marbles and widespread eclogitic lenses. Predominantly serpentinized ultramafic bodies are structurally integral parts of the Margarita Complex. Lower grade phyllites, schists and marbles of the Los Robles Group and Manzanillo Formation mantle the higher-grade core. Magmatic activity provides a geochronological reference system for Margaritan tectonic history. Metatrondhjemites (Fig. 1) predate high-pressure metamorphism, whereas the El Salado granite (Fig. 1) intruded into the waning stages of this metamorphic event. Small bodies of syntectonic gabbro and dyke swarms of basaltic to andesitic composition punctuate later tectonic history.


**Fig. 2:**

Depth-time trajectory of the Margarita Complex. The numbers indicate the 12 stages of crustal development defined by STÖCKHERT et al. (1995) and described in the text.

## Pressure-temperature-deformation-time evolution

STÖCKHERT et al. (1995) outlined the detailed P-T-d-t history of the Margarita Complex in a series of 12 stages. These can be conveniently summarized and grouped together in terms of an evolving sequence of clearly defined tectonic settings that allow correlation with proposed plate-tectonic models of the Caribbean. The depth-time trajectory of Figure 2 will serve as a convenient guide to emphasize the distinctive nature of this sequence.

### The protolith of the Margarita Complex (Stages 1 and 2)

The metabasic La Rinconada unit exhibits mid-ocean-ridge basalt (MORB) chemistry and can be regarded as basalts and gabbros of former oceanic crust. The ultrabasic massifs (serpentinized dunites, clinopyroxenites, harzburgites) are primarily associated with this unit (Fig. 1) and probably represent slivers of the underlying lithospheric mantle. Shallow-level trondhjemitic intrusions ("plagiogranite") are found in the La Rinconada unit. Concordant magmatic zircons yield U-Pb ages ranging from 116 to 109 Ma, constraining formation age of the protolith oceanic crust to the Aptian/Albian.

The protolith of the Juan Griego Group has usually been presumed to be a sedimentary sequence of Jurassic to Cretaceous age, comprising limestones, marls, pelites and sandstones. New data indicates that the unit comprises both Paleozoic basement as well as sediments of Aptian/Albian or younger age. Cretaceous ages are indicated by relics of the fossil *Heterohelix* in marbles. Some gneissic rocks in the Juan Griego Group contain features of older, high-grade crystalline basement, such as deformed quartz-feldspar-rich schlieren of anatectic origin. Zircon fractions from a granitic augen gneiss define a U-Pb discordia with a Paleozoic upper intercept of 315 (+ 35 / - 24) Ma. Thus, the Juan Griego unit includes older Paleozoic crust and must represent a continental fragment. The phyllite mantle represents intermediate to acid volcanics and pyroclastics as well as pelitic sediments, therefore also indicating continental affinity.

## The fore-arc setting (Stage 3)

The Juan Griego and La Rinconada units, as well as the ultrabasic rocks, were joined together in an accretionary complex and subjected to high-pressure metamorphism (Figs. 2, 3) after 109 Ma. Unequivocal high-pressure assemblages (eclogites, barroisite-bearing amphibolites) developed in the La Rinconada unit. Lenses of eclogite are also found in the Juan Griego unit, but only recently could high-pressure metamorphism be proven in enclosing Al-rich pelites (Fig. 3). The P-T-path constrained for the Juan Griego unit (Fig. 3) is compatible with eclogites of the coherent La Rinconada sequence, but the eclogite pods within the Juan Griego unit itself may have experienced somewhat higher maximum P-T-conditions. These data indicate that accretion of the Margarita Complex took place at depths of at least 40–50 km (Fig. 2). Some isolated eclogite lenses may even have been subducted to 70 km before incorporation into the Margarita Complex (Fig. 3). The phyllitic units record no high-pressure metamorphism and were obviously not involved in the accretionary stage.

K–Ar and Ar–Ar cooling ages on white-mica in high-pressure schists and eclogites yield ages between 90 and 80 Ma, indicating cooling below 400 °C and exhumation to depths of 15–20 km at this time. This signals the end of the accretionary, high-pressure event. The depth-time trajectory of Fig. 2 leads to an average velocity of subduction and subsequent exhumation of at least 3–4 mm per year.

