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Evolution of the Southern Caribbean Plate Boundary

It is generally accepted that the cores of the continents, called cratons, formed by the accretion of island arcs into proto-continents and then by proto-continental agglomeration to form the large continental masses. Mantle-wedge processes, combined with higher melting temperatures during the Archean (2.5–3.8 billion years ago) and possibly thrust stacking of highly depleted Archean oceanic lithosphere, produced a strong, buoyant, upper mantle chemical boundary layer. This stabilizing mantle layer, known as the tectosphere, has shielded the Archean cratons from most subsequent tectonic disruption and is highly depleted in iron, providing the positive buoyancy that is required to 'float' the continents more than four kilometers above the surrounding ocean basins.

What is not clear is whether today the continental mass is growing, shrinking, or is at steady state. A number of continental growth curves have been proposed; the most widely accepted models call for rapid continental growth in the late Archean and Paleoproterozoic (between 3.0 and ~1.7 billion years ago), followed by slow growth to the present. Whether modern continental accretion and something akin to tectosphere formation are occurring today is an open question. It is not clear how island arcs accrete to the continents, or if modern arcs contribute to continental growth. Seismic observations of arcs worldwide show that the crustal velocity structure is too fast, and hence the chemical composition too silica-poor, to generate an average continental crust without substantial chemical and/or mechanical refining during or subsequent to accretion.

Two coordinated multi-disciplinary projects, BOLIVAR and GEODINOS, are investigating continental growth and deformation processes along the southeastern Caribbean–South American plate boundary (Figure 1). BOLIVAR is the U.S. project Broadband Onshore-Offshore Lithospheric Investigation of Venezuela and the Antilles Arc Region; GEODINOS is the Venezuelan project Recent Geodynamics Along the Northern Limit of South America. The two projects combined consist of a suite of geochemical, active and passive seismic, structural geology, sedimentary basin, and neotectonic studies involving about 60 scientists and students from the United States and Venezuela.

One hypothesis that BOLIVAR and GEODINOS scientists are testing is that the Leeward Antilles and related terrains are accreting to South America, contributing to the continental landmass. The projects are designed to investigate both the crust and upper mantle structure, as well as the evolution of the crust-mantle processes by which the Leeward Antilles islands deform and accrete to South America (Figure 1). As part of the study of island arc accretion, the research will seek to determine how high-pressure/low-temperature (HP/LT) subduction-related metamorphic rocks are exhumed. The project is also aiding earthquake hazard assessment in the diffuse Southeast Caribbean plate boundary.

