Evolution of the Southern Caribbean Plate Boundary

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

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 model calls 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 multidisciplinary projects, BOLVAR and GEODINOS, are investigating continental growth and deformation processes along the southeastern Caribbean-South American plate boundary (Figure 1). BOLVAR is the US project Broadband Ocean-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 BOLVAR and GEODINOS scientists are testing is that the Lee- ward 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) subduc- tion-related metamorphic rocks are formed. The project is also addressing earthquake hazard assessed in the diffuse Southeast Caribbean plate boundary.

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 mil- lion 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 within the channel flows southward, and is connected upstream to monsoon-driven circula- tion and downstream to the interoceanic exchange system around South Africa. The Long-Term Ocean Climate Observa- tions (LOC0) program—funded by the Neth- erlands Organization for Scientific Research (NWO-oog), and carried out by the Royal Netherlands Institute for Sea Research (Royal NIOZ), the Institute for Marine and Atmo-

Observations of the Inter-Ocean Exchange Around South Africa

There is growing evidence that the inter-ocean exchange south of Africa is an impor- tant link in the global overturning circula- tion of the ocean, the so-called oceanic conveyor 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 terminus 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 Leak- age can lead to changes in the rate and the li- ability of the Atlantic overturning with possi- ble associated global climate variations (Hijili et al., 1999). Regional climate varia- tions in the tropical and sub tropical Indian Ocean are known to affect the whole system of the Agulhas Current, including the inter-oceanic exchange. This article reports on some of the seminal results of ongoing multinational, multidisciplinary projects that explore this exchange.

In the Mozambique Channel, between Madagascar and southeast Africa, inter-

annual ocean current fluctuations are cou- pled 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 cir- culation and downstream to the interoceanic exchange system around South Africa. The Long Term Ocean Climate Observa- tions (LOC0) program—funded by the Neth- erlands Organization for Scientific Research (NWO-oog), and carried out by the Royal Netherlands Institute for Sea Research (Royal NIOZ), the Institute for Marine and Atmo-

spheric Research Utrecht (MIAM), and the Royal Netherlands Meteorological Institute (KNMI)—is measuring time-varying mass and heat transports through the use of an array of instrumented moorings across the Mozam- bique 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. LOC0 is based on two other NWO proj- ects, the Mixting of Agulhas Rings Experi- ment (MARE, 1999–2004) and the Agulhas Current Sources Experiment (ACSEX, 2000–2001), carried out by researchers from IAM, Royal NIOZ, KNMI, and the University of Cape Town. In MARE, the rele- vant 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 con- centrated 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 layer that crosses the Atlantic Ocean 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 (Dronkers et al., 2004).
flipped from east-dipping to west-dipping initiating the eastern migration of the Caribbean, with the trench consuming a proto-Caribbean plate that had been rifted 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 American began moving westward just it during the Cretaceous, creating the tectonic configuration as 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 Bahama 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 plate reconstructions and tec- tonic, petologic, and sedimentological studies (e.g., Pradler et al. 2008).

Starting at 55 Ma, the mountain belts of northern South America were built diachronically from west to east to form the southern boundary of the Caribbean plate, frontal to the Great Arc, colliding obliquely with the South American margin (Pradler et al. 1998). This resulted in the transform-sequence development of the fold and thrust belt and basin systems and initiation of HP/LT rocks in arc volcanism along the southern edge of the Great Arc in the collision zone was progressively shut off with the arc shedding its quies- cent volcanic islands to the South American continental margin. Alternating transpression and transtension, (i.e., contraction and exten- sion superimposed on a largely transform fault system) since the initial collision has developed a strike-slip fault system linking California’s San Andreas fault in length, com- pletely and total displacement. Today the American Arc is subducting beneath the Caribbean plate in the east, the Cocos plate is subducting beneath it in the west and the Caribbean is subducting beneath or being covered by South Amer- ica in the southwest. The Atlantic subduction zone is the site of an active volcanic arc, whereas the southern Caribbean archipelago is largely avacata.

Project Experiments

Active seismic transects were acquired during an expedition of the research vessel (RV) Murea Euring in April to June 2004 along much of the plate boundary (Figure 1). Five transects approximately along the 70th, 76th, 67th, 65th, and 64th meridians, and from the Venezuela basin past Trinidad and Tobago to the Atlantic were heavily instru- mented. The seismic images along each of these transects provide a structural picture of the crust and mantle at different evolu- tionary stages of the Caribbean-South Amer- ican 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 Tin- idal-Tabago (Profile TRIN, Figure 2).