## The island-arc setting (Stage 4)

During exhumation from the accretionary complex to intermediate crustal levels, granitic calc-alkalic magmas intruded the Margarita Complex. Zircons from the El Salado granite yield concordant U-Pb data indicating an intrusion age of 86 Ma. The Si-rich composition of the magmatic phengites suggests a still very deep level of emplacement (Fig. 2).

## The greenschist-facies overprint in a transform plate margin (Stage 5)

Exhumation of the Margarita Complex was interrupted at intermediate crustal levels for the subsequent 30–40 Ma (Fig. 2). The Margarita Complex was caught up in a strike-slip regime such as the one presently found along the Caribbean/South American plate boundary. Ductile deformation concentrated in extensive shear zones is characteristic. The deformation is reponsible for the present east-northeast – west-southwest structural grain of the island, with an east-northeast – west-southwest subhorizontal stretching lineation. Foliation is steep and fold axes run generally parallel to this stretching lineation. The earlier high-pressure metamorphic history is predominantly preserved in rheologically competent rocks of the La Rinconada unit; it is largely obliterated in quartz-rich schists and gneisses of the Juan Griego unit and replaced by greenschist-facies assemblages. Ar–Ar determinations on magmatic amphibole from syntectonic gabbros yield a cooling age of 66 Ma.

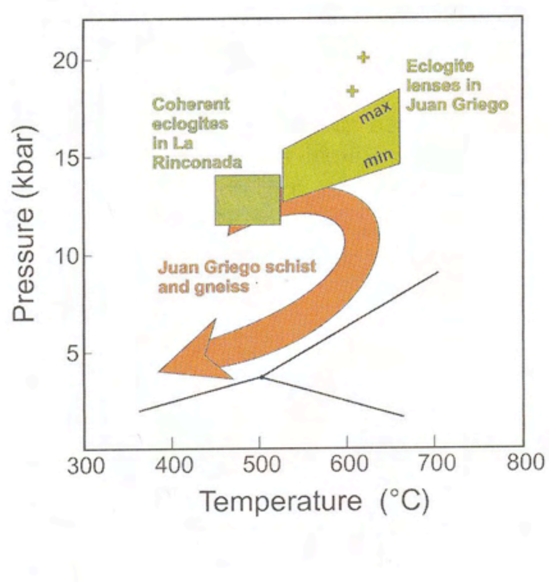



**Fig. 3:**

Thermobarometric data from rocks of the La Rinconada and Juan Griego Groups. For most eclogite lenses from the Juan Griego unit pressures can be estimated only within broad minimum/maximum limits. Two lenses contain additional phengite, allowing P-T conditions to be pinpointed more exactly (crosses).

## The upper crust (Stages 6 to 12)

With decreasing age, the crustal history of the Margarita Complex can be described in more detailed stages, but for this overview it is sufficient to summarize the final stages of rapid cooling, exhumation and emplacement into the shallow crust together.

Major tectonic reorganization must have affected the Margarita Complex at approximately 50 Ma (Fig. 2) in a remarkably short time. K–Ar dating of white mica formed during the greenschist-facies overprint consistently yields cooling ages of 55–50 Ma (Stage 6, Fig. 2). Backward modeling of Rb–Sr isotope data from thin slabs in mylonitized orthogneiss also leads to an age of 50 Ma for the last major isotopic reequilibration. Fission-track data are now available for zircons from various localities on Margarita Island and indicate that cooling below 280 ± 30 °C commenced at 53 ± 3 Ma. The age cluster around 55–50 Ma signals rapid cooling while the Margarita Complex was being emplaced into a shallow crustal level and a brittle deformational regime. Conjugate shear fractures formed in the brittle field as a consequence of east-northeast–west-southwest extension and were filled first by massive quartz veins and subsequently by basaltic to andesitic melts. Ar–Ar analyses of amphibole phenocrysts from these dykes do not yield clearly defined plateaus, but the total fusion ages again cluster around 52–47 Ma. Fission track ages on zircons range from 53 ± 3 Ma to 36 ± 2 Ma and suggest that in the brittle deformational field the terrane was dissected into blocks with variable exhumation rates and depth-time trajectories (Stage 7, Fig. 2).