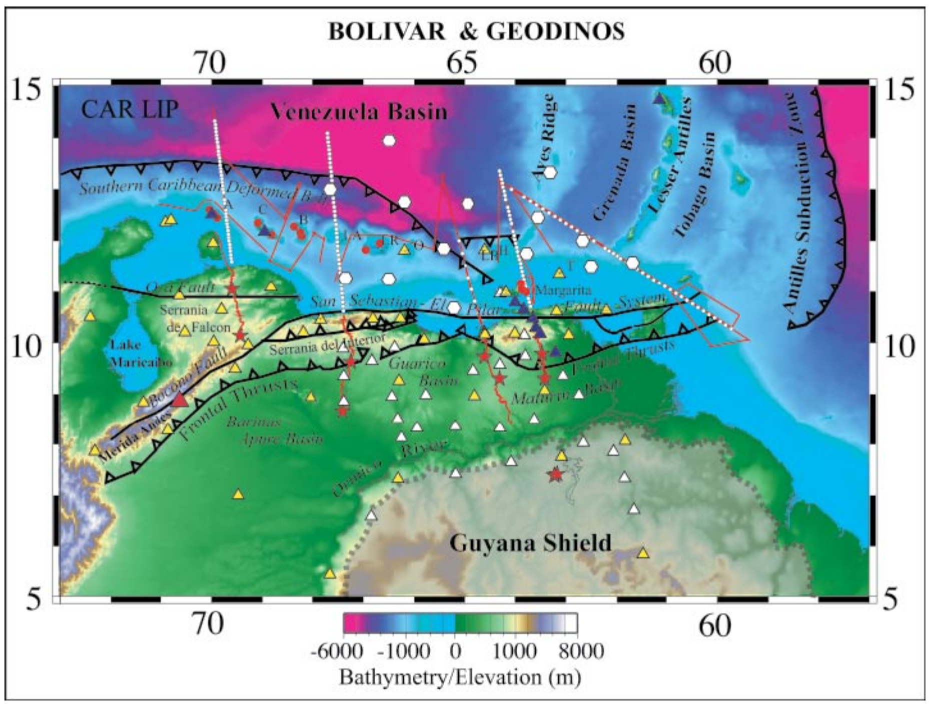

Fig. 1. Map of the southeastern Caribbean plate boundary, a diffuse plate boundary zone extending from the southern Caribbean deformed belt in the north to the southern edge of the foreland basin-fold and thrust belt system. The Leeward Antilles islands are A, Aruba; C, Curaçao; B, Bonaire; and the Venezuelan archipelago is LA, Las Aves; LR, Los Roques; O, Orchilla; LB, La Blanquilla; H, Los Hermanos; and T, Testigos. CAR LIP is the Caribbean Large Igneous Province. Solid red lines on sea indicate BOLIVAR marine reflection profiles; small white circles indicate coincident active source ocean-bottom seismographs (OBS); solid red lines on land indicate onshore-offshore and land refraction profiles, with red stars denoting land shots. Yellow triangles indicate the Venezuelan broadband seismograph network; white and blue trianges indicate the broadband PASSCAL and Rice seismographs, respectively. White hexagons indicate broadband OBSIP recorders.

Tectonic Setting

The history of Caribbean tectonics and the Caribbean plate originates with the mismatch in the opening of the North and South Atlantic during the Late Jurassic–Early Cretaceous, between ~125 and 180 million years ago. Westward migration of South America followed that of North America by ~55 million years, with the result that today the South American Pacific coast is due south of the North American Atlantic coast.

The basement rocks of most of the Caribbean islands are part of an island arc built in the Cretaceous along the western periphery of the Americas known as the 'Great Arc of the Caribbean,' which was formed by eastward subduction of the now largely subducted Farallon plate [e.g., *Pindell and Dewey*, 1982; *Burke*, 1988]. At about 110 Ma, subduction polarity along the Great Arc

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Observations of the Inter-Ocean Exchange Around South Africa

There is growing evidence that the inter-ocean exchange south of Africa is an important link in the global overturning circulation of the ocean, the so-called ocean conveyer belt. At this location, warm and salty Indian Ocean waters enter the South Atlantic and are pulled by currents that eventually reach the North Atlantic, where water cools and sinks.

A major contributor to the exchange is the frequent shedding of ring eddies from the termination of the Agulhas Current south of the tip of Africa. This shedding is controlled by developments far upstream in the Indian Ocean, and variations in this 'Agulhas Leakage' can lead to changes in the rate and stability of the Atlantic overturning, with possible associated global climate variations [*Weijer et al.*, 1999]. Regional climate variations in the tropical and subtropical Indian Ocean are known to affect the whole system of the Agulhas Current, including the inter-ocean exchanges. This article reports on some of the seminal results of ongoing multinational, multidisciplinary projects that explore these issues.

In the Mozambique Channel, between Madagascar and southeast Africa, interannual ocean current fluctuations are coupled to the climate modes of the Indian Ocean and to global climate variations, in an as yet unquantified way. The current within the channel flows southward, and is connected upstream to monsoon-driven circulation and downstream to the interocean exchange system around South Africa.

The Long-Term Ocean Climate Observations (LOCO) program—funded by the Netherlands Organization for Scientific Research (NWO-groot), and carried out by the Royal Netherlands Institute for Sea Research (Royal NIOZ), the Institute for Marine and Atmospheric Research Utrecht (IMAU), and the Royal Netherlands Meteorological Institute (KNMI)—is measuring time-varying mass and heat transports through the use of an array of instrumented mooring across the Mozambique Channel's narrowest section, around 17°S (Figures 1 and 2). This array has been deployed in 2000 and will remain in place at least until early 2008.