The meridional transects were acquired as marine reflection profiles and onshore-off- shore wide-angle seismic profiles, the latter using as many as 40 ocean bottom seismo- grams (OBS) and ~150 land seismographs in Venezuela, with additional seismographs on the Leeward Antilles. TRIN was acquired as a reflection profile and OBS profile. Signals from the existing sound source array and eight on-distant shaker shots were recorded These Leeward Antilles transects were later rec- ognized as low-fold reflection profiles for GEO- NIES. At present, data from the main tran- sects are still being analyzed.

To investigate upper mantle structure, a broadband seismic experiment was carried out consisting of 27 PASSCAL, 8 Rice land instru- ments, and 15 long-term deployment OBS instruments. Complementing these 50 instru- ments was the 35-element, permanent, broadband seismograph network installed by the Venezuelan Foundation for Seismo- logical Investigations, the FUNDIVIS, shortly after 2000, resulting in a combined network of more than 80 broadband stations. In addition to the geological experi- ments are structural geology studies and geophysical and geocronology analy- ses along some of the principle transects and in the Leeward Antilles Age-dating volcanics with sensitive high resolution optical and Rb-Sr isotope analyses to provide a precise chronology of Leeward Antilles magmatism: Basin studies in both the onshore and off- shore areas are providing information on Caribbean tectonics and paleogeography.

Preliminary Results

The marine reflection-wide-angle profile TRIN passing from the Atlantic to the Vene- zuela Basin provides a baseline seismic picture of the Leeward Antilles and Aruba, which are tectonically related to the Islands of the Leeward Antilles island arc system, according to South America (Figures 1 and 2). Velocity models across the Leeward Antil- les and continental mainland show large variations in crustal thickness variations: about 27 kilo- meters beneath the islands, less than 20 kilo- meters beneath the basins, and 25–45 kilo- meters 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 previ- ous geologic and geophysical investiga- tions have called into question whether all of the Lesser Antilles is island arc rocks in the traditional sense (e.g., White et al., 1996; Wright and Windley, 2004), further investiga- tions 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 Falcón, where both the over- thrusting of Caribbean accretionary terranes onto Venezuela and underthrusting of the Caribbean plate beneath South America are greatest. In eastern Venezuela, the seismic data suggest incipient subduction of the Carib- bean plate seaward of the plate boundary returning from North America/South America convergence.

A striking observation is the associa- tion of bodies of high compressional velocity rocks (~7.6 kilometers per second) at shallow crustal depths in the Osa-San Blas- ti-Enamillar strike 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 transcontinental and transtensional processes which have occurred during 55 million years of oblique plate convergence (e.g., deihthe- van der Meulen, 1997).

Initially a U.S.-Venezuelan collaboration, the combined project has now expanded to include seismic installations on Aruba and Curacao operated by the Netherlands Antilles Meteorological Service, and coop- erative seismic studies with the seismolo- gists at the Seismic Research Unit of the University of the West Indies, Trinidad, and Tobago. Although the initial objective of BOLIVAR/GEOGONIES was to study modern island arcs: accretion and deformation as a continental growth process, an added ben- efit 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 char- acterize the seismogenic faults, seismolo- gists, and earthquake hazards of the entire region. Also, the larger area of the project (covering an area of the size of California and its continental borderlands) will provide a better tectonic understanding of the evolution of the southeastern Caribbean plate boundary, an aid to hydrocar- bon exploration in this energy-rich area.

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Author Information

Alan Lavender Department of Earth Sciences, Rice University Houston, Tex. Email alan@rice.edu

Ming-Hua Wang Department of Earth Sciences, University of Houston, Houston, Texas

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Fig. 3. Positions profile of the Lesser Antil- les, the Aruba Ridge and the Leeward Antilles (in red) compared with a number of island arc systems in Venezuela/South America and continental arc. Also shown is the Christens and Mooney (1995) average crustal velocity profile for islands and continental arcs in South America which are slower than Yucatán and Bonaire and somewhat slower than the Antillean. They are generally higher in velocity than the Christens and 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.

Fig. 2. First arrival and Pn reflection traveltime tomography model along profile TRIN. The profile extends 550 kilometers from the Venezuela basin across the Arusz 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 Arusz Ridge and Lesser Antilles Arc is similar to that beneath the Leeward Antilles (see Figure 3). Figure from G. Christens, University of Texas Insti- tute for Geophysics.

Fig. 1. Plate cont. from page 97

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