The entire younger history of the Margarita Complex since Eocene time is characterized by brittle deformation, marked by reverse- and normal-faulting episodes mostly predating the deposition of the Neogene sediments. Fission track data for both zircon (46 ± 3 Ma) and apatite (23 ± 2) from a metatrondhjemite indicate average exhumation rates of only 0.3 to 0.4 mm per year after emplacement in the upper crust.

## Discussion and Conclusions

Detailed pressure-temperature-deformation-time trajectories of metamorphic and magmatic rocks yield important constraints for evaluating plate-tectonic models. The following aspects of the data presented here are of first-order significance for Caribbean plate-tectonic models. In Figure 4 a model is offered depicting a plate-tectonic scenario based on the "Pacific" model, which we prefer at present on the basis of our data. An alternative "intra-American" model is described by Meschede et al. (this volume).

The transition from an accretionary fore-arc setting to that of an island arc (stage 3 to 4) within less than 10–15 Ma requires an abrupt and distinctive change in tectonic setting that must be explained by plate-tectonic models. In the context of the "Pacific" model (Fig. 4), Aptian/Albian basaltic crust and peridotite, as well as continental crust and overlying sediments as fragments of Protocaribbean rifting, are available for accretion and high-pressure metamorphism in a fore-arc setting due to Farallon-Protocaribbean convergence (cf. time slab 118.7 Ma of the "Pacific" model, Fig. 4). Exhumation and cooling at 90 Ma, marking the end of the high-pressure accretionary event, coincide with the onset of calc-alkalic El Salado magmatism and an island-arc setting. This enigmatic and sudden shift in tectonic milieu can be elegantly explained by the mid-Cretaceous flip in subduction direction between the Farallon plate and the Protocaribbean indicated by the "Pacific" model (compare time slabs 118.7 and 100.0 Ma in Fig. 4). This correlation agrees well with the mounting evidence for such a flip summarized by Smith et al. (1999) from various localities around the Caribbean.

Beginning in Stage 5, Margarita-type crust was entrained in a major transform zone along northern South America, that led to a significant eastward translational component (time slabs 84.0, 59.2 Ma in Fig. 4). The relatively sudden phase of exhumation at 50 Ma for Margarita-type crust requires explanation in the plate-tectonic context. The "Pacific" model (Fig. 4, time slabs 59.2 Ma, 50.3 Ma) suggests that tectonic reorganization at this time could be related to extension caused by changes in relative motion vectors as the leading arc of the Caribbean plate passed the Colombian "corner" (cf. Avé Lallemant & Guth 1990), approximately near the present position of Guajíra Peninsula. Subsequent Margaritan history is confined to brittle deformation at a shallow level near