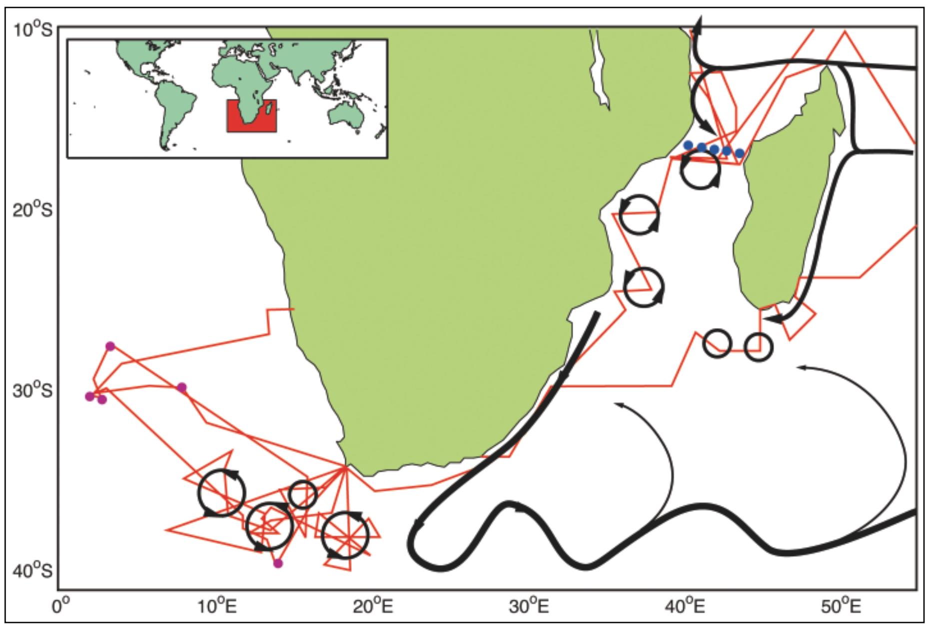

Fig. 1. The tracks of the MARE and ACSEX cruises. Black lines portray the surface ocean circulation; red lines portray cruise tracks. Blue dots indicate the locations of current meter moorings; red dots indicate sediment traps. Cruise tracks indicate the investigations that were carried out on Agulhas rings in the southeastern Atlantic Ocean as well as the hydrographic observations undertaken of eddies in the Mozambique Channel and south of Madagascar.

LOCO is based on two other NWO projects, the Mixing of Agulhas Rings Experiment (MARE, 1999–2004) and the Agulhas Current Sources Experiment (ACSEX, 2000–2001), carried out by researchers from IMAU, Royal NIOZ, KNMI, and the University of Cape Town. In MARE, the relevant processes related to the dissipation of rings from the Agulhas Leakage were investigated. Three cruises were dedicated to the evolution of one ring and included paleoceanographic and numerical model studies. During ACSEX, two cruises concentrated on the upstream developments in the Mozambique Channel and around Madagascar.

Agulhas Leakage and Ring Decay

During MARE, model studies using a Lagrangian method to follow water parcels have suggested that 90 percent of the upper water layers that cross the Atlantic equator northward are drawn from the Indian Ocean via the Agulhas Leakage and that less than 10 percent comes directly from the Pacific via the Drake Passage between Antarctica and South America [*Donners et al.,* 2004].

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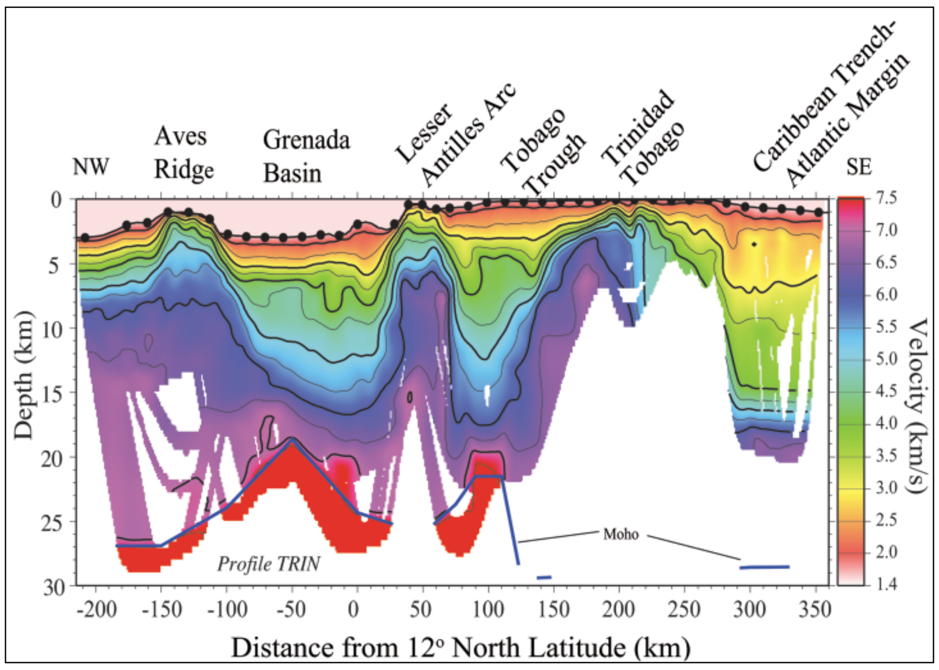

Fig. 2. First arrival and PmP reflection travel-time tomography model along profile TRIN. The profile extends 550 kilometers from the Venezuela basin across the Aves Ridge, the Lesser Antilles Arc passes between Trinidad and Tobago, and ends in the Atlantic. Crustal thickness varies from ~27–28 kilometers beneath the ridges to <20 kilometers beneath the Grenada and Tobago basins. The velocity structure under the Aves Ridge and Lesser Antilles Arc is similar to that beneath the Leeward Antilles (see Figure 3). Figure from G. Christeson, University of Texas Institute for Geophysics.

flipped from east-dipping to west-dipping, initiating the eastward migration of the Caribbean, with the trench consuming a proto-Caribbean plate that had formed by rifting and drifting between North and South America. The Caribbean plate, thought to be once part of Farallon, has moved little in the hotspot reference frame; the Americas began moving westward past it during the mid-Cretaceous, creating the tectonic configuration that is seen today. Prior to 80 Ma, the modern Caribbean plate became an oceanic plateau by poorly understood processes that have been attributed to fixed hot spots, transient plumes, and ridge subduction.

Modern Caribbean tectonics began with the collision of the Caribbean plate with South America and the Bahamas bank at about 55 Ma. Because the proto-Caribbean plate has been completely subducted, and much of the current Caribbean plate has been overprinted during the formation of the large igneous province, the only reliable magnetic anomaly data are in the Cayman trough spreading center, which also began at ~55 Ma. As a consequence, the pre-55 Ma history has been pieced together from global plate reconstructions and tectonic, petrologic, and sedimentological studies [e.g., *Pindell et al., 1988*].

Starting at 55 Ma, the mountain belts of northern South America were built diachronously from west to east as the southern periphery of the Caribbean plate, fronted by the Great Arc, collided obliquely with the South American margin [*Pindell et al.*, 1988]. This resulted in the time-transgressive development of the fold and thrust belt and foreland basin system, and exhumation of HP/LT rocks. Arc volcanism along the southern edge of the Great Arc in the collision zone was progressively shut off with the arc shedding its quiescent volcanic islands to the South American continental margin. Alternating transpression and transtension, (i.e., contraction and extension superimposed on a largely transcurrent fault system) since the initial collision have developed a strike-slip fault system rivaling California's San Andreas fault in length, complexity, and total displacement.

Today the Americas are subducting beneath the Caribbean plate in the east, the Cocos plate is subducting beneath it in the west, and the Caribbean itself is subducting beneath or being overthrust by South America in the southwest. The Atlantic subduction zone is the site of an active volcanic arc, whereas the southern Caribbean archipelago is largely avolcanic.

Project Experiments

Active seismic transects were acquired during an expedition of the research vessel (R/V) *Maurice Ewing* in April to June 2004 along much of the plate boundary (Figure 1). Five transects approximately along the 70th, 67th, 65th, and 64th meridians, and from the Venezuela basin past Trinidad and Tobago to the Atlantic were heavily instrumented. The seismic images along each of these transects provide a structural picture of the crust and mantle at different evolutionary stages of the Caribbean-South American plate interaction. This roughly gives snapshots of the time-transgressive structural evolution of the margin from ~55 to ~15 Ma on the meridional profiles, and the initial condition at 0 Ma along the profile past Trinidad-Tobago (Profile TRIN, Figure 2).

The meridional transects were acquired as marine reflection profiles and onshore-offshore wide-angle seismic profiles, the latter using as many as 49 ocean bottom seismographs (OBS) and ~550 land seismographs in Venezuela, with additional seismographs on the Leeward Antilles. TRIN was acquired as a reflection profile and OBS profile. Signals from the *Ewing* sound source array and eight on-land dynamite shots were recorded. Three of the Venezuelan transects were later reacquired as low-fold reflection profiles for GEODINOS. At present, data from the main transects are still being analyzed.