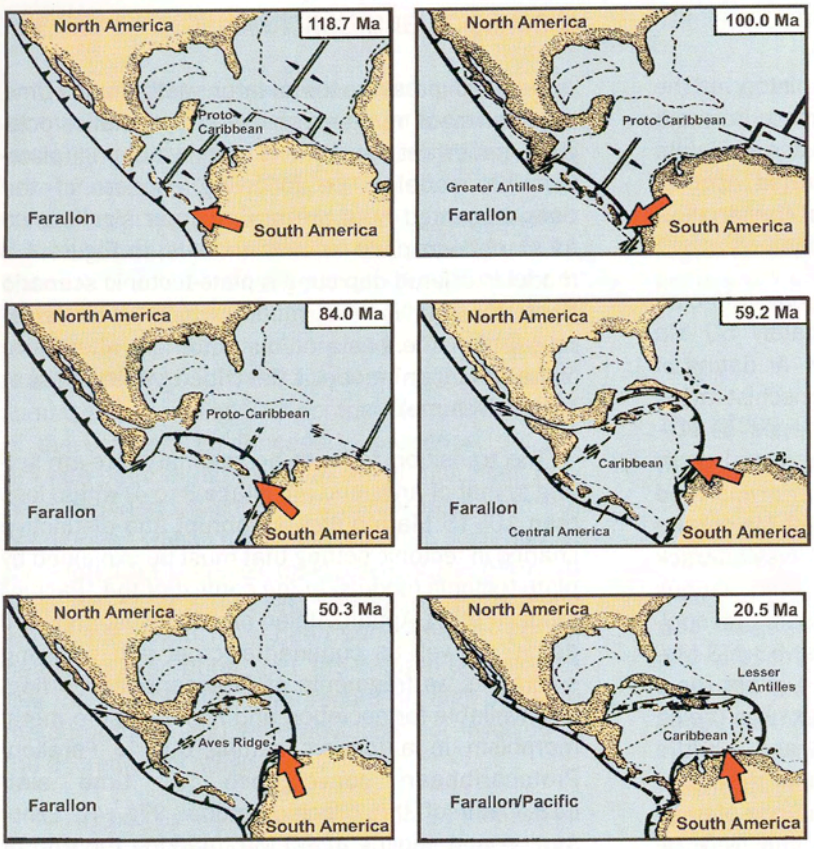



**Fig. 4:**

Plate-tectonic reconstructions simplified from the snap-shot sequence of ROSS & SCOTESE (1988), based mainly on data by PINDELL and co-workers (cf. PINDELL 1993). Arrows show presumed location of Margarita Complex with time. Modified from STÖCKHERT et al. (1995).

the east-west transform zone between the Caribbean plate and northern South America.

Beginning in the Early Paleocene, paleogeographic reconstructions of the northern South American plate margin, which draw on voluminous data from hydrocarbon exploration (e.g. PINDELL et al. 1998), allow the eastward progress of the Caribbean "plow" or "Great Arc" – and the suturing of allochthonous crustal slices onto the passive South American margin – to be described with considerable confidence. In the Early Paleocene, the "Great Arc" was impinging the South American margin west of Guajíra Peninsula. A steady and continuous process of diachronous, oblique encroachment was initiated, that can be followed to the present-day position of the Lesser Antilles (PINDELL et al. 1998). The uniformity of the evolution of the northern margin of South America is corroborated by the consistent ± 90° rotation of allochthonous units from the whole Caribbean – South American plate boundary zone from Guajíra Peninsula to Tobago (e.g. BURMESTER et al. 1996). These data indicate, that no major collision or subduction process with associated high-pressure metamorphism occurred along this margin after formation by rifting in the Late Jurassic. Thus, early ideas on in situ high-pressure metamorphism along the northern South American margin (e.g. MARESCH 1974; BEETS et al. 1984) are untenable. The "intra-American" model formulated in MESCHEDE & FRISCH (1998) and MESCHEDE et al. (this volume) also does not comply with the constraint that the leading edge of the Caribbean plate was west of Guajíra Peninsula before the Early Paleocene.

We conclude that at the present state of knowledge the history of Margarita-type crust along the southeastern borderlands of the Caribbean correlates best with the scenarios predicted by "Pacific"-type plate-tectonic models, without necessarily proposing or requiring a far-traveled Caribbean plate. As discussed by MESCHEDE & FRISCH (1998), a distant origin is implied only on the basis of the debatable assumption that the Galapagos hotspot is the cause of the thickened Caribbean crust. The "intra-American" model proposed by MESCHEDE & FRISCH (1998) and MESCHEDE et al. (this volume) draws its main strength from a comparison of paleomagnetic data obtained in Central America with current knowledge of Mesozoic plate kinematics. A near-equatorial position of the Caribbean plate is suggested throughout its existence, a conclusion that is at variance with the Mesozoic trajectory of plate motions predicted for the Pacific ocean floor. Clearly, these discrepancies must be clarified; revised models and more work on P-T-d-t trajectories in key areas of the Caribbean are called for.

### Acknowledgements

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