To investigate upper mantle structure, a broadband seismic experiment was fielded consisting of 27 PASSCAL, 8 Rice land instruments, and 15 long-term deployment OBS instruments. Complementing these 50 instruments was the 35-element, permanent broadband seismograph network installed by the Venezuelan Foundation for Seismological Investigations (FUNVISIS) shortly after 2000, resulting in a combined network of more than 80 broadband stations.

In addition to the geophysical experiments are structural geology studies and geothermometry and geobarometry analyses along some of the principle transects and in the Leeward Antilles. Age-dating using sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) instrumentation is providing a precise chronology of Leeward Antilles magmatism. Basin studies in both the onshore and offshore regions are providing information on Caribbean tectonics and paleogeography.

Preliminary Results

The marine reflection/wide-angle profile TRIN passing from the Atlantic to the Venezuela Basin provides a baseline seismic structure of the Lesser Antilles Arc and Aves Ridge, which are tectonically related to the islands of the Leeward Antilles islands now accreting to South America (Figures 1 and 2). Velocity models across the Leeward Antilles and continental mainland show large crustal thickness variations: about 27 kilometers beneath the islands, less than 20 kilometers beneath the basins, and ~25–40 kilometers beneath coastal Venezuela. Crustal velocities in the Leeward and Lesser Antilles are similar to, but lower than those of other modern island arcs (Figure 3). Though previous geologic and geochemical investigations have called into question whether all of the Leeward Antilles are island arc rocks in the traditional sense [e.g., *White et al.*, 1999; *Wright and Wyld*, 2004], further investigations are still needed to draw definitive conclusions.

Crustal thickening, thinning, and uplift are observed throughout the plate boundary zone, but particularly so in western Venezuela in the Sierra de Falcon, where both the overthrusting of Caribbean accretionary terranes onto Venezuela and underthrusting of the Caribbean plate beneath South America are greatest. In eastern Venezuela, the seismic data show incipient subduction of the Caribbean plate seaward of the plate boundary resulting from North America/South America convergence.

Another striking observation is the association of bodies of high compressional velocity rocks (~7.0 kilometers per second) at shallow crustal depths with the Oca-San Sebastian-El Pilar strike-slip fault system, the major plate-boundary strike-slip faults. These rocks are interpreted as formerly subducted HP/LT metamorphic and/or mantle rocks being exhumed by displacement partitioning and transtensional and transpressional processes which have occurred during 55 million years of oblique plate convergence [e.g., *Avé Lallemant*, 1997].

Initially a U.S.-Venezuelan collaboration, the combined project has now expanded to include seismic installations on Aruba and Curaçao operated by the Netherland Antilles Meteorological Service, and cooperative seismic studies with the seismologists at the Seismic Research Unit of the University of the West Indies, Trinidad-Tobago. Although the initial objective of BOLIVAR/GEODINOS was to study modern island arc accretion and deformation as a continental growth process, an added benefit of the studies will be to provide better locations and source mechanisms of small magnitude earthquakes recorded by the various seismic arrays. This will better characterize the seismogenic faults, seismotectonics, and earthquake hazards of the entire region. Also, the large scale of the project (covering an area about the size of California and its continental margin) will provide a better tectonic understanding of the evolution of the southeastern Caribbean plate boundary, an aid to hydrocarbon exploration in this energy-rich area.

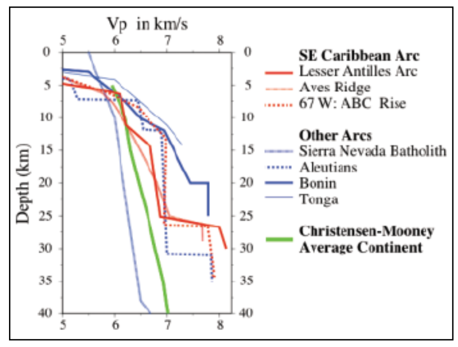

Fig. 3. P-velocity profiles from the Lesser Antilles, the Aves Ridge, and the Leeward Antilles (in red) compared with a number of island arcs and the Sierra Nevada batholith, a former continental arc. Also shown is the Christensen and Mooney *[1995] average crustal velocity profile. The Caribbean arcs are substantially slower than Tonga and Bonin and somewhat slower than the Aleutians. They are somewhat higher in velocity than the Christensen-Mooney average, and substantially higher than the Sierra Nevada. This indicates a composition somewhat more mafic than the crustal average, although less mafic than other island arcs. Figure from A. Arogunmati, Rice University.*

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